Optimal Monetary Policy in an Estimated DSGE Model of the Euro Area with Cross-Country Heterogeneity*

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This paper investigates the implications of cross-country heterogeneity within the euro area for the design of optimal monetary policy. We build an optimization-based multicountry model (MCM) describing the euro area in which differences between structural parameters across countries are allowed. Using Bayesian techniques, we estimate the MCM and its area-wide counterpart (AWM). We then question which model is the most appropriate for monetary policy purposes. Several results emerge. First, using an AWM induces relatively large and significant welfare losses. Second, this is not the use of a rule based on aggregated variables that is costly in terms of welfare, but rather the use of a suboptimal forecasting model. Third, allowing for habit on consumption has important implications for the dynamics of models, but taking into account differences in price indexation has more drastic effects on welfare losses.

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1. Introduction

The Maastricht Treaty (article 105) states that the primary objective of the European Central Bank (ECB) is to maintain price stability within the European Monetary Union. Although the ECB may use a battery of economic indicators—including country-specific ones—in order to fulfill this primary objective, it makes decisions on the basis of aggregate developments, while national idiosyncrasies are left to the care of national governments. The consequences of such a constraint on the monetary policy of the euro area are obviously related to the extent and the nature of heterogeneity of countries within the area. Since the decisions have to be made on the basis of aggregate developments only, it may be argued that, since objectives are defined in terms of aggregate variables, an area-wide model (AWM) would be sufficient for capturing most characteristics of the euro-area economy. On the other hand, a multicountry model (MCM) may help capture the heterogeneity of countries and therefore offer valuable information about the state of the euro-area economy. Consequently, it would help define a more appropriate monetary policy rule. As a result, it is not clear a priori what type of forecasting model (multicountry or area-wide) should be used for implementing an optimal monetary policy.

To investigate the role devoted to country-specific information in the decision process regarding the Eurosystem, the standard approach to policy evaluation can be followed (see the contributions in Taylor 1999): the optimal policy rule is determined so as to minimize the expected value of an intertemporal loss function, under the constraint provided by a low-dimensional multicountry model of the euro area. Assuming that the monetary authority is exclusively interested in area-wide objectives, it is possible to compare the performance of two optimal reaction functions based on an MCM and an AWM, respectively. Such a comparison has already been performed in a few sets of contributions, revealing that the loss associated with the neglect of country-specific information might be large.[1] However, in these studies, the underlying macroeconomic

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[1] The literature includes De Grauwe (2000), De Grauwe and Piskorki (2001), Aksoy, De Grauwe, and Dewachter (2002), Angelini et al. (2002), and Monteforte and Siviero (2003), among others.

models are not designed in an optimization-based framework. Consequently, the optimal monetary policy deduced from such models is subject to the Lucas critique, since it is based on reduced-form, rather than structural, parameters. This is a serious limitation when the welfare resulting from an optimal policy rule has to be evaluated.

The objective of this paper is to reassess and generalize the preceding results in investigating how heterogeneity of agents across euro-area countries is likely to affect the optimal monetary policy using an *optimization-based framework.* More precisely, we measure the welfare cost of using an AWM instead of an MCM to evaluate the optimal monetary policy. The basic idea is that the MCM is designed to capture the cross-country heterogeneity and thus to describe more accurately the way monetary policy affects the economy. Consequently, a welfare-maximizing central bank may be able to implement a more efficient monetary policy, even if the policy rule is assumed to be based on aggregate variables only. An obvious shortcoming of the MCM is that its estimation is much more demanding, since it requires modeling the joint dynamics of several economies as well as the international transmission mechanisms. In addition, the MCM is likely to induce a large amount of country-specific uncertainty, while an AWM may average these errors. Conversely, the estimation of an AWM is likely to induce an aggregation bias if structural parameters actually differ across countries. Such a bias has already been highlighted in the context of the Phillips curve (see Demertzis and Hughes Hallett 1998, Benigno and López-Salido 2006, or Altissimo, Mojon, and Zaffaroni 2007), but its consequences on the optimal monetary policy in a complete model have not been explored up to now.

In the class of dynamic stochastic general equilibrium (DSGE) models, several alternative models provide plausible frameworks to take heterogeneity into account. Our approach consists of designing a low-dimensional model that fits the data fairly well. The first reason for doing so is that in a simple structural model, the underlying mechanisms are easy to understand and the subsequent welfare analysis is transparent. Second, to measure the effect of cross-country heterogeneity on monetary policy, we need to estimate the structural parameters of all the individual economies. As a consequence, a low-dimensional model is required to obtain consistent estimates. Estimation is based on Bayesian techniques, which seem to be the best way to determine an empirically realistic specification of the heterogeneity.

The model we consider resorts to the “new open-economy macroeconomics” literature, initiated by Obstfeld and Rogoff (1995). In addition to significant frictions in the form of nominal rigidities, other mechanisms are introduced: (i) cross-country differences in the structural parameters are allowed, since we are primarily interested in the effect of such heterogeneity on the design of the optimal monetary policy, (ii) perfect risk sharing and a home bias in preferences are incorporated in the model to deal with exchange rate indeterminacy, and (iii) cross-country correlations between shocks are introduced to capture co-movement in the joint dynamics of national conditions.

Following the strategy described above, we first estimate two models, mimicking the way the ECB forecasts macroeconomic developments within the Eurosystem. In the first one, we adopt an open-economy framework and model the joint dynamics of the data for the major countries in the euro area (Germany, France, and Italy). In the second one, we model the dynamics of area-wide macroeconomic data. Our empirical evidence suggests that there exists some significant heterogeneity within the euro area, even among core countries. First, we obtain some significant differences between estimates of the structural parameters at the euro-area level and at the country level, suggesting an aggregation bias. But more importantly, we find that the main source of heterogeneity is the weak correlation between shocks across countries.

Then, we investigate how cross-country heterogeneity affects the design of optimal monetary policy within the euro area. We consider two alternative modeling approaches. In both of them, the central bank defines its preferences and its loss function at the area-wide level, and the reaction function is designed in terms of aggregate variables only. In the first approach the MCM, estimated using country-specific data, is used for computing the loss function, while in the second approach the AWM, estimated using aggregated data, is used. Then, we evaluate the optimal monetary policy that maximizes the aggregate welfare, both under the AWM and the MCM, and we measure the welfare cost of using the AWM (suboptimal) forecasting model. We obtain that the welfare cost is quite significant, both statistically and economically. It appears to be related mainly to nominal rigidities rather than to real rigidities.

The remainder of the paper is organized as follows. In section 2, we describe the theoretical MCM. In section 3, we present the data and the estimates of the MCM and AWM. In section 4, we determine the optimal monetary policy under the two forecasting models and evaluate the welfare implications of using the (suboptimal) AWM model. Section 5 summarizes our main findings and concludes.

2. Structure of the Stylized Multicountry Model

The euro area is modeled as the aggregate of several economies. For each country, we formulate a small-size open-economy model, which is inspired by recent theoretical models derived from the "new open-economy macroeconomics" literature.[2] The model is enriched in several dimensions to offer a comprehensive framework that encompasses other previous contributions. In terms of dynamics, first, key modifications are the explicit incorporation of habit formation in the households' preferences and partial indexation in a price-setting framework à la Calvo (1983). These assumptions provide us with microfounded "hybrid" versions of the IS and Phillips curves. Second, contrary to most recent studies on DSGE models, we do not assume that preferences and technologies are the same across countries, since we are interested in measuring the effect of heterogeneity on the optimal monetary policy of the area. In addition, domestic and foreign shocks are allowed to be imperfectly correlated. Third, we resort to the perfect-risk-sharing assumption. Although this assumption is admittedly heroic in empirical work, it avoids assuming nonrational expectations of exchange rate, which has been shown to be an alternative way of dealing with nonstationarity. Finally, households are assumed to have a taste bias toward goods produced in their home country. Since preferences differ across countries, the price of consumption bundles will differ when expressed in

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[2] See, among others, Monacelli (2001), Clarida, Galí, and Gertler (2002), Smets and Wouters (2002), Benigno and Benigno (2003), Devereux and Engel (2003), P. Benigno (2004), Corsetti and Pesenti (2005), and Galí and Monacelli (2005).

a common currency. The real exchange rate thus deviates from purchasing power parity (PPP).[3] This assumption is crucial, because it allows the perfect-risk-sharing equation to determine uniquely the dynamics of the terms of trade.

