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The exchange rate in a dynamic-optimizing business cycle model with nominal rigidities: a quantitative investigation

Robert Kollmann*

Department of Economics, University of Bonn, Adenauerallee 24-42, D-53113 Bonn, Germany

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Abstract

This paper studies a quantitative dynamic-optimizing business cycle model of a small open economy with staggered price and wage setting. The model exhibits exchange rate overshooting in response to money supply shocks. The predicted variability of the nominal and, especially, of the real exchange rate is noticeably higher than in standard Real Business Cycle models with *flexible* prices and wages. A positive domestic money supply shock is predicted to lower the domestic interest rate, raise GDP, and trigger a depreciation of both the nominal and real exchange rate. Increases in domestic productivity and in the world interest rate are also predicted to induce a nominal and real exchange rate depreciation.

Keywords: Exchange rates; Nominal rigidities; Business cycles

JEL classification: F31; F32; E32

1. Introduction

The nominal and real exchange rates of major currencies against the U.S. dollar are highly volatile. Also, nominal and real exchange rates are strongly positively correlated. For example, the standard deviations of Hodrick–Prescott (HP) filtered

*Tel.: +49-228-734-073; fax: +49-228-739-100.
E-mail address: kollmann@wipol.uni-bonn.de (R. Kollmann).

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(logged) quarterly nominal and real exchange rates of Japan, Germany, and the U.K. (G3, henceforth) vis-à-vis the U.S. were roughly 9% during the post-Bretton Woods era, compared to standard deviations of GDP of about 1.5%. The correlation between HP filtered nominal and real U.S. dollar exchange rates was about 0.97 for these countries.

In an attempt to explain key features of international macroeconomic data, much effort has recently been devoted to developing quantitative open economy business cycle models with explicit microfoundations. Following the Real Business Cycle (RBC) approach, this work has generally considered models without money or models in which money is (basically) neutral, since prices and wages are assumed to be fully flexible. In these models, productivity shocks are the main source of economic fluctuations. (See Backus et al. (1995) for a survey of that literature.) One striking limitation of these models is that they tend to generate a predicted variability of the nominal and, particularly, the real exchange rate that is much too small when compared to actual data for periods with floating exchange rates. For example, in Schlagenhauf and Wrase's (1995) monetary model with flexible prices and wages, the predicted standard deviations of exchange rates are five to ten times smaller than historical standard deviations of G3/U.S. exchange rates. Non-monetary models generate standard deviations of (real) exchange rates that are even smaller (see, for example, Backus et al., 1995).

The present paper studies a quantitative dynamic-optimizing business cycle model of a small open economy in which nominal prices and wages are sticky. Overlapping price and wage contracts, à la Calvo (1983), are assumed. The average interval between price and wage changes, at the micro-economic level, is set at four quarters, consistent with empirical evidence on price and wage adjustment. A flexible exchange rate and four types of exogenous shocks are assumed: shocks to the domestic money supply, domestic productivity, the foreign price level, and the foreign interest rate. The model is calibrated to post-Bretton Woods data for the G3 countries.

Predicted standard deviations of the nominal and, particularly, of the real exchange rate are noticeably higher — and, hence, closer to the data — in the nominal rigidities structure considered here, compared to a structure with flexible prices and wages. The nominal rigidities structure captures 40 to 50 percent of the historical standard deviations of nominal and real G3/U.S. exchange rates during the post-Bretton Woods era. It also generates improved predictions for other business cycle statistics: the predicted correlation between the nominal and the real exchange rate is markedly higher (and closer to the data) than when flexible prices and wages are assumed. In addition, the structure captures more closely the historical variability of GDP, consumption, and the nominal interest rate.

The nominal rigidities model predicts that an increase in the domestic money supply induces a sizable rise in domestic GDP, a depreciation of the country's currency, and a decline in the domestic interest rate. On impact, the nominal exchange rate overshoots its long-run response. Owing to the sluggishness of the price level, the nominal exchange rate depreciation produces, on impact, an almost equi-proportional *real* depreciation. By contrast, in a version of the model without nominal rigidities, money supply shocks have a negligible effect on the real exchange rate (and other real variables), and there is no overshooting of the nominal exchange rate. The nominal rigidities model also predicts that increases in domestic productivity and the foreign interest rate induce a nominal and real currency depreciation.

By assuming nominal rigidities, the model builds on Keynesian open economy models developed during the 1960s and 1970s (for example, Mundell, 1968; Dornbusch, 1976). However, these models lack the explicit micro-foundations for the private sector's consumption, investment, and production decisions that characterize the dynamic-optimizing approach adopted here.

The present paper is also related to Obstfeld and Rogoff's (1995) widely discussed dynamic-optimizing open economy model, in which nominal prices are fixed in the short run, as firms are assumed to set their prices *one* period in advance. However, these authors' analysis is entirely qualitative and their model is highly stylized — they consider an economy without physical capital and without uncertainty (except for one-time unanticipated shocks), in which the Law of One Price holds and the real exchange rate is constant. That model also seems unable to generate sufficient nominal exchange rate volatility.[1] Owing to one-period price stickiness, it generates very simple dynamics: for example, after a permanent money supply shock, the economy is predicted to adjust to its new long-run equilibrium in a single period.

In contrast, the present paper develops a quantitative (calibrated) stochastic *business cycle* model with physical capital, *multi-period* price and wage setting, and deviations from the Law of One Price. It predicts a gradual adjustment of prices to a money supply increase — which empirically seems more realistic — and, hence, a persistent increase in real balances and a persistent reduction in the nominal interest rate, nominal exchange rate overshooting, and a sizable real exchange rate response.

More recently, other papers have also studied dynamic-optimizing open economy models with nominal rigidities — see Lane (1999) for a detailed survey. Most of that research builds rather closely on the basic Obstfeld and Rogoff (1995) framework (prices set one period in advance, no capital), and offers only limited *quantitative* results. A contribution by Betts and Devereux (2000) shows that pricing to market (PTM) behavior by firms (limited pass-through of exchange rate movements into prices due to local currency price setting) increases nominal and real exchange rate volatility, compared to a setting where the Law of One Price holds. Given the empirical rejection of the Law of One Price (for example, Knetter, 1993), the present paper also assumes PTM. *Stochastic* extensions of the

[1] In the Obstfeld–Rogoff model, with prices set one period in advance, nominal exchange rate volatility (due to money shocks) is lower (for plausible parameter values) than if prices were flexible.

Obstfeld and Rogoff (1995) analysis are considered by Obstfeld and Rogoff (2000) and Engel and Devereux (2000). Based on a highly stylized structure, these authors derive *exact* closed-form model solutions that are used to study the welfare effects of alternative monetary policy regimes. In contrast, I here consider a richer business cycle model that is solved numerically.

The methodology used here builds on recent quantitative dynamic general equilibrium models of *closed* economies with sticky prices or wages. See, for example, Rotemberg and Woodford (1997) and Erceg et al. (1999). Quantitative *two-country* models with multi-period *price* stickiness have recently been considered by Betts and Devereux (1998) and Chari et al. (1998). The present paper differs from these studies, inter alia by using a model of a *small* open economy with price and *wage* stickiness.[2]

Section 2 discusses the model. Section 3 reports macroeconomic stylized facts for the G3. Section 4 presents simulation results. Section 5 concludes.

