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Business cycles with staggered prices and international trade in intermediate inputs ☆

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Abstract

International trade in intermediate inputs and, increasingly, in goods produced at multiple stages of processing has been widely studied in the real trade literature. We assess the role of this feature of modern world trade in accounting for some stylized facts about international business cycles. Our model with staggered prices and trade in intermediates across four stages of processing does well in explaining the observed international correlations in aggregate quantities, and it performs much better than a single-stage model with no trade in intermediates. The model in itself does not provide a full account of the cyclical behavior of the real exchange rate, but, compared to the single-stage model, it moves in the right direction.

JEL classification: E32; F31; F41

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1. Introduction

The importance attached to international trade in intermediate inputs in the real trade literature is quite remarkable.[1] Perhaps equally remarkable is the lack of attention to this feature in international business cycle studies. In this paper, we examine the role of trade in intermediate goods in accounting for some stylized facts about international business cycles.

Our model builds on the new open-economy macro (NOEM) literature pioneered by Obstfeld and Rogoff (1995) and others. We extend the standard NOEM model by incorporating trade in intermediate inputs at multiple stages of processing—an important feature that characterizes modern world trade.[2] Following the NOEM literature, we focus on business cycles driven by monetary shocks. To capture some of the observed incomplete exchange-rate pass-through, we assume that commodity prices are set in the buyers' local currency and pricing decisions are staggered in the spirit of Taylor (1980).[3]

Understanding the international transmission of monetary shocks seems to be particularly important in light of some recent empirical studies. These studies suggest a close connection between international monetary regimes and the behavior of real exchange rates and other variables (e.g., Basu and Taylor, 1999; Kiley, 1999). While in general the NOEM literature emphasizes the role of monetary shocks and nominal rigidities in shaping international business cycles (see Devereux, 1997; Lane, 2001 for two recent surveys), most studies focus on the welfare consequences of international monetary policy transmission or the behavior of exchange rates.[4] Our focus here is mainly positive: we examine our model's ability to account for two sets of empirical features of international business cycles. We find that incorporating international trade in intermediate inputs and staggered price setting makes our model an improvement over standard models—sometimes to a great degree, and other times more modestly.

1.1. Stylized facts

The first set of stylized facts concerns cross correlations in aggregate quantities between major industrialized economies. The contributions by Backus et al. (1992, 1995, henceforth BKK) and Baxter (1995) help establish the following consensus view about the correlations in aggregate quantities between the United States and other major OECD countries: (a) correlations in output, consumption, investment, and employment are generally positive and fairly high; and (b) output correlations are in general higher than consumption correlations.

[1]Trade in intermediates plays a central role in theories of effective protection and optimal tariff structures (e.g., Jones, 1975; Dixit and Grossman, 1982; Jones and Spencer, 1992; Markusen, 1990). It is also a key to understanding some issues about trade patterns and trade volume (e.g., Markusen, 1984, 1989; Flam and Helpman, 1987; Yi, 2003), as well as trade-related income distribution (e.g., Jones, 1975; Feenstra and Hanson, 1996). Trade in "middle products" produced at various stages of processing has received particular attention (e.g., Sanyal and Jones, 1982; Helpman, 1985; Feenstra, 1998; Markusen and Venables, 2004).

[2]Empirical evidence suggests that a large fraction of world trade consists of trade in intermediate inputs (e.g., Grubel and Lloyd, 1975) and, increasingly important over time, trade in intermediates produced at various stages of processing (e.g., Dickens, 1998; Hummels et al., 2001).

[3]For evidence of local currency pricing, see, for example, Page (1981) and Goldberg and Knetter (1997).

[4]See Obstfeld (2001) for a survey of the postwar analytical thinking on the welfare analysis in international macroeconomics. See Huang and Liu (2006) for an international welfare analysis in a model that incorporates trade in intermediate inputs, and Betts and Devereux (2000), Bergin and Feenstra (2001), and Chari et al. (2002, henceforth CKM) for some recent studies of the exchange-rate behavior in NOEM models.

The second set of stylized facts concerns the behavior of the real exchange rate under a flexible exchange rate regime, such as the one after the breakdown of the Bretton Woods system. The studies by Mussa (1986), Frankel and Meese (1987), Rogoff (1996), and others help establish the following consensus view on the behavior of exchange rates during the recent floats: (c) fluctuations in the real exchange rate are large and persistent, and (d) correlations between the real exchange rate and aggregate quantities, in particular, relative consumption, are quite small.