In order to lighten the notations, we assume that there are two countries in the euro area, denoted H (home) and F (foreign). Since commercial links are much stronger between countries within the area than with countries outside the area, we neglect trade with the rest of the world. The population of the euro area is a continuum of agents on the interval $[0, 1]$. The population of country H belongs to $[0, n)$, while the foreign population belongs to $[n, 1]$. Therefore, n is the relative measure of the home-country size in the euro area. An agent in the home country is indexed $h \in [0, n)$, while a foreign agent is indexed $f \in [n, 1]$. Variables in the home country are denoted X_t, while foreign variables are denoted X_t^*. The home economy produces a continuum of differentiated goods indexed on the interval $[0, n)$. Foreign goods (or, equivalently, goods produced in the rest of the area) are indexed on the interval $[n, 1]$. All goods are tradable.

2.1 Households

The home economy is populated by infinitively living households consuming Dixit-Stiglitz aggregates of domestic and imported goods. A home household h owns a firm producing goods h and receives dividends from it. We assume that households in a given country have the same preferences and endowments. Although there may be idiosyncratic shocks among households, we assume that households have access to complete markets for state-contingent claims, so that there is no heterogeneity among agents in a given country. Consequently, all households in the same country behave in the same manner, and then we consider the optimization problem of a representative household. The representative household in country H maximizes the following expected sequence of present and future utility flows

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[3] An earlier contribution that introduced home-country bias in preferences is due to Warnock (2000).

that depends positively on consumption (C_t) and negatively on labor (hours worked, L_t):[4]

$$\mathcal{U}_t = \mathbb{E}_t \sum_{k=0}^{\infty} \beta^k \varepsilon_{p,t+k} \left[\frac{1}{1-\sigma}(C_{t+k} - \gamma \mathcal{H}_{t+k})^{1-\sigma} - \frac{1}{1+\varphi}(L_{t+k})^{1+\varphi} \right], \tag{1}$$

subject to a series of real-period budget constraints:

$$C_t + \frac{B_{t+1}}{(1+i_t)P_t} + \frac{T_t}{P_t} = \frac{W_t L_t}{P_t} + \frac{B_t}{P_t} + \frac{\Pi_t}{P_t}, \tag{2}$$

where $\mathbb{E}_t$ denotes the expectation operator conditional on the information set at time t; β is the intertemporal discount factor, with $0 < \beta < 1$; σ is the inverse of the intertemporal elasticity of substitution of consumption; and φ is the inverse of the elasticity of labor disutility with respect to hours worked. In addition, W_t is the nominal wage income, Π_t is the dividend received from home firms, T_t represents nominal lump-sum government transfers, and i_t is the nominal interest rate. $\varepsilon_{p,t}$ denotes a country-specific preference shock that affects the intertemporal substitution of all households in the same manner in the home economy. Preferences display external habit formation as in Abel (1990). The habit stock is supposed to equal the level of aggregate consumption in the previous period ($\mathcal{H}_t = C_{t-1}$), and γ represents the habit-persistence parameter, measuring the effect of past consumption on current utility ($0 \leq \gamma < 1$). Finally, we assume complete markets for state-contingent claims. Consequently, households can transfer wealth to the next period by holding B_{t+1} units of the one-period nominal bond denominated in the domestic currency.[5]

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[4] We abstract from money in this model since the central bank adjusts money supply to satisfy money demand with a simple feedback rule.

[5] More precisely, at date t, home households hold $B(s^{t+1}) = B_{t+1}$ units of the one-period bond denominated in home currency that pay 1 at date $t+1$ if state s_{t+1} occurs and 0 otherwise, where $s^t = (s_0, \cdots, s_t)$ denotes the story of events up to date t. Foreign households hold $B^*_t(s^{t+1}) = B^*_{t+1}$ units of such bond. The price of this bond in home currency is denoted by $\Phi(s^t, s^{t+1}) = \Phi_{t,t+1}$. The price at date t of the portfolio held by home households is thus given by $E_t[\Phi_{t,t+1}B_{t+1}]$. We define the one-period interest rate as $1 + i_t = 1/E_t[\Phi_{t,t+1}]$.

The maximization problem of the home household consists in maximizing equation (1) subject to constraint (2), yielding the optimal profile of consumption—holdings of domestic bond and labor supply. The first-order conditions imply[6]

$$\mathcal{U}_{C,t} = \varepsilon_{p,t}(C_t - \gamma\mathcal{H}_t)^{-\sigma}, \tag{3}$$

$$(1+i_t)^{-1} = \beta\mathbb{E}_t\left[\frac{\mathcal{U}_{C,t+1}}{\mathcal{U}_{C,t}}\frac{P_t}{P_{t+1}}\right], \tag{4}$$

$$\frac{\mathcal{U}_{L,t}}{\mathcal{U}_{C,t}} = \frac{W_t}{P_t}, \tag{5}$$

where $\mathcal{U}_{X,t}$ denotes the derivative of utility $\mathcal{U}$ with respect to variable X at period t. Equation (3) defines the marginal utility of consumption. Equation (4) is the usual Euler equation for intertemporal consumption flows. It establishes that the ratio of marginal utility of future and current consumption is equal to the inverse of the real interest rate. Equation (5) is the condition for the optimal consumption-leisure arbitrage, implying that the marginal rate of substitution between consumption and labor is equated to the real wage.

2.1.1 Composite Consumption Index

The aggregate consumption index for home households and the corresponding consumption index for foreign households are defined by[7]

$$C_t = \frac{(C_{H,t})^{\omega}(C_{F,t})^{1-\omega}}{\omega^{\omega}(1-\omega)^{1-\omega}} \quad \text{and} \quad C_t^* = \frac{\left(C_{H,t}^*\right)^{\omega^*}\left(C_{F,t}^*\right)^{1-\omega^*}}{(\omega^*)^{\omega^*}(1-\omega^*)^{1-\omega^*}}, \tag{6}$$

where ω and ω^* denote the share of home goods in the consumption of home and foreign households, respectively. $C_{H,t}$ (resp. $C_{F,t}$)

Note that, since bonds are state-contingent, including bonds denominated in foreign currency would be redundant. For more details, see Chari, Kehoe, and McGrattan (2002).

[6] We abstract here from the optimal intratemporal allocations between domestic and foreign goods.

[7] As shown by Corsetti and Pesenti (2005), the Cobb-Douglas consumption index is a sufficient condition for the trade to be invariably balanced.

is the subindex of consumption of imperfectly substitutable home (resp. foreign) goods, which is in turn given by the following CES aggregators:

$$C_{H,t} = \left[\left(\frac{1}{n} \right)^{1/\theta} \int_0^n C_t(h)^{\frac{\theta-1}{\theta}} \mathrm{d}h \right]^{\frac{\theta}{\theta-1}} \quad \text{and}$$

$$C_{F,t} = \left[\left(\frac{1}{1-n} \right)^{1/\theta} \int_n^1 C_t(f)^{\frac{\theta-1}{\theta}} \mathrm{d}f \right]^{\frac{\theta}{\theta-1}}, \tag{7}$$

where $C_t(h)$ (resp. $C_t(f)$) is consumption of the generic good h (resp. f) produced in country H (resp. F). Parameter θ denotes the elasticity of substitution across goods produced within a given country. The corresponding consumption price indexes (CPIs) are given by

$$P_t = (P_{H,t})^{\omega}(P_{F,t})^{1-\omega} \quad \text{and} \quad P_t^* = \left(P_{H,t}^*\right)^{\omega^*} \left(P_{F,t}^*\right)^{1-\omega^*}.$$

Here, $P_{H,t}$ (resp. $P_{F,t}$) is the price subindex for home-produced (resp. foreign-produced) goods expressed in the home currency, defined as

$$P_{H,t} = \left[\frac{1}{n} \int_0^n P_{H,t}(h)^{1-\theta} \mathrm{d}h \right]^{\frac{1}{1-\theta}} \quad \text{and}$$

$$P_{F,t} = \left[\frac{1}{1-n} \int_n^1 P_{F,t}(f)^{1-\theta} \mathrm{d}f \right]^{\frac{1}{1-\theta}},$$

where $P_{H,t}(h)$ (resp. $P_{F,t}(f)$) is the price in units of country H of a generic good h (resp. f) produced in country H (resp. F).