2. The model

I consider a small open economy with a representative household, firms, and a government that issues a national currency. The country produces a single non-tradable final good and a continuum of tradable intermediate goods indexed by $s \in [0, 1]$; it imports a continuum of foreign intermediate goods, also indexed by $s \in [0, 1]$. Domestic and foreign intermediate goods are used by perfectly competitive firms to produce the final good; the latter is consumed and used for investment. There is monopolistic competition in intermediate goods markets — each intermediate good is produced or imported by a single firm. Intermediate goods producers use domestic capital and labor as inputs — capital and labor are immobile internationally. The household owns all domestic firms and the capital stock, which it rents to firms. The rental market for capital is competitive. Capital can be moved across firms without cost. The household supplies a continuum of differentiated labor services, indexed by $h \in [0, 1]$; it acts as a wage setter.

2.1. Final good production

The final good is produced using the aggregate technology

$$Z_t = \{(\alpha^d)^{1/\vartheta}(Q_t^d)^{(\vartheta-1)/\vartheta} + (\alpha^m)^{1/\vartheta}(Q_t^m)^{(\vartheta-1)/\vartheta}\}^{\vartheta/(\vartheta-1)} \quad (1)$$

[2] The basic structure here was developed before I became aware of these studies (Kollmann, 1993, 1996). The present study is, thus, an independent and complementary analysis. Betts and Devereux (1998) focus on the international transmission of monetary and fiscal policy shocks. The Chari et al. model can generate more real exchange rate volatility than standard RBC models, provided highly risk averse households are postulated, but it assumes longer periods of price stickiness than the paper here.

with $\alpha^d, \alpha^m > 0$, $\alpha^d + \alpha^m = 1$, $\vartheta > 0$. Z_t is final good output at date t; Q_t^d, Q_t^m are quantity indices of domestic and imported intermediate goods, respectively: $Q_t^i = \{\int_0^1 q_t^i(s)^{(\nu-1)/\nu}\, ds\}^{\nu/(\nu-1)}$ with $\upsilon > 1$, for $i = d, m$, where $q_t^d(s)$ and $q_t^m(s)$ are quantities of the domestic and imported type 's' intermediate goods. Let $p_t^d(s)$ and $p_t^m(s)$ be the prices of these goods, in domestic currency. Cost minimization in final good production implies:

$$q_t^i(s) = (p_t^i(s)/\mathscr{P}_t^i)^{-\nu} Q_t^i, \quad Q_t^i = \alpha^i(\mathscr{P}_t^i/P_t)^{-\vartheta} Z_t \text{ for } i = d, m \tag{2}$$

with

$$\mathscr{P}_t^i \equiv \left\{ \int_0^1 (p_t^i(s))^{1-\nu}\, ds \right\}^{1/(1-\nu)}, \quad P_t \equiv \{\alpha^d(\mathscr{P}_t^d)^{1-\vartheta} + \alpha^m(\mathscr{P}_t^m)^{1-\vartheta}\}^{1/(1-\vartheta)}. \tag{3}$$

$\mathscr{P}_t^d$ [$\mathscr{P}_t^m$] is a price index for domestic [imported] intermediate goods. Perfect competition in the final good market implies that the good's price is P_t (its marginal cost is $\{\alpha^d(\mathscr{P}_t^d)^{1-\vartheta} + \alpha^m(\mathscr{P}_t^m)^{1-\vartheta}\}^{1/(1-\vartheta)}$).

2.2. Intermediate goods firms

The technology of the firm that produces domestic intermediate good 's' is:

$$y_t(s) = \theta_t(\mathscr{K}_t(s))^{\psi}(\mathscr{L}_t(s))^{1-\psi}, \quad 0 < \psi < 1. \tag{4}$$

$y_t(s)$ is the firm's output at date t; θ_t is an exogenous productivity parameter that is identical for all domestic intermediate goods producers; $\mathscr{K}_t(s)$ and $\mathscr{L}_t(s)$ are the capital stock and an index of the labor types used by the firm: $\mathscr{L}_t(s) = \{\int_0^1 \ell_t(h; s)^{(\gamma-1)/\gamma}\, dh\}^{\gamma/(\gamma-1)}$, with $\gamma > 1$, where $\ell_t(h; s)$ is the quantity of type h labor.

Let R_t and $w_t(h)$ be the rental rate of capital and the wage rate for type h labor. Cost minimization conditions for the firm can be written as:

$$\ell_t(h; s) = (1-\psi)\psi^{-1} w_t(h)^{-\gamma}(W_t)^{\gamma-1} R_t \mathscr{K}_t(s), \text{ with } W_t = \left\{ \int_0^1 (w_t(h))^{1-\gamma}\, dh \right\}^{1/(1-\gamma)}. \tag{5}$$

The firm's marginal cost is:

$$\mathfrak{C}_t \equiv (1/\theta_t)(R_t)^{\psi}(W_t)^{1-\psi}\psi^{-\psi}(1-\psi)^{-(1-\psi)}. \tag{6}$$

The firm's good is sold in the domestic market and exported: $y_t = q_t^d(s) + q_t^x(s)$, where $q_t^d(s)$ [$q_t^x(s)$] is domestic [export] demand. The export demand function is assumed to resemble the domestic demand function (2):

$$q_t^x(s) = (p_t^x(s)/\mathscr{P}_t^x)^{-\nu} Q_t^x, \quad \text{with} \quad Q_t^x = (\mathscr{P}_t^x/P_t^*)^{-\eta}, \quad \eta > 0, \tag{7}$$

where $p_t^x(s)$ is the firm's export price, in foreign currency, while

$$Q_t^x \equiv \left\{ \int_0^1 (q_t^x(s))^{(\nu-1)/\nu} \, \mathrm{d}s \right\}^{\nu/(\nu-1)}, \quad \mathscr{P}_t^x = \left\{ \int_0^1 (p_t^x(s))^{1-\vartheta} \, \mathrm{d}s \right\}^{1/(1-\nu)} \tag{8}$$

are a quantity index and a price index for the country's exports. P_t^* is the foreign price level and also represents the purchase price of foreign intermediate goods paid by domestic importers; P_t^* is exogenous.

The profits of a domestic intermediate good producer, π_t^{dx}, and of an intermediate good importer, π_m^t, are:

$$\pi_t^{dx}(p_t^d(s), p_t^x(s)) \equiv (p_t^d(s) - \mathfrak{C}_t)(p_t^d(s)/\mathscr{P}_t^d)^{-\nu} Q_t^d + (e_t p_t^x(s) - \mathfrak{C}_t)(p_t^x(s)/\mathscr{P}_t^x)^{-\nu} Q_t^x,$$
$$\pi_t^m(p_t^m(s)) \equiv (p_t^m(s) - e_t P_t^*)(p_t^m(s)/\mathscr{P}_t^m)^{-\nu} Q_t^m,$$

where e_t is the nominal exchange rate, expressed as the domestic currency price of foreign currency.