Explaining these facts has been challenging in the international business cycle literature. Indeed, the discrepancy between the predictions from standard models and the first set of facts, especially (b), is so robust that it is known as the "quantity anomaly." The standard models do not fare better in explaining the second set of facts. The inability of the standard models to explain the weak link between exchange-rate behaviors and other macroeconomic variables is known as the "exchange-rate disconnect puzzle" (e.g., Baxter and Stockman, 1989; Obstfeld and Rogoff, 2000).

1.2. Features that help fit the facts

Our model contains two features that help fit the stylized facts: staggered price contracts and international trade in intermediate inputs produced at multiple stages of processing. Both features are essential for our model's empirical success. If pricing decisions are synchronized, the performance of a multi-stage model would be similar to a single-stage model. Thus, without the help of staggered prices, trade in intermediate inputs would not serve as an effective monetary propagation mechanism. On the other hand, in a single-stage model with no trade in intermediate inputs, staggered price setting by itself would not generate enough real effects of monetary shocks, so that a single-stage model does not do well in fitting the facts (e.g., CKM, 2002). In either case, the stylized facts would remain puzzling, much as they are in the standard models.

It is the interaction of the two features in our model that generates a powerful international monetary transmission mechanism: multiple border crossings of intermediate inputs, along with staggered prices, progressively dampen the movements in marginal costs and the incentives for firms to change prices, leading to sluggish and gradual adjustments in the price levels and large and persistent responses of real variables in both countries following monetary shocks. Our benchmark model with four stages of production and trade in intermediate inputs and staggered two-quarter price contracts does fairly well in explaining (a) and (b). Although the model is less successful in providing a full account of (c) and (d), it works in the right direction.

In what follows, we describe the model in Section 2, then discuss the calibration and some measurement issues in Section 3. With the help of impulse response functions, we provide in Section 4 some intuition about the model's transmission mechanism. In Section 5, we present our simulation results and discuss the model's quantitative implications for international business cycle correlations and for the cyclical behavior of the real exchange rate. We conclude in Section 6.

2. A two-country model with trade in intermediate goods

The world economy consists of a home country and a foreign country. Each country is populated by a large number of identical, infinitely lived households, each consuming an aggregate consumption good and supplying labor and capital to domestic firms. The production of final consumption or investment goods in each country requires $N \geqslant 1$ stages of processing, from raw materials to intermediate goods, then to more advanced intermediate goods, and so on. At each stage, there is a continuum of domestic firms producing differentiated products indexed in the interval $[0, 1]$, with an elasticity of substitution $\theta > 1$. The production of each type of intermediate good at stage $n \in \{2, \ldots, N\}$ uses all types of intermediate goods produced at stage $n-1$, domestically produced or imported, along with labor and capital supplied by domestic households. The production of goods at the first stage uses domestic primary factors only.

At each date t, the world economy experiences a realization of shocks s_t. The history of events up to t is denoted by $s^t \equiv (s_0, \ldots, s_t)$, with probability $\pi(s^t)$. The initial realization s_0 is given.

The representative household in the home country has preferences represented by the expected utility function

$$\sum_{t=0}^{\infty} \sum_{s^t} \beta^t \pi(s^t) U(C(s^t), M(s^t)/\bar{P}_N(s^t), L(s^t)),$$

where the period utility function is given by

$$U(C, M/\bar{P}_N, L) = \left\{ \left[bC^v + (1-b)\left(\frac{M}{\bar{P}_N}\right)^v \right]^{1/v} (1-L)^{\xi} \right\}^{1-\sigma} \Big/ (1-\sigma). \tag{1}$$

In these expressions, $C(s^t)$ is consumption, $M(s^t)$ is money balances, $L(s^t)$ is labor hours, $\bar{P}_N(s^t)$ is the home price level, $\beta \in (0, 1)$ is a subjective discount factor, $\sigma > 0$ is a risk aversion parameter, v governs the elasticity of substitution between consumption and real money balances, $b \in [0, 1]$ measures the weight of consumption relative to real balances, and $\xi > 0$ determines the Frisch elasticity of labor supply.