We also assume that prices are set in the producer currency and that the law of one price holds. We then have $P_{H,t}(h) = P_{H,t}^*(h)S_t$ and $P_{F,t}(f) = P_{F,t}^*(f)S_t$, where S_t is the nominal exchange rate expressed as units of domestic currency needed for one unit of foreign currency.[8] Since we assume the same elasticity of substitution

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[8] Although it has been investigated in a number of recent papers, we do not consider here the presence of imperfect exchange rate pass-through. A reason is that it is not likely to be an important feature across countries within the euro area. In addition, this feature is obviously irrelevant from the euro-area point of view.

among goods in a given country, we also have $P_{H,t} = P^*_{H,t} S_t$ and $P_{F,t} = P^*_{F,t} S_t$. Yet, from the definition of the CPI, we obtain that

$$P_t = P^*_t S_t \left(\frac{P_{H,t}}{P_{F,t}} \right)^{\omega - \omega^*}.$$

Therefore, if we assume that there exists a home bias in preferences ($\omega \neq \omega^*$), PPP does not necessarily hold; i.e., $P_t \neq P^*_t S_t$. We expect $\omega > \omega^*$, so that home households put a higher weight on home goods than foreign households.

2.1.2 International Risk Sharing

Under the assumption of complete markets, domestic and foreign households trade in state-contingent claims denominated in the home currency. This implies the following perfect-risk-sharing condition (Chari, Kehoe, and McGrattan 2002):

$$Q_t = \kappa \frac{\mathcal{U}^*_{C^*,t}}{\mathcal{U}_{C,t}}, \tag{8}$$

where the real exchange rate, defined as $Q_t \equiv S_t P^*_t / P_t$, is proportional to the ratio of the marginal utility of consumption between the two countries.[9] The assumption of international market completeness ensures that, in our model, the real exchange rate and consumption are stationary variables (see also G. Benigno 2004).

Since the real exchange rate deviates from PPP because of home bias in preferences, we also have

$$Q_t = \left(\frac{S_t P^*_{H,t}}{P_{H,t}} \right)^{\omega^*} \left(\frac{S_t P^*_{F,t}}{P_{F,t}} \right)^{1-\omega^*} \left(\frac{P_{F,t}}{P_{H,t}} \right)^{\omega - \omega^*} = (\mathcal{T}_t)^{\omega - \omega^*}, \tag{9}$$

where $\mathcal{T}_t$ represents the home terms of trade, i.e., the relative price between foreign and home bundles of goods as perceived by the home resident. It is defined as[10]

$$\mathcal{T}_t = \frac{P_{F,t}}{P_{H,t}} = \frac{S_t P^*_{F,t}}{P_{H,t}}. \tag{10}$$

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[9] $\kappa = [S_0 P^*_0 \mathcal{U}_{C,0}]/[P_0 \mathcal{U}^*_{C^*,0}]$ is a constant that depicts the initial condition.

[10] The foreign terms of trade are simply given by $\mathcal{T}^*_t = P^*_{H,t}/P^*_{F,t} = 1/\mathcal{T}_t$, because the law of one price holds.

Using equations (3), (8), and (9), this definition implies the following:

$$(\mathcal{T}_t)^{\omega-\omega^*} = \kappa \frac{\varepsilon^*_{p,t}(C_t - \gamma C_{t-1})^{\sigma}}{\varepsilon_{p,t}\left(C^*_t - \gamma^* C^*_{t-1}\right)^{\sigma^*}}. \tag{11}$$

Note that, when there is no home bias in preferences ($\omega = \omega^*$), the perfect-risk-sharing assumption does not allow us to determine the terms of trade anymore.

Combining Euler equation (4) with the perfect-risk-sharing equation (8), we obtain the following dynamics for the real exchange rate and the terms of trade:

$$\mathbb{E}_t\left[\frac{Q_{t+1}}{Q_t}\right] = \mathbb{E}_t\left[\frac{\mathcal{U}^*_C(C^*_{t+1})\mathcal{U}_C(C_t)}{\mathcal{U}^*_C(C^*_t)\mathcal{U}_C(C_{t+1})}\frac{P^*_t P_{t+1}}{P_t P^*_{t+1}}\right] = \frac{1+i_t}{1+i^*_t} \tag{12}$$

$$\mathbb{E}_t\left[\frac{\mathcal{T}_{t+1}}{\mathcal{T}_t}\right] = \mathbb{E}_t\left[\frac{P^*_{F,t+1}P_{H,t}}{P_{H,t+1}P^*_{F,t}}\frac{1+i_t}{1+i^*_t}\right]. \tag{13}$$

Equation (12) is the uncovered interest rate parity (UIP) condition, which states that the expected change in the exchange rate is exactly compensated by the real interest rate differential. It is worth emphasizing that the UIP condition is not an additional implication in the model, but rather a redundant relation.

2.2 Firms

There is a continuum of infinitely living and monopolistically competitive firms indexed by h on the interval $[0, n)$ for the home country and by f on the interval $[n, 1]$ for the foreign country. These firms produce differentiated goods that are bundled into homogeneous home and foreign goods by a constant returns to scale of the Dixit-Stiglitz form:

$$Y_t = \left[\left(\frac{1}{n}\right)^{1/\theta}\int_0^n Y_t(h)^{\frac{\theta-1}{\theta}}\mathrm{d}h\right]^{\frac{\theta}{\theta-1}} \quad \text{and}$$

$$Y^*_t = \left[\left(\frac{1}{1-n}\right)^{1/\theta}\int_n^1 Y^*_t(f)^{\frac{\theta-1}{\theta}}\mathrm{d}f\right]^{\frac{\theta}{\theta-1}}.$$

The production technology of the representative home firm h combines labor as primary input and a country-specific productivity shock:

$$Y_t(h) = \varepsilon_{a,t} L_t(h). \tag{14}$$

Output is normalized by population size, so that it is expressed in per capita terms. We thus deduce that total home labor demand is given by

$$L_t = \int_0^n L_t(h)\mathrm{d}h = \frac{\Delta_t Y_t}{\varepsilon_{a,t}}, \tag{15}$$

where $\Delta_t = \int_0^n \frac{Y_t(h)}{Y_t}\mathrm{d}h$ represents the dispersion of production across firms in the home economy.

Since input markets are perfectly competitive and country specific, the standard static first-order condition for cost minimization implies that all domestic firms have identical real marginal cost, MC_t, given by

$$MC_t = \frac{1}{(1+\vartheta)} \frac{W_t}{P_{H,t}\varepsilon_{a,t}}, \tag{16}$$

where ϑ is a subsidy for output that offsets the effect of imperfect competition in goods markets on the steady-state level of output $(0 \leq \vartheta < 1)$.

A firm's price-setting decision is modeled through a modified version of Calvo's (1983) staggering mechanism. In addition to the baseline mechanism, we allow for the possibility that firms that do not optimally set their prices may nonetheless adjust them to keep up with the previous-period increase in the general price level (see Sbordone 2003 and Christiano, Eichenbaum, and Evans 2005 for details concerning this assumption). In each period, a firm faces a constant probability, $1 - \alpha$, of being able to reoptimize its price and chooses the new price $\tilde{P}_{H,t}(h)$ that maximizes the expected discounted sum of profits

$$\mathbb{E}_t \sum_{k=0}^{\infty} \alpha^k \Upsilon_{t,t+k} \left[\frac{\tilde{P}_{H,t}(h)\Psi^H_{t,t+k}}{P_{H,t+k}} - MC_{t+k} \right] Y_{t+k}(h), \tag{17}$$

subject to the sequence of demand equations

$$Y_{t+k}(h) = \left(\frac{\tilde{P}_{H,t}(h)\Psi^H_{t,t+k}}{P_{H,t+k}} \right)^{-\theta} Y_{t+k}, \tag{18}$$

where $\Upsilon_{t,t+k} = \beta^k \mathcal{U}_C(C_{t+k})/\mathcal{U}_C(C_t)$ is the discount factor between time t and $t+k$, and

$$\Psi^H_{t,t+k} = \begin{cases} \prod_{\nu=0}^{k-1} (\bar{\pi}_H)^{1-\xi}(\pi_{H,t+v})^{\xi} & k > 0 \\ 1 & k = 0, \end{cases} \tag{19}$$

where $\bar{\pi}_H$ is the domestic trend inflation and the coefficient $\xi \in [0,1]$ indicates the degree of indexation to past prices during the periods in which the firm is not allowed to reoptimize. $\Psi^H_{t,t+k}$ is a correcting term that accounts for the fact that if the firm h does not reoptimize its price, it updates its price according to the rule

$$P_{H,t}(h) = (\bar{\pi}_H)^{1-\xi}(\pi_{H,t-1})^{\xi} P_{H,t-1}(h). \tag{20}$$

Consequently, the first-order condition associated with the profit maximization implies that firms set their price equal to the discounted stream of expected future real marginal costs:

$$\mathbb{E}_t \sum_{k=0}^{\infty} \alpha^k \Upsilon_{t,t+k} \left[(\bar{\pi}_H)^{(1-\xi)k} \left(\frac{P_{H,t+k-1}}{P_{H,t-1}} \right)^{\xi} \frac{\tilde{P}_{H,t}(h)}{P_{H,t+k}} - \frac{\theta}{\theta - 1} MC_{t+k} \right] \times Y_{t+k}(h) = 0. \tag{21}$$

If flexible prices is assumed ($\alpha = 0$), this expression gives the optimal relative price $\tilde{P}_{H,t}(h)/P_{H,t} = \mu MC_t$, where $\mu \equiv \theta/(\theta - 1)$ is the optimal markup in a flexible-price economy. As there are no firm-specific shocks in this economy, all firms that are allowed to reoptimize their price at date t select the same optimal price $\tilde{P}_{H,t}(h) = \tilde{P}_{H,t}$, $\forall h$.