Motivated by the empirical failure of the Law of One Price, and in particular by widespread pricing-to-market behavior (e.g., Knetter, 1993), it is assumed that intermediate goods firms can price discriminate between domestic and foreign markets ($p_t^d(s) \neq e_t p_t^x(s)$ is possible), and that they set prices in terms of the currencies of their customers.

There is staggered price setting, à la Calvo (1983): domestic intermediate goods firms cannot change prices, in buyer currency, unless they receive a random 'price-change signal'. The probability that the price (in buyer currency) of a given intermediate good can be changed in any particular period is $1 - \mathfrak{d}$, a constant. Thus, the mean price-change-interval is $1/(1 - \mathfrak{d})$. Firms are assumed to meet the demand for their good, at the posted price, until a new 'price-change signal' is received.

Consider an intermediate good producer that, at t, sets a new price in the domestic market, $p_{t,t}^d$. With probability $\mathfrak{d}^\tau$, $p_{t,t}^d$ is still in force at $t + \tau$. The firm sets

$$p_{t,t}^d = \operatorname*{Arg\,Max}_{\mathfrak{p}} \sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t\{\rho_{t,t+\tau} \pi_{t+\tau}^{dx}(\mathfrak{p}, p_{t+\tau}^x(s))/P_{t+\tau}\},$$

where $\rho_{t,t+\tau}$ is a pricing kernel (for valuing date $t + \tau$ pay-offs) that is assumed to equal the household's intertemporal marginal rate of substitution in consumption: $\rho_{t,t+\tau} = \beta^\tau U_{C,t+\tau}/U_{C,t}$ where $U_{C,t+\tau}$ is the household's marginal utility of consumption at $t + \tau$ (household preferences are described in Section 2.3). Let $\Xi_{t,t+\tau}^i \equiv \rho_{t,t+\tau} Q_{t+\tau}^i (\mathscr{P}_{t+\tau}^i)^\nu / P_{t+\tau}$, for $i = d$, x, m. The solution of the firm's maximization problem regarding $p_{t,t}^d$ is:

$$p^d_{t,t} = (\nu/(\nu-1))\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^d_{t,t+\tau}\mathfrak{C}_{t+\tau}\right\}\Big/\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^d_{t,t+\tau}\right\}. \tag{9}$$

Analogously, an intermediate good producer and an intermediate good importer that get to choose a new export price/new sales price in the domestic market set these prices at, respectively:

$$p^x_{t,t} = (\nu/(\nu-1))\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^x_{t,t+\tau}\,\mathfrak{C}_{t+\tau}\right\}\Big/\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^x_{t,t+\tau} e_{t+\tau}\right\}, \tag{10}$$

$$p^m_{t,t} = (\nu/(\nu-1))\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^m_{t,t+\tau}\, e_{t+\tau} P^*_{t+\tau}\right\}\Big/\left\{\sum_{\tau=0}^{\tau=\infty} \mathfrak{d}^\tau E_t \Xi^m_{t,t+\tau}\right\}. \tag{11}$$

(9)–(11) imply that, up to a certainty-equivalent approximation, prices set at t equal a weighted average of current and expected future marginal costs (or foreign purchase prices), multiplied by the markup factor $\nu/(\nu-1) > 1$.

The price indices $\mathcal{P}^d_t$, $\mathcal{P}^m_t$, $\mathcal{P}^x_t$ (see (3), (8)) evolve according to:

$$(P^{\mathbf{i}}_t)^{1-\nu} = \mathfrak{d}(\mathcal{P}^{\mathbf{i}}_{t-1})^{1-\nu} + (1-\mathfrak{d})(p^{\mathbf{i}}_{t,t})^{1-\nu}, \quad i = d, m, x. \tag{12}$$

2.3. The representative household

The preferences of the representative household are described by:

$$E_0 \sum_{t=0}^{t=\infty} \beta^t U\left(C_t, \mathcal{M}_t/P_t, \int_0^1 l_t(h)\,\mathrm{d}h\right). \tag{13}$$

E_0 denotes the mathematical expectation conditional on date $t = 0$ information. $0 < \beta < 1$ is a subjective discount factor, and U is a utility function. C_t is period t consumption, $\mathcal{M}_t$ is the household's stock of domestic money at the beginning of t, and $l_t(h)$ is the amount of type h labor provided by the household ($h \in [0, 1]$). The utility function U takes the following form:

$$U(C, \mathcal{M}/P, \int l(h)\,\mathrm{d}h) = (1-\Psi)^{-1}\{[C^\sigma + \kappa(\mathcal{M}/P)^\Gamma]^{1/\sigma}\}^{1-\Psi} - \int l(h)\,\mathrm{d}h.$$

As indicated earlier, the household owns all domestic firms and accumulates physical capital. The law of motion of the capital stock is:

$$K_{t+1} + \phi(K_{t+1}, K_t) = K_t(1-\delta) + I_t, \tag{14}$$

where I_t is gross investment, $0 < \delta < 1$ is the depreciation rate of capital, and ϕ is an adjustment cost function:

$$\phi(K_{t+1}, K_t) = 0.5\Phi\{K_{t+1} - K_t\}^2/K_t, \; \Phi > 0.$$

The household also holds domestic money and nominal one-period domestic and foreign currency bonds. Its period t budget constraint is:

$$\mathcal{M}_{t+1} + A_{t+1} + e_t B_{t+1} + P_t(C_t + I_t) = \mathcal{M}_t + T_t + A_t(1 + i_{t-1}) + e_t B_t(1 + i^*_{t-1}) + R_t K_t + \int_0^1 (\pi_t^{dx}(s) + \pi_t^m(s))\,\mathrm{d}s + \int_0^1\int_0^1 w_t(h)\ell_t(h; s)\,\mathrm{d}h\,\mathrm{d}s. \quad (15)$$

A_t and B_t are net stocks of domestic and foreign currency bonds that mature in period t. i_{t-1} and i^*_{t-1} are the nominal interest rates on these bonds. The foreign rate, i^*, is exogenous. T_t is a government cash transfer. The last two terms in (15) are the household's dividend and labor income.

There is staggered wage setting by the household, subject to the constraint that the wage rate for labor of a given type can be changed only when a random 'wage-change signal' is received for that type; at any given date, the probability of receiving this signal is $1 - \mathfrak{D}$, a constant. Let $w_{t,t}$ be the wage set at t. The date t wage for type h labor, $w_t(h)$, equals the wage set the last time (up to t), for that type:

$$w_t(h) = w_{\tau(h;t),\tau(h;t)}, \text{ with } \tau(h; t) \equiv \max\{\tau\colon s_\tau(h) = 1, \tau \le t\}, \quad (16)$$

where $s_\tau(h) \in \{0, 1\}$ is an i.i.d. random variable, with $\text{Prob}(s_\tau(h) = 1) = 1 - \mathscr{D}$ (a wage change for type h labor can occur at date τ iff $s_\tau(h) = 1$).

The household is assumed to take the *average* wage (W) as given when setting $w_{t,t}$, and to always meet the demand for each labor type, at the prevailing wage:

$$l_t(h) = \int_0^1 \ell_t(h; s)\,\mathrm{d}s, \quad (17)$$

where $l_t(h)$ is the amount of type h labor provided by the household (see (13)), while $\int_0^1 \ell_t(h; s)\,\mathrm{d}s$ is total demand for type h labor by firms (see (5)).