The household faces a sequence of budget constraints

$$\begin{aligned} &\bar{P}_N(s^t) Y_N(s^t) + \sum_{s^{t+1}} D(s^{t+1}|s^t) B(s^{t+1}) + M(s^t) \\ &\quad \leqslant W(s^t)L(s^t) + R(s^t)K(s^{t-1}) + \Pi(s^t) + B(s^t) + M(s^{t-1}) + T(s^t) \end{aligned} \tag{2}$$

for all t and all s^t, where $B(s^{t+1})$ is a one-period nominal bond that costs $D(s^{t+1}|s^t)$ units of the home currency at s^t and pays off one unit of the home currency at $t+1$ if s^{t+1} is realized, $W(s^t)$ is the nominal wage rate, $R(s^t)$ is the capital rental rate, $K(s^{t-1})$ is the beginning-of-period capital stock, $\Pi(s^t)$ is the household's claim to firms' profits, and $T(s^t)$ is a nominal lump-sum transfer from the home government. The term $Y_N(s^t)$ in the budget constraint is the purchase of final goods to be used for consumption or investment. In particular, it is given by

$$Y_N(s^t) = C(s^t) + K(s^t) - (1-\delta)K(s^{t-1}) + \psi \frac{(K(s^t) - K(s^{t-1}))^2}{K(s^{t-1})}, \tag{3}$$

where $K(s^t)$ denotes the end-of-period capital stock, $\delta \in (0, 1)$ is the depreciation rate of capital, and $\psi > 0$ is a capital adjustment cost parameter.

The final good is an aggregate of two composites of finished goods (i.e., those produced at stage N). The aggregation technology is given by

$$Y_N(s^t) = \bar{Y}_{NH}(s^t)^{\gamma} \bar{Y}_{NF}(s^t)^{1-\gamma}, \tag{4}$$

where $\bar{Y}_{NH} = (\int_0^1 Y_{NH}(i)^{(\theta-1)/\theta} \mathrm{d}i)^{\theta/(\theta-1)}$ is a composite of goods produced by home firms and $\bar{Y}_{NF} = (\int_0^1 Y_{NF}(i)^{(\theta-1)/\theta} \mathrm{d}i)^{\theta/(\theta-1)}$ is a composite of goods imported from the foreign country, both produced at stage N. The parameter θ determines the steady-state markup of price over marginal cost, and the parameter γ measures the share of expenditures on domestically produced goods in total expenditures on all goods.

The household maximizes utility subject to (2)–(4) and a borrowing constraint $B(s^t) \geqslant -\bar{B}$, for some large positive number $\bar{B}$, for each s^t and each $t \geqslant 0$, with initial conditions $K(s^{-1})$, $M(s^{-1})$, and $B(s^0)$ given. The resulting demand functions for a type i finished good produced in the home country and imported from the foreign country are respectively given by

$$Y^d_{NH}(i, s^t) = \frac{\gamma \bar{P}_N(s^t)}{\bar{P}_{NH}(s^t)} \left[\frac{P_{NH}(i, s^t)}{\bar{P}_{NH}(s^t)}\right]^{-\theta} Y_N(s^t), \tag{5}$$

$$Y^d_{NF}(i, s^t) = \frac{(1-\gamma) \bar{P}_N(s^t)}{\bar{P}_{NF}(s^t)} \left[\frac{P_{NF}(i, s^t)}{\bar{P}_{NF}(s^t)}\right]^{-\theta} Y_N(s^t), \tag{6}$$

where $\bar{P}_{NH}(s^t) = (\int_0^1 P_{NH}(i, s^t)^{1-\theta} \mathrm{d}i)^{1/(1-\theta)}$ is the price index of finished goods produced and sold in the home country, and $\bar{P}_{NF}(s^t) = (\int_0^1 P_{NF}(i, s^t)^{1-\theta} \mathrm{d}i)^{1/(1-\theta)}$ is the price index of finished goods imported from the foreign country. The price level in the home country is an average of the two price indices of finished goods, that is,

$$\bar{P}_N(s^t) = \bar{\gamma} \bar{P}_{NH}(s^t)^{\gamma} \bar{P}_{NF}(s^t)^{1-\gamma}, \tag{7}$$

where $\bar{\gamma} = \gamma^{-\gamma}(1-\gamma)^{\gamma-1}$.