Staggered price setting under partial indexation implies the following expression for the evolution of the domestic price index:

$$P_{H,t} = \left[\alpha((\bar{\pi}_H)^{1-\xi}(\pi_{H,t-1})^{\xi} P_{H,t-1})^{1-\theta} + (1-\alpha)(\tilde{P}_{H,t})^{1-\theta} \right]^{\frac{1}{1-\theta}}. \tag{22}$$

The price-setting problem solved by firms in the foreign country is similar and leads to an optimal rule analogous to equation (21). However, we allow foreign structural parameters (α^*, ξ^*) and country-specific shocks $(\varepsilon^*_{a,t})$ to differ from their home-country counterparts.

2.3 Market-Clearing Conditions

Demands for goods are given by the subindex of consumption (7); the allocation of demand across each of the goods produced within a given country for consumers H, F is given by

$$C_t(h) = \frac{1}{n}\left(\frac{P_{H,t}(h)}{P_{H,t}}\right)^{-\theta} C_{H,t} \quad \text{and} \quad C^*_t(h) = \frac{1}{n}\left(\frac{P^*_{H,t}(h)}{P^*_{H,t}}\right)^{-\theta} C^*_{H,t},$$

$$C_t(f) = \frac{1}{1-n}\left(\frac{P_{F,t}(f)}{P_{F,t}}\right)^{-\theta} C_{F,t} \quad \text{and}$$

$$C^*_t(f) = \frac{1}{1-n}\left(\frac{P^*_{F,t}(f)}{P^*_{F,t}}\right)^{-\theta} C^*_{F,t}.$$

The consumption aggregator (6) implies that home and foreign demands for composite home and foreign goods are given by

$$C_{H,t} = \omega\left(\frac{P_t}{P_{H,t}}\right) C_t \quad \text{and} \quad C^*_{H,t} = \omega^*\left(\frac{P^*_t}{P^*_{H,t}}\right) C^*_t,$$

$$C_{F,t} = (1-\omega)\left(\frac{P_t}{P_{F,t}}\right) C_t \quad \text{and} \quad C^*_{F,t} = (1-\omega^*)\left(\frac{P^*_t}{P^*_{F,t}}\right) C^*_t.$$

Then, goods market clearing in the home and foreign countries implies

$$\begin{aligned} Y_t(h) &= nC_t(h) + (1-n)C^*_t(h) \\ &= \left(\frac{P_{H,t}(h)}{P_{H,t}}\right)^{-\theta}\left(\frac{P_t}{P_{H,t}}\right)\left(\omega C_t + \mathcal{T}_t^{\omega-\omega^*}\frac{1-n}{n}\omega^* C^*_t\right) \end{aligned}$$

and

$$\begin{aligned} Y_t^*(f) &= nC_t(f) + (1-n)C_t^*(f) \\ &= \left(\frac{P_{F,t}(f)}{P_{F,t}}\right)^{-\theta}\left(\frac{P_t}{P_{F,t}}\right)\left(\frac{n}{1-n}(1-\omega)C_t + (1-\omega^*)\mathcal{T}_t^{\omega-\omega^*}C_t^*\right), \end{aligned}$$

so that aggregate outputs in home and foreign goods are

$$Y_t = \omega(\mathcal{T}_t)^{1-\omega}C_t + \frac{1-n}{n}\omega^*(\mathcal{T}_t)^{1-\omega^*}C_t^* \qquad (23)$$

and

$$Y_t^* = (1-\omega)(\mathcal{T}_t)^{-\omega}\frac{n}{1-n}C_t + (1-\omega^*)(\mathcal{T}_t)^{-\omega^*}C_t^*. \qquad (24)$$

Together with equation (10), these relations show that aggregate output only depends on home and foreign consumptions and preference shocks.

2.4 Log-Linear Equilibrium

In order to estimate the model, we log-linearize it around the steady state. We also close the model by specifying a fairly simple monetary policy rule for each country, in which the short-term nominal interest rate responds to lagged interest rate as well as to deviations of inflation to its steady-state value and deviations of domestic aggregate output to its flexible-price equilibrium (or natural) value. This specification includes an additional monetary policy shock. Notice that, since the historical policy rule has not been necessarily optimal, the parameters of the reaction function cannot be viewed as structural ones. Consequently, we adopt for the moment a widely accepted specification, in order to estimate structural parameters reflecting the behavior of private agents.[11] Finally, we need to specify the dynamics of the shocks. We assume that the preference, productivity, and monetary policy shocks follow AR(1) processes,

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[11] See Dieppe, Küster, and McAdam (2005) for a comparison of several policy rules using an AWM.

with autoregressive parameters denoted ρ_p, ρ_a, and ρ_i and standard deviations denoted σ_p, σ_a, and σ_i, respectively.

The resulting system, expressed in percentage deviation around the steady state, is presented in appendix 1. Details of the construction of the flexible-price output are provided in appendix 2. The determination of the optimal monetary policy consistent with our structural model is performed in section 4.

In the case of an area with more than two countries, the broad structure of the model remains essentially unchanged. The major change is that, in an N-country model, international transmission mechanisms pass through $(N - 1)$ independent terms of trade. Consequently, since the Phillips curve depends on the terms of trade through movements in real marginal cost, inflation dynamics is affected by demand conditions in all countries. Moreover, domestic consumption is affected by the average of real interest rates prevailing in all countries of the area.

3. Estimation

We now concentrate on the two models that we will use to evaluate the optimal monetary policy rules: (i) an MCM that incorporates information on individual countries, allowing model parameters to differ from one country to another, and (ii) an AWM that implicitly assumes that the heterogeneity of behaviors and the asymmetry of shocks across countries can be neglected in the design of monetary policy.[12]

Models used for policy analysis must naturally make quantitative predictions that can match observed regularities in the data. In this way, our small DSGE models search to match, in broad terms, the relationship among consumption (or output), inflation, and interest rates. But we do not explore the details of our model's fit to the data in this research. A technical appendix (available from the authors upon request) gives all the details concerning the empirical performance of the models and shows that both the MCM and the AWM

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[12] For the AWM, we resort to the closed-economy version of the model described above, estimated over aggregated data of the euro area.

are able to reproduce most dynamics of the data, although the data do not support all the restrictions imposed by the DSGE.[13]

It is clear that introducing additional mechanisms would enrich the model and substantially improve its fit. Such an extension would be crucial especially if the model was to be used for implementing policy applications (alternative policy scenarios, forecasting, etc.). In our context, we emphasize the ability of our models to provide some evidence on the consequences of heterogeneity for optimal monetary policy. As we will show in the next section, even within our simple framework, we obtain that the use of an AWM induces relatively large and significant welfare losses. The omitted heterogeneity is actually incorporated in shocks that do not play a great role in the welfare measure (only the preference shocks enter the welfare measure). Since we obtain a large gap between the two welfare measures even when not all the sources of heterogeneity are taken into account, adding additional sources would result in even higher welfare losses. In section 4.4, we discuss some alternative modeling specifications.

Estimation is performed using Bayesian techniques.[14] The dynamical systems are cast in a state-space representation for the set of observable variables. The Kalman filter is then used to evaluate the likelihood of the observed variables and form the posterior distribution of the structural parameters by combining the likelihood function with a joint density characterizing some prior beliefs. Given the specification of the model, the posterior distribution cannot be recovered analytically but can be evaluated numerically, using a Markov-Chain Monte Carlo (MCMC) sampling approach. More specifically, we rely on the Metropolis-Hastings (MH) algorithm to obtain random draws from the posterior distribution of the parameters.[15]

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[13] In the technical appendix, we first compare the posterior distributions of the DSGE and VAR models (see Geweke 1999); then we compare the DSGE-based cross-covariances (or autocorrelations) and/or impulse-response functions with those obtained from a VAR model.

[14] The Bayesian strategy has been proposed by, among others, Schorfheide (2003), Smets and Wouters (2003), and Fernandez-Villaverde and Rubio-Ramirez (2004).