The household chooses a strategy $\{A_{t+1}, B_{t+1}, M_{t+1}, K_{t+1}, C_t, w_{t,t}\}_{t=0}^{t=\infty}$ to maximize its expected lifetime utility (13), subject to constraints (14)–(17) and to initial values A_0, B_0, M_0, K_0, $\{w_{t,t}\}_{t=-\infty}^{t=-1}$. Ruling out Ponzi schemes, the following equations are first-order conditions of this decision problem:

$$1 = (1 + i_t)\beta E_t\{(U_{C,t+1}/U_{C,t})(P_t/P_{t+1})\} \quad (18)$$

$$1 = (1 + i^*_t)\beta E_t\{(U_{C,t+1}/U_{C,t})(P_t e_{t+1})/(P_{t+1}e_t)\}, \quad (19)$$

$$1 = \beta E_t\{(U_{C,t+1}/U_{C,t})(R_{t+1}/P_{t+1} + 1 - \delta - \phi_{2,t+1})/(1 + \phi_{1,t})\}, \quad (20)$$

$$E_t\{(C_{t+1})^{1-\sigma}(\mathcal{M}_{t+1}/P_{t+1})^{\Gamma-1}U_{C,t+1}/P_{t+1}\}\kappa\Gamma/\sigma = i_t E_t\{U_{C,t+1}/P_{t+1}\}, \quad (21)$$

$$w_{t,t} = (\gamma/(\gamma - 1)) \sum_{\tau=0}^{\tau=\infty} (\beta\mathfrak{D})^{\tau} E_t \chi_{t+\tau} \Big/ \sum_{\tau=0}^{\tau=\infty} (\beta\mathfrak{D})^{\tau} E_t \{\chi_{t+\tau} U_{C,t+\tau} / P_{t+\tau}\}, \quad (22)$$

where $\chi_{t+\tau} \equiv (1-\psi)\psi^{-1}(W_{t+\tau})^{\gamma-1} R_{t+\tau} \int_0^1 \mathscr{K}_{t+\tau}(s)\ \mathrm{d}s$, $\phi_{1,t} \equiv \partial\phi(K_{t+1}, K_t)/\partial K_{t+1}$ and $\phi_{2,t+1} \equiv \partial\phi(K_{t+2}, K_{t+1})/\partial K_{t+1}$. (18)–(20) are Euler conditions, (21) can be viewed as a money demand condition, and (22) determines the contract wage, $w_{t,t}$. The wage index W_t (see (5)) evolves according to:

$$(W_t)^{1-\gamma} = \mathfrak{D}(W_{t-1})^{1-\gamma} + (1-\mathfrak{D})(W_{t,t})^{1-\gamma}. \quad (23)$$

2.4. Government

The government prints the local currency. Let M_t be the money stock at beginning of date t. M is exogenous. Increases in M are paid to the household, as a transfer (T):

$$M_{t+1} = M_t + T_t. \quad (24)$$

2.5. Market clearing conditions

Supply equals demand in markets for labor and intermediate goods as, by assumption, the household and intermediate goods firms always meet the demand for labor/their goods. Market clearing for the final good and rental capital requires:

$$Z_t = C_t + I_t \quad \text{and} \quad K_t = \int_0^1 \mathscr{K}_t(s)\ \mathrm{d}s, \quad (25)$$

where Z_t is final good output, K_t is the aggregate capital stock, and $\int_0^1 \mathscr{K}_t(s)\ \mathrm{d}s$ is total demand for rental capital by intermediate goods firms.

It is assumed that foreigners do not hold the country's currency or bonds denominated in that currency. Thus, money market equilibrium requires:

$$M_t = \mathscr{M}_t \quad (26)$$

where M_t and $\mathscr{M}_t$ are the domestic money stock and the household's desired money balances, respectively; market clearing for domestic currency bonds requires that the household's (net) stock of bonds of this type is zero:

$$A_t = 0. \quad (27)$$

2.6. Solution method

An approximate model solution is obtained by taking a linear approximation of Eqs. (1)–(12), (14)–(27) around the deterministic steady state in which the country's net foreign asset position is zero. (Log-)linear stochastic processes are specified for the shocks (see (28)). The resulting linear dynamic model is solved using Blanchard and Kahn's (1980) formulae.

2.7. Parameter values

The household's coefficient of relative risk aversion is set at $\Psi = 2$. I focus on business cycles in Japan, Germany and the U.K. (G3). $\Psi = 2$ is consistent with estimates of Ψ for these countries (Barrionuevo, 1991) and is also in the range of values typically used in macro models. As is usual in models calibrated to quarterly data, the steady state real interest rate, r, is set at $r = 0.01$ (which corresponds roughly to the long-run average return on capital), while the subjective discount factor is set at $\beta = 1/1.01$ (the existence of a deterministic steady state requires that $(1 + r)\beta = 1$ holds).

Up to a certainty-equivalent approximation, (21) can be written as $(\mathcal{M}_{t+1}/P_{t+1})^{\Gamma-1}\kappa\Gamma/\sigma = (C_{t+1})^{\sigma-1}i_t + \eta_{t+1}$, where η_{t+1} is a forecast error ($E_t\eta_{t+1} = 0$). Thus, the elasticities of money demand with respect to the interest rate and to consumption are $\varepsilon_i \equiv 1/(\Gamma - 1)$ and $\varepsilon_c \equiv (\sigma - 1)/(\Gamma - 1)$, respectively. Based on Fair's (1987) estimates of ε_i for the G3 countries, and Faig's (1989) estimates of ε_c (for Germany and the U.K.), I set $\varepsilon_i = -0.04$ and $\varepsilon_c = 0.33$. The preference parameter κ is set so that the steady state consumption velocity of money, PC/M, is 0.5 (which corresponds roughly to average post-Bretton Woods Ml velocity in the G3).

The price elasticities of the country's aggregate imports and exports (see (2), (7)) are set at $\vartheta = \eta = 0.6$; this is the median value of the estimates of ϑ and η for the G3 countries reported by Hooper and Marquez (1995). α^m (see (1)) is set so that the steady state imports/GDP ratio is 25%, consistent with U.K. and German data. (The imports/GDP ratio is $\approx$10% for Japan; using a 10% steady state ratio does not change the key results.)

The steady state markup of price over marginal cost for intermediate goods is set at $1/(v - 1) = 0.2$, consistent with the findings of Martins et al. (1996) for the G3 countries. The technology parameter ψ (see (4)) is set at $\psi = 0.24$, which entails a 60% steady state labor income/GDP ratio, consistent with G3 data. Aggregate data suggest a quarterly capital depreciation rate of about 2.5%; thus, $\delta = 0.025$ is used. The capital adjustment cost parameter Φ is set at $\Phi = 15$, in order to match the fact that the standard deviation of investment is three to four times larger than that of GDP in G3 countries.[3]

[3]Linearizing the model yields equations in aggregate variables that do not depend on γ (see (5)); thus, no value needs to be assigned to γ.