A defining feature of the model is that the production of finished goods in each country involves multiple stages of processing and multiple border crossings of intermediate goods. The production of a stage-1 good of type $i \in [0, 1]$ in the home country requires home primary factors as inputs, with a Cobb–Douglas production function given by

$$Y_{1H}(i, s^t) + Y^*_{1H}(i, s^t) = K_1(i, s^t)^{\alpha} L_1(i, s^t)^{1-\alpha}, \tag{8}$$

where K_1 and L_1 are home capital and labor inputs, and $\alpha \in (0, 1)$ is the cost share of capital. The output is either sold in the home country ($Y_{1H}(i)$) or exported ($Y^*_{1H}(i)$) to the foreign country.

To produce a stage-n good of type $i \in [0, 1]$, for $n \in \{2, \ldots, N\}$, requires not only home primary factors but a composite of stage-$(n-1)$ goods, both domestically produced and imported. The production function is a constant-return-to-scale technology given by

$$Y_{nH}(i, s^t) + Y^*_{nH}(i, s^t) = \bar{Y}_{n-1}(i, s^t)^{\phi} [K_n(i, s^t)^{\alpha} L_n(i, s^t)^{1-\alpha}]^{1-\phi}, \tag{9}$$

where K_n and L_n are home capital and labor inputs, and $\bar{Y}_{n-1} = \bar{Y}_{n-1,H}(s^t)^{\gamma} \bar{Y}_{n-1,F}(s^t)^{1-\gamma}$ is an intermediate input. The intermediate input is an aggregate of two composites of intermediate goods. The first composite, $\bar{Y}_{n-1,H} = (\int_0^1 Y_{n-1,H}(i)^{(\theta-1)/\theta} \mathrm{d}i)^{\theta/(\theta-1)}$, is purchased from domestic firms; and the second, $\bar{Y}_{n-1,F} = (\int_0^1 Y_{n-1,F}(i)^{(\theta-1)/\theta} \mathrm{d}i)^{\theta/(\theta-1)}$, is imported from foreign producers.

Firms at each processing stage are price-takers in their input markets and monopolistic competitors in their output markets, where they set prices in the buyers' local currency. Pricing decisions are staggered between firms within each processing stage. More specifically, at each date, and at each stage of processing and trade, half of the home producers cannot adjust their prices. For those that can, they each choose a pair of new prices: $P_{nH}(i, s^t)$ in the home currency unit for its product to be sold in the home market and $P^*_{nH}(i, s^t)$ in the foreign currency unit for its product to be exported to the foreign market. Once a new price is set, it will remain in effect for two periods.

At each date t, upon the realization of s^t, a home firm $i \in [0, 1]$ at stage $n \in \{1, \ldots, N\}$ that can set new prices chooses $P_{nH}(i, s^t)$ and $P^*_{nH}(i, s^t)$ to maximize

$$\sum_{\tau=t}^{t+1} \sum_{s^\tau} D(s^\tau|s^t)\{[P_{nH}(i, s^t) - V_n(i, s^\tau)] Y^d_{nH}(i, s^\tau) + [e(s^\tau)P^*_{nH}(i, s^t) - V_n(i, s^\tau)] Y^{*d}_{nH}(i, s^\tau)\}, \tag{10}$$

taking as given the unit cost function, $V_n(i, s^\tau)$, the output demand schedules, $Y^d_{nH}(i, s^\tau)$ and $Y^{*d}_{nH}(i, s^\tau)$, and the nominal exchange rate, $e(s^t)$, measured in units of the domestic currency per unit of the foreign currency.

The unit cost function V_1 for a firm at stage 1 can be derived from minimizing the cost $WL_1 + RK_1$ subject to the production function (8). It is given by

$$V_1(s^t) \equiv V_1(i, s^t) = \bar{\alpha} R(s^t)^\alpha W(s^t)^{1-\alpha}, \tag{11}$$

where $\bar{\alpha} = \alpha^{-\alpha}(1-\alpha)^{-(1-\alpha)}$. The unit cost function V_n, for $n \geqslant 2$, can similarly be derived from minimizing $\int_0^1 P_{n-1,H}(j) Y_{n-1,H}(i,j)\,dj + \int_0^1 P_{n-1,F}(j) Y_{n-1,F}(i,j)\,dj + WL_n + RK_n$ subject to (9). The resulting unit cost function is given by