[15] We simulate a sample of 200,000 random draws. The first 50,000 observations are discarded to eliminate any dependence on the initial values. The mode and the Hessian of the posterior distribution evaluated at the mode are used to initialize the MH algorithm.

3.1 Data

The data are drawn from OECD's Business Sector Database for individual countries. The sample period runs from 1970:Q1 to 1998:Q4 at a quarterly frequency. We suppose that the euro area is represented by the three largest countries of the area (Germany, France, and Italy), which cover some 70 percent of the area-wide GDP. The MCM is then estimated for these three countries, while the AWM is estimated on the weighted average of series pertaining to the three countries under study.

The estimation of the model is based ultimately on three key macroeconomic variables for each country: real consumption, the inflation rate, and the nominal short-term interest rate. Neither the terms of trade nor the real marginal cost are necessary for the estimation of the model, since they are defined as exact functions of the other macroeconomic variables. Consumption is defined as real consumption expenditures, linearly detrended. We measure inflation as the annualized quarterly percent change in the implicit GDP deflator. The interest rate is the three-month money-market rate. Figure 1 displays the historical path of the various series under consideration for each country or area. In the case of the euro area, we also plot the series extracted from the AWM database provided by Fagan, Henry, and Mestre (2005). We first notice that the two data sets for the euro area look very similar. We also observe a downward trend in inflation and interest rate, which mainly corresponds to the convergence process of economic conditions within the euro area. The structural model presented above is clearly not designed to capture such an empirical feature. Therefore, inflation and the nominal interest rate are detrended by the same quadratic trend in inflation.[16]

3.2 Prior Distribution and Calibrated Parameters

In the definition of the prior distributions, we followed the now standard procedure, assuming a beta distribution for parameters bounded between zero and one, a uniform distribution for standard

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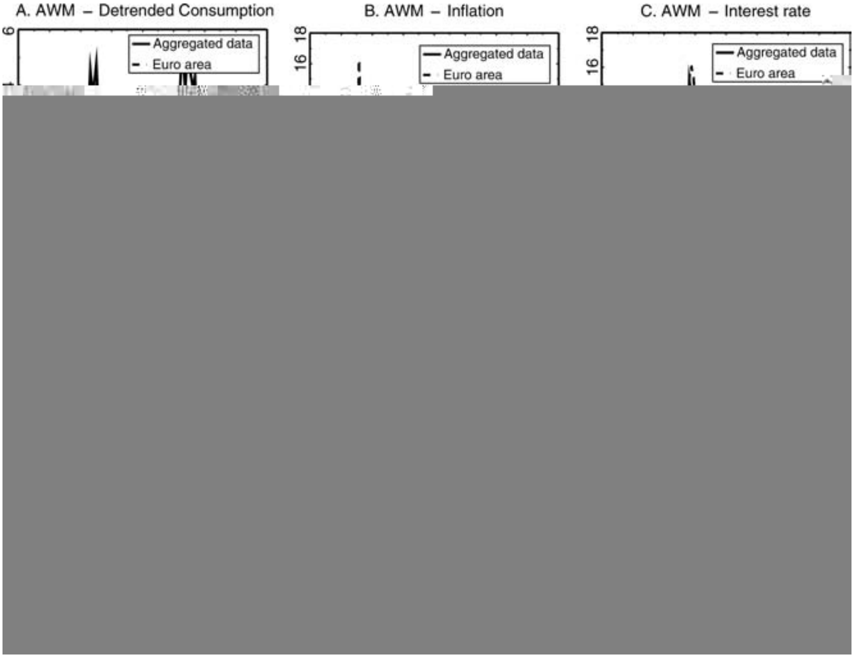
[16] We also examined if the estimates are modified when consumption is detrended using the regression on a quadratic time trend or a Hodrick-Prescott filter. The results were not altered in any significant way.

Figure 1. Data



deviations of shocks, and a normal distribution for the remaining parameters. The main characteristics of the prior distributions are reported in table 1. In most cases, distribution parameters are the same as in Smets and Wouters (2003) for the euro area, but we also incorporate some information drawn from Onatski and Williams (2004).[17]

While the shocks in a given country are assumed to be uncorrelated, we allow a nonzero correlation between a given shock in two countries. We thus denote δ_p, δ_a, and δ_i the correlations between domestic and foreign preference shocks, productivity shocks, and monetary policy shocks, respectively. Correlations across countries are assumed to follow a normal distribution, with a mean of 0.2 and

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[17] Onatski and Williams (2004) provide an interesting investigation of some shortcomings of the standard Bayesian approach in the context of DSGE models. In particular, they put forward that parameter estimates are very sensitive to the way priors are introduced. We took advantage of some of their results.

Notice that $s = \bar{C}/\bar{Y}$ and $s^* = \bar{C}^*/\bar{Y}^*$.

Taylor-Type Rules

- Home monetary policy rule:

$$\hat{\imath}_t = \psi_i \hat{\imath}_{t-1} + (1-\psi_i)\left[\psi_\pi \hat{\pi}_{H,t} + \psi_y\left(\hat{y}_t - \hat{y}_t^n\right)\right] + \hat{\varepsilon}_{i,t} \tag{42}$$

- Foreign monetary policy rule:

$$\hat{\imath}_t^* = \psi_i^* \hat{\imath}_{t-1}^* + \left(1-\psi_i^*\right)\left[\psi_\pi^* \hat{\pi}_{F,t}^* + \psi_y^*\left(\hat{y}_t^* - \hat{y}_t^{*n}\right)\right] + \hat{\varepsilon}_{i,t}^* \tag{43}$$

- Home monetary policy shock:

$$\hat{\varepsilon}_{i,t} = \rho_i \hat{\varepsilon}_{i,t-1} + \eta_{i,t} \tag{44}$$

- Foreign monetary policy shock:

$$\hat{\varepsilon}_{i,t}^* = \rho_i^* \hat{\varepsilon}_{i,t-1}^* + \eta_{i,t}^* \tag{45}$$

Appendix 2. The Log-Linearized Flexible-Price Output

The so-called natural output is obtained as the level of output that would prevail under flexible prices in the absence of cost-push shocks. In this case, the optimal pricing decision for the firm h—i.e., the price that would maximize profits at each period—is given by

$$P_{H,t}(h) = \frac{\mu}{(1+\vartheta)} \frac{W_t}{\varepsilon_{a,t}},$$

where $\mu \equiv \theta/(\theta-1)$ is the optimal markup and ϑ is the subsidy for output that offsets the effect on imperfect competition in goods markets on the steady-state level of output. Using the demand for good h, $Y_t(h) = \left(\frac{P_{H,t}(h)}{P_{H,t}}\right)^{-\theta} Y_t$, we note that the relative supply of good h must in turn satisfy

$$\left(\frac{Y_t(h)}{Y_t}\right)^{-1/\theta} = \frac{\mu}{(1+\vartheta)} \frac{W_t}{P_{H,t}\varepsilon_{a,t}}.$$

Note also that, in steady state,

$$\frac{\bar{\mathcal{U}}_{\bar{L}}}{\bar{\mathcal{U}}_{\bar{C}}} = \frac{(1+\vartheta)}{\mu} = 1.$$

Because all wages are the same in the case of flexible wages, we have $W_t(h) = W_t$ and $L_t(h) = L_t$ for all h. This implies that all sellers supply a quantity Y_t^n satisfying

$$\begin{aligned}
1 &= \frac{\mathcal{U}_{L^n,t}}{\mathcal{U}_{C^n,t}} \frac{P_t}{P_{H,t}} \frac{1}{\varepsilon_{a,t}} = \frac{\left(L_t^n\right)^{\varphi}}{\left(C_t^n - \gamma C_t^n\right)^{-\sigma}} \frac{\left(\mathcal{T}_t^n\right)^{1-\omega}}{\varepsilon_{a,t}} \\
&= \frac{\left(Y_t^n/\varepsilon_{a,t}\right)^{\varphi}}{\left(C_t^n - \gamma C_{t-1}^n\right)^{-\sigma}} \frac{\left(\mathcal{T}_t^n\right)^{1-\omega}}{\varepsilon_{a,t}}.
\end{aligned}$$

Log-linearizing this expression yields

$$\hat{y}_t^n = -\frac{\sigma}{(1-\gamma)\varphi}\hat{c}_t^n + \frac{\sigma\gamma}{(1-\gamma)\varphi}\hat{c}_{t-1}^n - \frac{(1-\omega)}{\varphi}\hat{\tau}_t^n + \frac{(1+\varphi)}{\varphi}\hat{\varepsilon}_{a,t}.$$