In G3 countries, wages are generally changed once a year (Bruno and Sachs, 1985). Thus, the average wage-change-interval is set at 4 periods, i.e. $\mathfrak{D}=0.75$ is used, as the model is calibrated to quarterly data. I am not aware of estimates of the frequency of price changes in the G3. In the U.S., the average price-change-interval is about 1 year, for many goods (Romer, 1996). Thus, the mean price-change-interval is set at 4 periods: $\mathfrak{d}=0.75$.

Domestic money and productivity, and the foreign price level and expected *real* interest rate $(r_t^* \equiv (1+i_t^*)E_t(P_t^*/P^*_{t+1})-1)$ follow these processes:

$$\begin{aligned}&\ln(M_{t+1}/M_t)=\rho^m \ln(M_t/M_{t-1})+\varepsilon_t^m, \quad \ln(\theta_t)=\rho^\theta \ln(\theta_{t-1})+\varepsilon_t^\theta,\\&\ln(P_t^*/P_{t-1}^*)=\rho^P \ln(P_{t-1}^*/P_{t-2}^*)+\varepsilon_t^P, \quad r_t^*=(1-\rho^r)r+\rho^r r_{t-1}^*+\varepsilon_t^r\end{aligned} \tag{28}$$

where ε_t^m, ε_t^θ, ε_t^p, and ε_t^r are independent white noises with deviations σ^m, σ^θ, σ^p, and σ^r. The parameters of the money and productivity processes are set at $\rho^m=0.15$, $\sigma^m=0.017$, $\rho^\theta=0.82$, $\sigma^\theta=0.011$. These values are parameter estimates (for quarterly post-Bretton Woods data) that were averaged across the G3 countries.[4] G3/U.S. exchange rates are considered below. Using the U.S. CPI and the U.S. 3-month CD rate (Citibase series FYUSCD) as measures of the foreign price level P_t^* and nominal interest rate i_t^*, the following parameter estimates are obtained for 1973Q1–94Q4: $\rho^P=0.80$, $\sigma^P=0.005$, $\rho^r=0.76$, $\sigma^r=0.005$. These values are used in the simulations.[5]

3. Stylized facts about economic fluctuations (Post-Bretton Woods era)

Table 1 reports statistics on the cyclical behavior of key G3 quarterly macroeconomic time series since 1973 (all series have been logged, with the exception of interest rates, and Hodrick–Prescott (HP) filtered).

Most statistics are similar across the G3 countries. The standard deviation of GDP is roughly 1.5%; consumption is about as volatile as GDP; physical investment is more volatile. With standard deviations of about 9%, the nominal and real exchange rates of the G3 countries (vis-à-vis the U.S.) are more volatile than the other variables in Table 1. The correlation between nominal and real exchange rates is high (about 0.97).

Consumption, investment and the money stock are procyclical (positive correlation with domestic GDP), while net exports and the price level are countercyclical. The variables in Table 1 are highly autocorrelated.

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[4]For the Ml money series in Table 1 and Kollmann's (1998) linearly detrended log total factor productivity series (75Q1–91Q3), the following estimates are obtained (by OLS; an intercept was included in empirical regressions): $\rho^m=0.14$, 0.12, 0.19; $\sigma^m=0.015$, 0.017, 0.018; $\rho^\theta=0.82$, 0.85, 0.80; $\sigma^\theta=0.012$, 0.014, 0.009 for Japan, Germany, and the UK, respectively.

[5]Constructing a series for r_t^* using the formula $r_t^* \cong i_t^* - \rho^p \ln(P_t^*/P_{t-1}^*)$, with $\rho^p=0.80$, and fitting an AR(1) process to r_t^* yields $\rho^r=0.76$, $\sigma^r=0.005$.

Table 1
Historical statistics: post-Bretton Woods era[a]

Statistic	Country			Average
	Japan	Germany	U.K.	
	(1)	(2)	(3)	(4)
Standard deviation (in %)				
GDP	1.28 (.16)	1.57 (.15)	1.70 (.15)	1.52
Consumption	1.19 (.16)	1.27 (.14)	1.88 (.19)	1.45
Investment	3.37 (.28)	6.46 (.78)	6.85 (.72)	5.55
Net exports	6.82 (1.0)	2.63 (.35)	3.57 (.39)	4.34
Price level	1.92 (.49)	1.09 (.06)	2.27 (.22)	1.75
Money	1.97 (.20)	2.50 (.26)	2.87 (.46)	2.45
Nominal interest rate	0.45 (.06)	0.43 (.06)	0.51 (.06)	0.46
Nominal $ exchange rate	9.14 (1.0)	9.02 (1.2)	9.23 (.92)	9.13
Real $ exchange rate	9.16 (1.1)	8.63 (1.1)	8.89 (.96)	8.89
Correlation with domestic GDP				
Consumption	0.64 (.04)	0.60 (.08)	0.81 (.05)	0.69
Investment	0.81 (.02)	0.83 (.04)	0.75 (.04)	0.80
Net exports	−0.30 (.10)	−0.30 (.15)	−0.26 (.12)	−0.29
Price level	−0.39 (.24)	−0.53 (.14)	−0.58 (.08)	−0.50
Money	0.01 (.15)	0.31 (.16)	0.44 (.11)	0.25
Nominal interest rate	0.02 (.28)	0.32 (.09)	0.08 (.10)	0.14
Nominal $ exchange rate	0.06 (.18)	−0.21 (.17)	−0.06 (.10)	−0.07
Real $ exchange rate	0.15 (.14)	−0.18 (.17)	−0.01 (.11)	−0.01
Autocorrelation				
GDP	0.79 (.03)	0.80 (.05)	0.76 (.06)	0.78
Nominal $ exchange rate	0.82 (.02)	0.79 (.05)	0.78 (.05)	0.80
Real $ exchange rate	0.81 (.02)	0.78 (.05)	0.75 (.04)	0.78
Correlation between nominal and real $ exchange rate	0.97 (.01)	0.98 (.00)	0.97 (.01)	0.97

[a] Notes: The figures in parentheses are standard errors (obtained by GMM, assuming tenth-order serial correlation in residuals). All series were logged (with exception of interest rates) and HP filtered. Col. (4): arithmetic average of the statistics, across the 3 countries. The data are quarterly; unless otherwise indicated, data are from OECD Main Economic Indicators [MEI] and cover 1973Q1–1994Q4. GDP: real GDP (for Germany: GNP) from International Financial Statistics [IFS]. Consumption: total private consumption, in constant prices. Investment: gross fixed capital formation plus inventory change, in constant prices. Net exports: *exp*/*imp*, where *exp* (*imp*) is volume index of exports (imports) of goods and services. Price level: CPI. Money supply: Ml (German Ml series: 1973Q1–1990Q1). Nominal interest rate: short-term rates from Citibase (series FYGECM, FYJPCM, FYGBBB), expressed on a quarterly basis. Nominal $ exchange rate: from IFS. Real $ exchange rate: based on relative CPIs. Exchange rates are measured as domestic currency prices of the U.S. dollar. German series pertain to *West* Germany.