$$V_n(s^t) \equiv V_n(i, s^t) = \bar{\phi} \bar{P}_{n-1}(s^t)^\phi V_1(s^t)^{1-\phi}, \tag{12}$$

where $\bar{\phi} = \phi^{-\phi}(1-\phi)^{-(1-\phi)}$, and $\bar{P}_{n-1}(s^t)$ is the price index of all goods produced by home and foreign firms at stage $n-1$ and used by i at stage n as inputs. In particular, the price index of all stage-n goods is given by

$$\bar{P}_n(s^t) = \bar{\gamma} \bar{P}_{nH}(s^t)^\gamma \bar{P}_{nF}(s^t)^{1-\gamma}, \tag{13}$$

where $\bar{P}_{nH} = (\int_0^1 P_{nH}(i)^{1-\theta} di)^{1/(1-\theta)}$ and $\bar{P}_{nF} = (\int_0^1 P_{nF}(i)^{1-\theta} di)^{1/(1-\theta)}$ are the price indices of stage-n home goods and of stage-n imported goods, respectively.

The output demand schedules resulting from the cost-minimization problems are

$$Y^d_{nH}(i, s^t) = \left[\frac{\phi}{1-\phi}\right]^{1-\phi} \left[\frac{P_{nH}(i, s^t)}{\bar{P}_{nH}(s^t)}\right]^{-\theta} \frac{\gamma \bar{P}_n(s^t)}{\bar{P}_{nH}(s^t)} \left[\frac{\bar{P}_n(s^t)}{V_1(s^t)}\right]^{-(1-\phi)} \tilde{Y}_{n+1}(s^t), \tag{14}$$

$$Y^d_{nF}(i, s^t) = \left[\frac{\phi}{1-\phi}\right]^{1-\phi} \left[\frac{P_{nF}(i, s^t)}{\bar{P}_{nF}(s^t)}\right]^{-\theta} \frac{(1-\gamma) \bar{P}_n(s^t)}{\bar{P}_{nF}(s^t)} \left[\frac{\bar{P}_n(s^t)}{V_1(s^t)}\right]^{-(1-\phi)} \tilde{Y}_{n+1}(s^t), \tag{15}$$

for $n \in \{1, \ldots, N-1\}$, where $\tilde{Y}_{n+1} \equiv \int_0^1 [Y_{n+1,H}(j) + Y^*_{n+1,H}(j)]\,dj$ is a linear aggregate of all goods produced at stage $n+1$ in the home country. According to these equations, the demand for a type i good produced at stage n should be higher if its price relative to the price index of all such goods is lower, if the price index of these goods relative to the overall price index of stage-n goods is lower, or if the cost of materials relative to the cost of primary factors is lower. We can similarly derive the demand schedules $Y^{*d}_{n\mathrm{H}}(i,s^t)$ and $Y^{*d}_{n\mathrm{F}}(i,s^t)$ for the foreign country.

With the unit cost functions and output demand schedules derived from the appropriate cost-minimization problems, maximizing (10) gives rise to the optimal price-setting rules

$$P_{n\mathrm{H}}(i,s^t) = \frac{\theta}{\theta-1}\frac{\sum_{\tau=t}^{t+1}\sum_{s^\tau} D(s^\tau|s^t)V_n(s^\tau)Y^d_{n\mathrm{H}}(i,s^\tau)}{\sum_{\tau=t}^{t+1}\sum_{s^\tau} D(s^\tau|s^t)Y^d_{n\mathrm{H}}(i,s^\tau)}, \tag{16}$$

$$P^*_{n\mathrm{H}}(i,s^t) = \frac{\theta}{\theta-1}\frac{\sum_{\tau=t}^{t+1}\sum_{s^\tau} D(s^\tau|s^t)V_n(s^\tau)Y^{*d}_{n\mathrm{H}}(i,s^\tau)}{\sum_{\tau=t}^{t+1}\sum_{s^\tau} D(s^\tau|s^t)e(s^\tau)Y^{*d}_{n\mathrm{H}}(i,s^\tau)}, \tag{17}$$

where $n \in \{1,\ldots,N\}$. The price-setting rule in (16) says that the optimal price set for the home market in the home currency unit is a constant markup over a weighted average of the firm's marginal costs within the duration of its price contract, where the weights are the normalized quantity of demand for its output in the corresponding periods. The price-setting rule in (17) can be interpreted similarly, where the currency units are appropriately converted using the nominal exchange rate.