By using the terms-of-trade expression

$$\begin{aligned}
\hat{\tau}_t^n = \frac{1}{\omega - \omega^*}\Bigg[&\frac{\sigma}{1-\gamma}\hat{c}_t^n - \frac{\gamma\sigma}{1-\gamma}\hat{c}_{t-1}^n - \frac{\sigma^*}{1-\gamma^*}\hat{c}_t^{*n} \\
&+ \frac{\gamma^*\sigma^*}{1-\gamma^*}\hat{c}_{t-1}^{*n} + \hat{\varepsilon}_{p,t}^* - \hat{\varepsilon}_{p,t}\Bigg]
\end{aligned}$$

with the definition of the aggregate output

$$\hat{y}_t^n = \omega s \hat{c}_t^n + (1-\omega s)\hat{c}_t^{n*} + [(1-\omega)\omega s + (1-\omega^*)(1-\omega s)]\hat{\tau}_t^n,$$

we obtain

$$\begin{aligned}
\left(\frac{\sigma}{1-\gamma} + \varphi\omega s + \frac{\sigma\Psi}{(1-\gamma)}\right)\hat{c}_t^n &= \frac{\gamma\sigma}{1-\gamma}(1+\Psi)\hat{c}_{t-1}^n \\
&- \left(\varphi(1-\omega s) - \frac{\sigma^*\Psi}{(1-\gamma^*)}\right)\hat{c}_t^{*n} - \frac{\gamma^*\sigma^*\Psi}{(1-\gamma^*)}\hat{c}_{t-1}^{*n} \\
&- \Psi\left(\hat{\varepsilon}_{p,t}^* - \hat{\varepsilon}_{p,t}\right) + (1+\varphi)\hat{\varepsilon}_{a,t} \qquad (46)
\end{aligned}$$

and

$$\begin{aligned}
\hat{y}_t^n = &\left(\omega s + \frac{\sigma\tilde{\Psi}}{(1-\gamma)}\right)\hat{c}_t^n - \left(\frac{\gamma\sigma\tilde{\Psi}}{(1-\gamma)}\right)\hat{c}_{t-1}^n + \left(1 - \omega s - \frac{\sigma^*\tilde{\Psi}}{(1-\gamma^*)}\right)\hat{c}_t^{*n} \\
&+ \left(\frac{\gamma^*\sigma^*\tilde{\Psi}}{(1-\gamma^*)}\right)\hat{c}_{t-1}^{*n} + \tilde{\Psi}\left(\hat{\varepsilon}_{p,t}^* - \hat{\varepsilon}_{p,t}\right), \qquad (47)
\end{aligned}$$

where $\Psi = [(1-\omega)(1+\varphi\omega s) + \varphi(1-\omega^*)(1-\omega s)]/(\omega-\omega^*)$ and $\tilde{\Psi} = [(1-\omega)\omega s + (1-\omega^*)(1-\omega s)]/(\omega-\omega^*)$.

The same calculations for the foreign country yield

$$\begin{aligned}\left(\frac{\sigma^*}{1-\gamma^*} + \varphi^*(1-\omega^*)s^* + \frac{\sigma^*\Psi^*}{(1-\gamma^*)}\right)\hat{c}_t^{*n} &= \frac{\gamma^*\sigma^*}{1-\gamma^*}(1+\Psi^*)\hat{c}_{t-1}^{*n} \\ &- \left(\varphi^*[1-(1-\omega^*)s^*] - \frac{\sigma\Psi^*}{(1-\gamma)}\right)\hat{c}_t^n - \frac{\gamma\sigma\Psi^*}{(1-\gamma)}\hat{c}_{t-1}^n \\ &+ \Psi^*\left(\hat{\varepsilon}_{p,t}^* - \hat{\varepsilon}_{p,t}\right) + (1+\varphi^*)\hat{\varepsilon}_{a,t}^* \end{aligned} \tag{48}$$

and

$$\begin{aligned}\hat{y}_t^{*n} = &\left[1-(1-\omega^*)s^* - \frac{\sigma\tilde{\Psi}^*}{(1-\gamma)}\right]\hat{c}_t^n + \frac{\gamma\sigma\tilde{\Psi}^*}{(1-\gamma)}\hat{c}_{t-1}^n \\ &+ \left((1-\omega^*)s^* + \frac{\sigma^*\tilde{\Psi}^*}{(1-\gamma^*)}\right)\hat{c}_t^{*n} - \frac{\gamma^*\sigma^*\tilde{\Psi}^*}{(1-\gamma^*)}\hat{c}_{t-1}^{*n} \\ &- \tilde{\Psi}^*\left(\hat{\varepsilon}_{p,t}^* - \hat{\varepsilon}_{p,t}\right),\end{aligned} \tag{49}$$

where $\Psi^* = [\omega[1+\varphi^*(1-(1-\omega^*)s^*)] + \omega^*\varphi^*(1-\omega^*)s^*]/(\omega-\omega^*)$ and $\tilde{\Psi}^* = (\omega[1-(1-\omega^*)s^*] + \omega^*(1-\omega^*)s^*)/(\omega-\omega^*)$.

Appendix 3. Approximation of the Welfare Criterion

The second-order approximation of the home representative household's utility is derived in this section, using methods discussed in more detail in Woodford (2003). The average utility flow of the representative household at date t is given by

$$\mathbb{W}_t = \mathbb{U}(C_t, \mathcal{H}_t, \varepsilon_{p,t}) - \frac{1}{n}\int_0^n \mathbb{V}(L_t(h), \varepsilon_{p,t})\mathrm{d}h, \tag{50}$$

where

$$\mathbb{U}(C_t, \mathcal{H}_t, \varepsilon_{p,t}) = \frac{\varepsilon_{p,t}}{1-\sigma}(C_t - \gamma\mathcal{H}_t)^{1-\sigma} \quad \text{and}$$

$$\mathbb{V}(L_t(h), \varepsilon_{p,t}) = \frac{\varepsilon_{p,t}}{1+\varphi}(L_t(h))^{1+\varphi}.$$

Taylor Expansion of the Utility Function

The second-order Taylor expansion of $\mathbb{U}(C_t, \mathcal{H}_t, \varepsilon_{p,t})$ around the steady state $\bar{\mathbb{U}} = \mathbb{U}(\bar{C}, \bar{\mathcal{H}}, \bar{\varepsilon}_p)$ yields

$$\begin{aligned}\mathbb{U}(C_t, \mathcal{H}_t, \varepsilon_{p,t}) \approx\ & \bar{\mathbb{U}} + \bar{\mathbb{U}}_{\bar{C}}\tilde{C}_t + \bar{\mathbb{U}}_{\bar{\mathcal{H}}}\tilde{\mathcal{H}}_t + \bar{\mathbb{U}}_{\bar{\varepsilon}_p}\tilde{\varepsilon}_{p,t} + \frac{1}{2}\bar{\mathbb{U}}_{\bar{C}\bar{C}}\tilde{C}_t^2 \\ & + \frac{1}{2}\bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\mathcal{H}}}\tilde{\mathcal{H}}_t^2 + \frac{1}{2}\bar{\mathbb{U}}_{\bar{\varepsilon}_p\bar{\varepsilon}_p}(\tilde{\varepsilon}_{p,t})^2 + \bar{\mathbb{U}}_{\bar{C}\bar{\mathcal{H}}}\tilde{C}_t\tilde{\mathcal{H}}_t \\ & + \bar{\mathbb{U}}_{\bar{C}\bar{\varepsilon}_p}\tilde{C}_t\tilde{\varepsilon}_{p,t} + \bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\varepsilon}_p}\tilde{\mathcal{H}}_t\tilde{\varepsilon}_{p,t} + \mathcal{O}(\|\zeta\|^3), \end{aligned} \tag{51}$$

where $\tilde{X}_t = X_t - \bar{X}$, $\mathcal{O}(\|\zeta\|^3)$ denotes the order of residual and $\|\zeta\|$ is a bound on the amplitude of exogenous disturbances.