4. Simulation results

Simulation results are reported in Table 2. Columns (6)–(10) pertain to the nominal rigidities model; Cols. (1)–(5) consider a structure *without* nominal rigidities (in which the price/wage adjustment parameters $\mathfrak{d}$, $\mathfrak{D}$ are set at $\mathfrak{d} = \mathfrak{D} = 0$). The country's output and price level are measured by its real GDP and the price of the final good, P_t; the real exchange rate is defined as $RER_t = e_t P_t^{*}/P_t$. Variants are considered in which each of the four types of shocks occurs separately, as well as variants with the four simultaneous shocks. Model statistics pertain to variables that have been logged (with the exception of the interest rate) and HP filtered.

4.1. Money supply shocks

Cols. (1) and (6) of Table 2 show results for the case with only money shocks. When prices and wages are flexible ($\mathfrak{d} = \mathfrak{D} = 0$), then these shocks have little effect on GDP, consumption, investment, net exports and the real exchange rate: the predicted standard deviations of these variables do not exceed 0.10% (Col. 1); in contrast, the standard deviation of the price level (2.43%) is roughly consistent with the data; due to the weak effect on the real exchange rate (when $\mathfrak{d} = \mathfrak{D} = 0$), the standard deviation of the nominal exchange rate is nearly identical to that of the price level.

In the nominal rigidities structure ($\mathfrak{d} = \mathfrak{D} = 0.75$), money shocks have a much stronger effect on real variables — predicted standard deviations of GDP and the real exchange rate: 1.77% and 3.07%, respectively (Col. 6); the standard deviation of the nominal exchange rate is also higher: 3.73% (compared to 2.43% when prices and wages are flexible). The predictions regarding the standard deviations of consumption, investment, net exports and the nominal interest rate also improve when $\mathfrak{d} = \mathfrak{D} = 0.75$ is assumed.

For the nominal rigidities model, Panel (a) in Figure 1 shows responses to a one-standard-deviation (1.70%) money supply innovation (the following responses represent relative deviations from pre-shock values). The shock induces a rise in the price level (impact effect: 0.45%). which increases however less rapidly than the money supply. As a result, there is a persistent increase in *real* money balances, which explains why the shock induces a reduction in the domestic nominal interest rate that lasts several periods. The expected *real* interest rate in terms of the final good also falls (not shown in Figure) as the expected inflation rate rises. This raises consumption and investment and, hence, GDP (by 1.47%, on impact).

On impact, a 1.70% money shock induces a 3.13% depreciation of the nominal exchange rate, in the nominal rigidities structure; the long-run effect is a 2.28% depreciation. Note that (18), (19) imply that uncovered interest parity holds (up to

Table 2
Predictions: model *without* nominal rigidities and nominal rigidities model[a]

	Model without nominal rigidities					Nominal rigidities model					
	Shocks to:					Shocks to:					
	M	***θ***	***r****	***P****	***r**, *P**, *M*&*θ***	***M***	***θ***	***r****	***P****	***r**, *P**, *M*&*θ***	**Data**
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Standard deviation (in %)											
GDP	0.06	0.97	0.09	0.00	**0.97**	1.77	0.53	0.05	0.05	**1.83**	**1.52**
C	0.10	0.54	0.30	0.00	**0.61**	1.34	0.34	0.14	0.02	**1.37**	**1.45**
I	0.04	2.32	1.29	0.00	**2.64**	6.70	1.38	0.59	0.02	**6.79**	**5.55**
NX	0.10	0.90	2.61	0.00	**2.78**	1.77	0.36	0.84	0.33	**2.02**	**4.34**
P	2.43	0.57	0.35	0.00	**2.53**	1.48	0.29	0.12	0.01	**1.51**	**1.75**
M	2.36	0.00	0.00	0.00	**2.36**	2.36	0.00	0.00	0.00	**2.36**	**2.45**
i	0.06	0.08	0.04	0.00	**0.11**	0.19	0.05	0.02	0.08	**0.20**	**0.46**
e	2.43	0.65	1.92	1.65	**3.59**	3.73	0.57	2.01	1.62	**4.54**	**9.13**
RER	0.01	1.21	1.57	0.00	**2.00**	3.07	0.84	1.93	0.05	**3.71**	**8.89**
Correlation with GDP											
C	0.99	0.99	−0.98	u	**0.82**	0.99	0.99	0.68	-0.92	**0.99**	**0.69**
I	−0.99	0.99	−0.99	u	**0.81**	0.99	0.99	0.70	−0.36	**0.98**	**0.80**
NX	−0.99	0.98	0.99	u	**0.40**	−0.90	0.59	−0.50	0.99	**−0.72**	**−0.29**
P	−0.42	−0.99	0.98	u	**−0.24**	0.21	−0.98	−0.47	0.97	**0.16**	**−0.50**
M	0.34	u	u	u	**0.01**	0.31	u	u	u	**0.30**	**0.25**
i	−0.99	−0.99	0.98	u	**−0.68**	−0.98	−0.99	−0.62	0.90	**−0.98**	**0.14**
e	−0.43	0.98	0.99	u	**0.20**	0.91	0.95	−0.94	−0.71	**0.71**	**−0.07**
RER	−0.95	0.99	0.99	u	**0.67**	0.99	0.98	−0.95	0.81	**0.83**	**−0.01**
Autocorrelation											
GDP	0.04	0.60	0.56	u	**0.60**	0.61	0.81	0.51	0.89	**0.62**	**0.78**
e	0.69	0.51	0.56	0.92	**0.69**	0.64	0.66	0.55	0.92	**0.65**	**0.80**
RER	0.10	0.60	0.56	u	**0.58**	0.57	0.74	0.53	0.64	**0.57**	**0.78**
Correlation between nominal and real exchange rate	0.16	0.99	0.99	u	**0.53**	0.92	0.98	0.99	−0.63	**0.87**	**0.97**

[a] Notes: *C*: consumption; *I*: Investment; *P*: price level; *M*: money supply; *i*: nominal interest rate; *e*/RER: nominal/real exchange rate; NX: net exports (defined as Q_t^x/Q_t^m, where Q_t^x [Q_t^m] is quantity index of exports [imports]; see (1), (8)). u: correlation not defined (series with zero variance). Cols. labelled 'Shocks to *M*', 'Shocks to *θ*' etc. pertain to cases in which shocks to just *one* of the exogenous variables are assumed (*θ*: domestic productivity; *P** : foreign price level; *r** : foreign real interest rate). Cols. labelled 'Shocks to *r**, *P**, *M*&*θ*': four types of shocks used simultaneously. 'Data' Col. (11): average of historical statistics across G3 countries (from Table 1). The theoretical statistics (Cols. (1)–(10)) are averages of moments computed over 1000 simulation runs with a length of 88 periods each (which corresponds to the length of the historical time series used in Table 1). All series were logged (with exception of interest rates) and HP filtered.