Applying a second-order Taylor expansion ($\tilde{X}_t/\bar{X} = \hat{x}_t + \frac{1}{2}\hat{x}_t^2 + \mathcal{O}(\|\zeta\|^3)$, where $\hat{x}_t = \ln X_t - \ln \bar{X}$), we obtain

$$\begin{aligned}\mathbb{U}(C_t, \mathcal{H}_t, \varepsilon_{p,t}) \approx\ & \bar{\mathbb{U}} + \bar{\mathbb{U}}_{\bar{C}}\bar{C}\left(\hat{c}_t + \frac{1}{2}\hat{c}_t^2\right) + \bar{\mathbb{U}}_{\bar{\mathcal{H}}}\bar{\mathcal{H}}\left(\hat{h}_t + \frac{1}{2}\hat{h}_t^2\right) \\ & + \bar{\mathbb{U}}_{\bar{\varepsilon}_p}\bar{\varepsilon}_p\left(\hat{\varepsilon}_{p,t} + \frac{1}{2}\hat{\varepsilon}_{p,t}^2\right) + \frac{1}{2}\bar{\mathbb{U}}_{\bar{C}\bar{C}}\bar{C}^2\hat{c}_t^2 \\ & + \frac{1}{2}\bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\mathcal{H}}}\bar{\mathcal{H}}^2\hat{h}_t^2 + \frac{1}{2}\bar{\mathbb{U}}_{\bar{\varepsilon}_p\bar{\varepsilon}_p}\bar{\varepsilon}_p^2\hat{\varepsilon}_{p,t}^2 + \bar{\mathbb{U}}_{\bar{C}\bar{\mathcal{H}}}\bar{C}\bar{\mathcal{H}}(\hat{c}_t\hat{h}_t) \\ & + \bar{\mathbb{U}}_{\bar{C}\bar{\varepsilon}_p}\bar{C}\bar{\varepsilon}_p(\hat{c}_t\hat{\varepsilon}_{p,t}) + \bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\varepsilon}_p}\bar{\mathcal{H}}\bar{\varepsilon}_p(\hat{h}_t\hat{\varepsilon}_{p,t}) + \mathcal{O}(\|\zeta\|^3) \end{aligned} \tag{52}$$

with

$$\begin{aligned}
&\bar{\mathbb{U}}_{\bar{C}} = \bar{\varepsilon}_p(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma}, \\
&\bar{\mathbb{U}}_{\bar{C}\bar{C}} = -\sigma\bar{\varepsilon}_p(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma-1} = \tfrac{-\sigma}{(\bar{C}-\gamma\bar{\mathcal{H}})}\bar{\mathbb{U}}_{\bar{C}}, \\
&\bar{\mathbb{U}}_{\bar{\mathcal{H}}} = -\gamma\bar{\varepsilon}_p(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma} = -\gamma\bar{\mathbb{U}}_{\bar{C}}, \\
&\bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\mathcal{H}}} = -\gamma^2\sigma\bar{\varepsilon}_p(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma-1} = \tfrac{-\gamma^2\sigma}{(\bar{C}-\gamma\bar{\mathcal{H}})}\bar{\mathbb{U}}_{\bar{C}}, \\
&\bar{\mathbb{U}}_{\bar{C}\bar{\mathcal{H}}} = \sigma\gamma\bar{\varepsilon}_p(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma-1} = \tfrac{\sigma\gamma}{(\bar{C}-\gamma\bar{\mathcal{H}})}\bar{\mathbb{U}}_{\bar{C}}, \\
&\bar{\mathbb{U}}_{\bar{\varepsilon}_p} = \tfrac{1}{1-\sigma}(\bar{C} - \gamma\bar{\mathcal{H}})^{1-\sigma} = \tfrac{(\bar{C}-\gamma\bar{\mathcal{H}})}{(1-\sigma)\bar{\varepsilon}_p}\bar{\mathbb{U}}_{\bar{C}}, \\
&\bar{\mathbb{U}}_{\bar{\varepsilon}_p\bar{\varepsilon}_p} = 0, \\
&\bar{\mathbb{U}}_{\bar{C}\bar{\varepsilon}_p} = (\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma} = \tfrac{\bar{\mathbb{U}}_{\bar{C}}}{\bar{\varepsilon}_p}, \\
&\bar{\mathbb{U}}_{\bar{\mathcal{H}}\bar{\varepsilon}_p} = -\gamma(\bar{C} - \gamma\bar{\mathcal{H}})^{-\sigma} = \tfrac{-\gamma}{\bar{\varepsilon}_p}\bar{\mathbb{U}}_{\bar{C}}.
\end{aligned}$$

Replacing $\mathcal{H}_t$ with C_{t-1}, the utility of consumption simplifies to

$$\mathbb{U}(C_t, C_{t-1}, \varepsilon_{p,t}) \approx \bar{\mathbb{U}}_{\bar{C}}\bar{C}\left\{(\hat{c}_t - \gamma\hat{c}_{t-1}) + \frac{1}{2}\left(\hat{c}_t^2 - \gamma\hat{c}_{t-1}^2\right)\right.$$
$$\left. - \frac{\sigma}{2(1-\gamma)}(\hat{c}_t - \gamma\hat{c}_{t-1})^2 + \hat{c}_t\hat{\varepsilon}_{p,t} - \gamma\hat{c}_{t-1}\hat{\varepsilon}_{p,t}\right\}$$
$$+ t.i.p. + \mathcal{O}(\|\zeta\|^3), \tag{53}$$

where *t.i.p.* denotes terms independent of the actual policy, such as constant terms involving only exogenous variables.

Taylor Expansion of the Disutility of Work

The second-order Taylor expansion for $\mathbb{V}(L_t(h), \varepsilon_{p,t})$ around the steady state $\bar{\mathbb{V}} = \mathbb{V}(\bar{L}, \bar{\varepsilon}_p)$ is

$$\mathbb{V}(L_t(h),\varepsilon_{p,t}) \approx \bar{\mathbb{V}} + \bar{\mathbb{V}}_{\bar{L}}\bar{L}\left(\hat{l}_t(h) + \frac{1}{2}\hat{l}_t^2(h)\right) + \bar{\mathbb{V}}_{\bar{\varepsilon}_p}\bar{\varepsilon}_p\left(\hat{\varepsilon}_{p,t} + \frac{1}{2}(\hat{\varepsilon}_{p,t})^2\right)$$
$$+ \frac{1}{2}\bar{\mathbb{V}}_{\bar{L}\bar{L}}\bar{L}^2\hat{l}_t^2(h) + \frac{1}{2}\bar{\mathbb{V}}_{\bar{\varepsilon}_p\bar{\varepsilon}_p}\bar{\varepsilon}_p^2\hat{\varepsilon}_{p,t}^2 + \bar{\mathbb{V}}_{\bar{L}\bar{\varepsilon}_p}\bar{L}\bar{\varepsilon}_p(\hat{l}_t(h)\hat{\varepsilon}_{p,t})$$
$$+ \mathcal{O}(\|\zeta\|^3) \tag{54}$$

with

$$\begin{aligned}
&\bar{\mathbb{V}}_{\bar{L}} = \bar{\varepsilon}_p\bar{L}^{\varphi},\\
&\bar{\mathbb{V}}_{\bar{\varepsilon}_p} = \tfrac{1}{1+\varphi}(\bar{L})^{1+\varphi} = \tfrac{\bar{L}}{(1+\varphi)\bar{\varepsilon}_p}\bar{\mathbb{V}}_{\bar{L}},\\
&\bar{\mathbb{V}}_{\bar{L}\bar{L}} = \varphi\bar{\varepsilon}_p\bar{L}^{\varphi-1} = \tfrac{\varphi}{\bar{L}}\bar{\mathbb{V}}_{\bar{L}},\\
&\bar{\mathbb{V}}_{\bar{\varepsilon}_p\bar{\varepsilon}_p} = 0,\\
&\bar{\mathbb{V}}_{\bar{L}\bar{\varepsilon}_p} = \bar{L}^{\varphi} = \tfrac{\bar{\mathbb{V}}_{\bar{L}}}{\bar{\varepsilon}_p}.
\end{aligned}$$

The disutility of work becomes

$$\mathbb{V}(L_t(h), \varepsilon_{p,t}) \approx \bar{\mathbb{V}}_{\bar{L}}\bar{L}\left\{\hat{l}_t(h) + \frac{1+\varphi}{2}\hat{l}_t^2(h) + \hat{l}_t(h)\hat{\varepsilon}_{p,t}\right\}$$
$$+ t.i.p. + \mathcal{O}(\|\zeta\|^3). \tag{55}$$

Individual Labor to Composite Labor

Now define the composite labor index:

$$L_t = \int_0^n L_t(h)\mathrm{d}h = \int_0^n \frac{Y_t(h)}{\varepsilon_{a,t}}\mathrm{d}h = \frac{Y_t}{\varepsilon_{a,t}}\int_0^n \left(\frac{\tilde{P}_t(h)}{P_t}\right)^{-\theta} \mathrm{d}h.$$