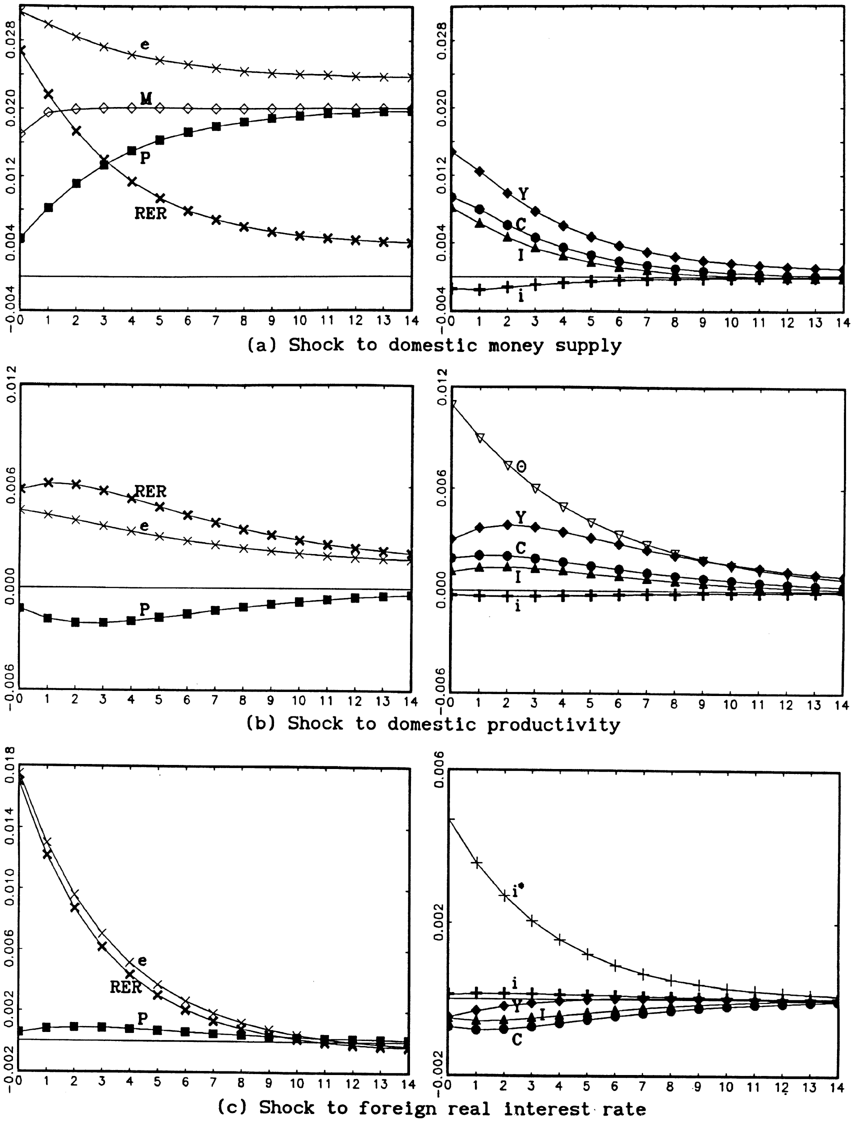

Fig. 1. Nominal rigidities model. Dynamic responses to 1 standard deviation innovations to domestic money supply, domestic productivity and foreign expected real interest rate. Interest rate responses expressed as differences from initial position; consumption and investment responses shown in units of initial GDP; responses of other variables shown as relative deviations from initial position. Period t money stock response pertains to end of period money stock (M_{t+1}). Abscissa: periods after shock. ◇: money, M; ∇: productivity, θ; +: foreign nominal interest rate, i^*; ■: price level, P; ×: nominal exchange rate, e; ×: real exchange rate, RER; ●: consumption, C; ▲: investment, I; ♦: real GDP, Y; +: domestic nominal interest rate, i.

a certainty-equivalent approximation): $(1+i_t) \cong (l+i_t^*)E_t e_{t+1}/e_t$. The drop in the domestic interest rate hence requires a subsequent appreciation of the currency. On impact, the exchange rate thus overshoots its long run response (as in Dornbusch, 1976). In contrast, there is no overshooting in the structure with flexible prices and wages.[6]

Due to the sluggishness of the domestic price level, the nominal exchange rate depreciation induces, on impact, a roughly equi-proportional *real* depreciation (subsequently the real exchange rate appreciates).

The foregoing explains why money shocks induce markedly higher standard deviations of the nominal and especially the *real* exchange rate, in the nominal rigidities structure (compared to flexible prices and wages), and a strong positive nominal-real exchange rate correlation, 0.92.

Fig. 1 also explains why the nominal rigidities model (with money shocks) predicts that GDP and exchange rates are positively autocorrelated, that consumption, investment, and money are procyclical, and that net exports are countercyclical, as is consistent with the data (the strong rise in consumption and investment triggered by a positive money shock drives down net exports (not shown in Fig. 1)). The model does not, however, capture the countercyclicality of the price level. Also, nominal and real exchange rates are predicted to be strongly procyclical while, empirically, G3 exchange rates are basically acyclical (see Table 1).

The prediction that positive money shocks lower the domestic interest rate, raise output and the price level, and induce a nominal and real currency depreciation is consistent with empirical evidence on the effect of monetary policy in G3 countries; see, e.g., Fung and Kasumovich (1998).

4.2. Other types of shocks

Under price-wage flexibility, *productivity* shocks have a stronger effect on real variables than money shocks, but a weaker effect on the nominal exchange rate (standard dev. of GDP and of real and nominal exchange rates: 0.97%, 1.21%, 0.65%, with just productivity shocks). Price–wage stickiness dampens the effect of productivity shocks on real variables (Cols. 2, 7).

Whether prices and wages are flexible or not, shocks to the *foreign expected real interest rate* have a sizable effect on nominal and real exchange rates (predicted standard deviations about 2%, when just these shocks are assumed), but

[6] In that structure the expected *real* interest rate is hardly affected by money shocks, and a positive money shock raises the nominal interest rate, as the shock raises the expected inflation rate (due to positive serial correlation of money growth) — thus, no nominal exchange rate overshooting.

only a weak effect on GDP (Cols. 3 and 8). Shocks to the *foreign price level* have a significant effect on the nominal exchange rate but little effect on the remaining variables (Cols. 4 and 9).

For the nominal rigidities structure, Panels (b) and (c) in Fig. 1 show the effects of shocks to domestic productivity and to the foreign expected real interest rate. A positive *productivity shock* causes a rise in GDP, a fall in the price level and a nominal and real currency depreciation. A positive shock to the *foreign real interest rate* similarly induces a nominal and real exchange rate depreciation.

4.3. Combined effect of four types of shocks

In the nominal rigidities structure, money shocks induce larger standard deviations of endogenous variables than the other shocks. When simultaneously subjected to the four shocks, that structure generates predicted statistics that are, thus, largely similar to those reported when just money shocks are used; with the four shocks, the standard deviations of nominal and real exchange rates, 4.54% and 3.71%, are larger than those predicted under flexible prices and wages, 3.59% and 2.00% (Cols. (5) and (10)). The nominal rigidities model with four shocks captures 49% [41%] of the (average) standard deviation of post-Bretton Woods nominal [real] G3/U.S. exchange rates. It also yields a predicted correlation between nominal and real exchange rates, 0.87, which is markedly higher than that under flexible prices and wages, 0.53 (historical correlation: 0.97).

4.4. Sensitivity analysis

The result that nominal rigidities raise the variability of output and of the nominal and (especially) the real exchange rate, as well as the nominal–real exchange rate correlation, is robust to changes in preference and technology parameters (sensitivity analysis available from author).

Here I discuss alternative assumptions about price and wage adjustment. A variant of the model was considered in which just wages are sticky, with a mean wage-change-interval of 4 periods (while prices are flexible; $\mathfrak{d} = 0$, $\mathfrak{D} = 0.75$), as well as a variant with just sticky prices ($\mathfrak{d} = 0.75$, $\mathfrak{D} = 0$). The key precondition for money shocks to have a noticeable effect on real activity (and to cause exchange rate overshooting) is sufficient domestic *price level* (P) sluggishness (the latter implies that a positive nominal money shock raises real balances, which triggers a fall in the interest rate and a rise in output; see Section 4.1). Wage stickiness dampens the response of P as wages are a key determinant of marginal cost (see (6)). Therefore, the structures with just sticky wages or just sticky prices generate higher output and exchange rate variability, and higher nominal–real exchange rate correlations than the structure with price–wage flexibility; however simultaneous price–wage stickiness generates higher variability than the structures with just sticky wages or prices.[7]

Increasing the average time lag between price and wage changes raises predicted output and exchange rate variability. For example, when that lag is set at 6 periods, the model with four shocks captures 59% [54%] of the historical standard deviations of nominal [real] G3/U.S. exchange rates. The average lag must be set at about 15 periods for the model to *exactly* match the historical standard deviations of nominal and real G3/U.S. exchange rates. Such a long lag lacks empirical plausibility.

5. Conclusion

This paper has examined a quantitative dynamic-optimizing business cycle model of a small open economy with nominal rigidities. Predicted exchange rate variability and correlations between nominal and real exchange rates are higher than in standard Real Business Cycle models that postulate flexible prices and wages. The nominal rigidities model, with an average interval between price and wage changes of 4 quarters, captures roughly 40–50% of the volatility of the exchange rates of Japan, Germany, and the U.K. vis-à-vis the U.S., during the post-Bretton Woods era. Clearly, there is scope for exploring additional mechanisms that induce greater exchange rate variability. For example, the current model could be extended by assuming features that may generate multiple equilibria and permit 'sunspot fluctuations' in the exchange rate (and in other variables) — in other words, movements that are not related to changes in the money stock and other fundamentals. Features of this type include production technologies with increasing returns (e.g. Guo and Sturzenegger, 1998) and 'noise traders' in exchange markets (Jeanne and Rose, 1999). A key question for future work is whether incorporating these features into the nominal rigidities model would allow to capture *simultaneously* the high volatility of exchange rates and the other key macroeconomic facts considered here.

[7] When there are solely money shocks, the standard deviations of GDP, of nominal and real exchange rates, and the nominal–real exchange rate correlation are 1.06%, 2.95%, 1.33%, 0.87 with just sticky wages, and 1.31%, 3.26%, 2.35%, 0.87 with just sticky prices — compared to 0.06%, 2.43%, 0.01%, 0.16 without nominal rigidities, and to 1.77%, 3.73%, 3.07%, 0.92 with sticky prices *and* wages. With the four shocks, the corresponding statistics are 1.60%, 3.93%, 2.46%, 0.74 with just sticky wages; 1.40%, 4.22%, 3.15%, 0.83 with just sticky prices; 0.97%, 3.59%, 2.00%, 0.53 without nominal rigidities; 1.83%, 4.54%, 3.71%, 0.87 with sticky prices *and* wages.

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References

Backus, D., Kehoe, P., Kydland, F., 1995. International business cycles: theory and evidence. In: Cooley, T. (Ed.), Frontiers of Business Cycle Research. Princeton University Press, Princeton, pp. 331–356.

Barrionuevo, J., 1991. Asset prices in the international economy. Working paper, University of Chicago.

Betts, C., Devereux, M., 1998. The international effects of monetary and fiscal policy in a two-country model. Manuscript.

Betts, C., Devereux, M., 2000. Exchange rate dynamics in a model of pricing-to-market. Journal of International Economics 50, 215–244.

Blanchard, O., Kahn, C., 1980. The solution of linear difference models under rational expectations. Econometrica 48, 1305–1311.

Bruno, M., Sachs, J., 1985. Economics of Worldwide Stagflation. Harvard University Press, Cambridge, MA.

Calvo, G., 1983. Staggered prices in a utility-maximizing framework. Journal of Monetary Economics 12, 383–398.

Chari, V.V., Kehoe, P., McGrattan, E., 1998. Monetary shocks and real exchange rates in sticky price models of international business cycles. Manuscript, Research Department, Federal Reserve Bank of Minneapolis.

Dornbusch, R., 1976. Expectations and exchange rate dynamics. Journal of Political Economy 84, 1161–1176.

Engel, C., Devereux, M., 2000. Monetary policy in the open economy revisited. Working paper 7665, National Bureau of Economic Research.

Erceg, C., Levin, A., Henderson, D., 1999. Optimal monetary policy with staggered wage and price contracts. Journal of Monetary Economics 46, 281–313.

Faig, M., 1989. Seasonal fluctuations and the demand for money. Quarterly Journal of Economics 104, 847–861.

Fair, R., 1987. International evidence on the demand for money. Review of Economics and Statistics 69, 473–480.

Fung, B., Kasumovich, M., 1998. Monetary shocks in the G-6 Countries: is there a puzzle? Journal of Monetary Economics 42, 575–592.

Guo, J., Sturzenegger, F., 1998. Crazy explanations of international business cycles. International Economic Review 29, 111–133.

Hooper, P., Marquez, J., 1995. Exchange rates, prices and external adjustment in the United States and Japan. In: Kenen, P. (Ed.), Understanding Interdependence. Princeton University Press, Princeton, pp. 107–168.

Jeanne, O., Rose, A., 1999. Noise trading and exchange rate regimes. Working paper 7104, National Bureau of Economic Research.

Knetter, M., 1993. International comparison of pricing to market behavior. American Economic Review 83, 473–486.

Kollmann, R., 1993. International business cycles. Research proposal submitted to Social Sciences and Humanities Research Council (Canada).

Kollmann, R., 1996. The exchange rate in a dynamic-optimizing current account model with nominal rigidities. D.P. 1496, CRDE, Universite de Montreal.

Kollmann, R., 1998. U.S. trade balance dynamics. Journal of International Money and Finance 17, 637–669.

Lane, P., 1999. The new open economy macroeconomics: a survey. Forthcoming, Journal of International Economics.

Martins, J., Scarpetta, S., Pilat, D., 1996. Mark-up pricing, market structure and the business cycle. OECD Economic Studies 27, 71–105.

Mundell, R., 1968. International Economics. MacMillan, New York.

Obstfeld, M., Rogoff, K., 1995. Exchange rate dynamics redux. Journal of Political Economy 103, 624–660.

Obstfeld, M., Rogoff, K., 2000. New directions for stochastic open economy models. Journal of International Economics 50, 117–153.

Romer, D., 1996. Advanced Macroeconomics. McGraw-Hill, New York.

Rotemberg, J., Woodford, M., 1997. An optimization-based econometric framework for the evaluation of economic policy. NBER Macroeconomics Annual 12, 297–346.

Schlagenhauf, D., Wrase, J., 1995. Liquidity and real activity in a simple open economy model. Journal of Monetary Economics 35, 431–461.