Taking a second-order Taylor expansion of the logarithm of this equation yields

$$\hat{l}_t = \hat{y}_t - \hat{\varepsilon}_{a,t} + \hat{u}_t, \tag{56}$$

where $\hat{u}_t = \ln \int_0^n \left(\frac{\tilde{P}_t(h)}{P_t}\right)^{-\theta} \mathrm{d}h$ is of second order. As shown by Woodford (2003, chap. 6), one has

$$\hat{u}_t = \frac{\theta\alpha}{2(1-\alpha)(1-\beta\alpha)}(\hat{\pi}_{H,t} - \xi\hat{\pi}_{H,t-1})^2 + \mathcal{O}(\|\zeta\|^3). \tag{57}$$

Welfare Expressions

We first integrate equation (55) over h and replace $\int_0^n L_t(h)\mathrm{d}h$ and $\hat{u}_t$ with their respective expressions. We then take the present discounted sum of equations (53) and (55) and subtract the second expression from the first one to obtain

$$\begin{aligned}\sum_{t=0}^{\infty}\beta^t\mathbb{W}_t = \bar{\mathbb{U}}_{\bar{C}}\bar{C}\sum_{t=0}^{\infty}\beta^t \Bigg\{ &(\hat{c}_t - \gamma\hat{c}_{t-1}) + \frac{1}{2}\left(\hat{c}_t^2 - \gamma\hat{c}_{t-1}^2\right) \\ &- \frac{\sigma}{2(1-\gamma)}(\hat{c}_t - \gamma\hat{c}_{t-1})^2 + \hat{c}_t\hat{\varepsilon}_{p,t} - \gamma\hat{c}_{t-1}\hat{\varepsilon}_{p,t} - s^{-1}\hat{y}_t \\ &- \frac{1+\varphi}{2s}(\hat{y}_t - \hat{\varepsilon}_{a,t})^2 - s^{-1}\hat{y}_t\hat{\varepsilon}_{p,t} - \frac{\theta\alpha}{2(1-\alpha)(1-\beta\alpha)s} \\ &\times (\hat{\pi}_{H,t} - \xi\hat{\pi}_{H,t-1})^2\Bigg\} + t.i.p. + \mathcal{O}(\|\zeta\|^3). \end{aligned} \tag{58}$$

Recall that $\bar{\mathbb{V}}_{\bar{L}} = \bar{\mathbb{U}}_{\bar{C}}$ and $s = \bar{C}/\bar{Y}$. Given that

$$\sum_{t=0}^{\infty}\beta^t x_{t-1} = x_{-1} + \beta\sum_{t=0}^{\infty}\beta^t x_t = \beta\sum_{t=0}^{\infty}\beta^t x_t + t.i.p.$$

and using the fact that

$$(1+\varphi)\hat{\varepsilon}_{a,t} = A_1\hat{c}_t^n + A_2\hat{c}_{t-1}^n + A_3\hat{c}_t^{*n} + A_4\hat{c}_{t-1}^{*n} + A_5\hat{\varepsilon}_{p,t} + A_6\hat{\varepsilon}_{p,t}^*,$$

where parameters A_j $(j = 1, \cdots, 6)$ find their counterparts in equation (46), it yields

$$\begin{aligned}
\mathcal{W}_0 = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbb{W}_t = -\bar{\mathbb{U}}_{\bar{C}}\bar{C}\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ &- (1-\beta\gamma)\hat{c}_t + s^{-1}\hat{y}_t \\
&+ \frac{\sigma}{2(1-\gamma)}(\hat{c}_t - \gamma\hat{c}_{t-1})^2 - \frac{(1-\beta\gamma)}{2}\hat{c}_t^2 + \frac{1+\varphi}{2s}\hat{y}_t^2 \\
&+ (\gamma\beta\rho_p - 1)\hat{c}_t\hat{\varepsilon}_{p,t} \\
&- s^{-1}\big(A_1\hat{c}_t^n + A_2\hat{c}_{t-1}^n + A_3\hat{c}_t^{*n} + A_4\hat{c}_{t-1}^{*n} + A_5\hat{\varepsilon}_{p,t} + A_6\hat{\varepsilon}_{p,t}^*\big)\hat{y}_t \\
&+ s^{-1}\hat{y}_t\hat{\varepsilon}_{p,t} + \frac{\theta\alpha}{2(1-\alpha)(1-\beta\alpha)s}(\hat{\pi}_{H,t} - \xi\hat{\pi}_{H,t-1})^2 \Big\} \\
&+ t.i.p. + \mathcal{O}(\|\zeta\|^3). \qquad (59)
\end{aligned}$$

Finally, replacing the cross-product $x_{1,t}x_{2,t}$ with $(x_{1,t}^2 + x_{2,t}^2 - (x_{1,t} - x_{2,t})^2)/2$, we can rewrite the home welfare criterion as

$$\begin{aligned}
\mathcal{W}_0 = -\frac{\bar{\mathbb{U}}_{\bar{C}}\bar{C}}{2}\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \Big\{ &(\hat{c}_t - \Psi_c)^2 + \frac{(1+\hat{y}_t)^2}{s} \\
&+ (\beta\gamma(1+\rho_p) - 3)\hat{c}_t^2 \\
&+ \frac{1+\varphi - A_1 - A_2 - A_3 - A_4 - A_5 - A_6}{s}\hat{y}_t^2 \\
&+ \frac{\sigma}{(1-\gamma)}(\hat{c}_t - \gamma\hat{c}_{t-1})^2 - (\beta\gamma\rho_p - 1)(\hat{c}_t - \hat{\varepsilon}_{p,t})^2 \\
&+ \frac{A_1}{s}\big(\hat{y}_t - \hat{c}_t^n\big)^2 + \frac{A_2}{s}\big(\hat{y}_t - \hat{c}_{t-1}^n\big)^2 + \frac{A_3}{s}\big(\hat{y}_t - \hat{c}_t^{*n}\big)^2 \\
&+ \frac{A_4}{s}\big(\hat{y}_t - \hat{c}_{t-1}^{*n}\big)^2 - \frac{1-A_5}{s}(\hat{y}_t - \hat{\varepsilon}_{p,t})^2 + \frac{A_6}{s}\big(\hat{y}_t - \hat{\varepsilon}_{p,t}^*\big)^2 \\
&+ \frac{\theta\alpha}{(1-\alpha)(1-\beta\alpha)s}(\hat{\pi}_{H,t} - \xi\hat{\pi}_{H,t-1})^2 \Big\} + t.i.p. + \mathcal{O}(\|\eta\|^3),
\end{aligned}$$

where $\Psi_c = (1-\beta\gamma)$.

The calculations for the welfare of the foreign representative household yield

$$\begin{aligned}\mathcal{W}_0^* = -\frac{\bar{\mathbb{U}}^*_{\bar{C}^*}\bar{C}^*}{2}\mathbb{E}_0\sum_{t=0}^{\infty}\beta^t\Bigg\{&\left(\hat{c}_t^* - \Psi_c^*\right)^2 + \frac{\left(1+\hat{y}_t^*\right)^2}{s^*}\\ &+ \left(\beta\gamma^*\left(1+\rho_p^*\right) - 3\right)\hat{c}_t^{*2}\\ &+ \frac{1+\varphi^* - A_1^* - A_2^* - A_3^* - A_4^* - A_5^* - A_6^*}{s^*}\hat{y}_t^{*2}\\ &+ \frac{\sigma^*\gamma^*}{(1-\gamma^*)}\left(\hat{c}_t^* - \gamma^*\hat{c}_{t-1}^*\right)^2 - \left(\beta\gamma^*\rho_p^* - 1\right)\left(\hat{c}_t^* - \hat{\varepsilon}_{p,t}^*\right)^2\\ &+ \frac{A_1^*}{s^*}\left(\hat{y}_t^* - \hat{c}_t^n\right)^2 + \frac{A_2^*}{s^*}\left(\hat{y}_t^* - \hat{c}_{t-1}^n\right)^2 + \frac{A_3^*}{s^*}\left(\hat{y}_t^* - \hat{c}_t^{*n}\right)^2\\ &+ \frac{A_4^*}{s^*}\left(\hat{y}_t^* - \hat{c}_{t-1}^{*n}\right)^2 + \frac{A_5^*}{s^*}\left(\hat{y}_t^* - \hat{\varepsilon}_{p,t}\right)^2 - \frac{1-A_6^*}{s^*}\left(\hat{y}_t^* - \hat{\varepsilon}_{p,t}^*\right)^2\\ &+ \frac{\theta\alpha^*}{(1-\alpha^*)(1-\beta\alpha^*)s^*}\left(\hat{\pi}_{F,t}^* - \xi^*\hat{\pi}_{F,t-1}^*\right)^2\Bigg\} + t.i.p. + \mathcal{O}(\|\eta\|^3),\end{aligned}$$

where $\Psi_c^* = (1-\beta\gamma^*)$.

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