The problems facing the households and firms in the foreign country are analogous.

We now specify monetary policy processes. There is a monetary authority in each country. Newly created money by the monetary authority in one country is injected into the domestic economy via a lump-sum transfer to domestic households so that $T(s^t) = M(s^t) - M(s^{t-1})$ and $T^*(s^t) = M^*(s^t) - M^*(s^{t-1})$. The money stocks in the two countries grow according to $M(s^t) = \mu(s^t)M(s^{t-1})$ and $M^*(s^t) = \mu^*(s^t)M^*(s^{t-1})$, where the money growth rates $\mu(s^t)$ and $\mu^*(s^t)$ follow stationary stochastic processes given by

$$\ln\mu(s^t) = \rho_\mu \ln\mu(s^{t-1}) + \varepsilon_t, \quad \ln\mu^*(s^t) = \rho_\mu \ln\mu^*(s^{t-1}) + \varepsilon^*_t, \tag{18}$$

where $\rho_\mu \in (0,1)$, and ε_t and ε^*_t are uncorrelated Gaussian processes with zero mean and finite variance σ^2_μ.

Finally, the market clearing conditions for the primary factors in the home country requires that $\sum_{n=1}^N \int_0^1 K^d_n(i,s^t)\,\mathrm{d}i = K(s^{t-1})$ and $\sum_{n=1}^N \int_0^1 L^d_n(i,s^t)\,\mathrm{d}i = L(s^t)$. The market clearing conditions for the primary factors in the foreign country are similar. The world bond market clearing condition requires that $B(s^t) + B^*(s^t) = 0$.

An equilibrium for this economy is a collection of allocations $\{C(s^t), K(s^t), L(s^t), M(s^t), B(s^{t+1})\}$ for households in the home country; allocations $\{C^*(s^t), K^*(s^t), L^*(s^t), M^*(s^t), B^*(s^{t+1})\}$ for households in the foreign country; allocations $\{Y_{n\mathrm{H}}(i,s^t), Y^*_{n\mathrm{H}}(i,s^t), K_n(i,s^t), L_n(i,s^t)\}$ and prices $\{P_{n\mathrm{H}}(i,s^t), P^*_{n\mathrm{H}}(i,s^t)\}$ for firms in the home country, where $i \in [0,1]$ and $n \in \{1,\ldots,N\}$; allocations $\{Y_{n\mathrm{F}}(i,s^t), Y^*_{n\mathrm{F}}(i,s^t), K^*_n(i,s^t), L^*_n(i,s^t)\}$ and prices $\{P_{n\mathrm{F}}(i,s^t), P^*_{n\mathrm{F}}(i,s^t)\}$ for firms in the foreign country, where $i \in [0,1]$ and $n \in \{1,\ldots,N\}$; price indices $\{\bar{P}_n(s^t), \bar{P}^*_n(s^t)\}$,for $n \in \{1,\ldots,N\}$; wages $\{W(s^t), W^*(s^t)\}$; capital rental rates $\{R(s^t), R^*(s^t)\}$; and bond prices $D(s^{t+1}|s^t)$ that satisfy the following four conditions: (i) taking wages, capital rental rates, and prices as given, the households' allocations solve their utility maximization problems; (ii) taking wages, capital rental rates, and all prices but its own as given, each firm's allocations and price solve its profit-maximization problem; (iii) domestic capital, labor, and money markets and world asset markets clear; (iv) monetary policies are as specified.

Given the Markov money growth process in (18), a stationary equilibrium in this open economy consists of stationary decision rules that are functions of the state of the economy. The state of the economy in period t must record the prices set in period $t-1$ and the beginning-of-period capital stocks, as well as the exogenous money growth rates. To induce stationarity, we divide all nominal variables by the appropriate money stocks. Thus, the state at s^t is given by

$$\left[K(s^{t-1}), K^*(s^{t-1}), \mu(s^t), \mu^*(s^t), \left\{\frac{P_{n\mathrm{H}}(s^{t-1})}{M(s^t)}, \frac{P^*_{n\mathrm{H}}(s^{t-1})}{M(s^t)}, \frac{P^*_{n\mathrm{F}}(s^{t-1})}{M^*(s^t)}, \frac{P_{n\mathrm{F}}(s^{t-1})}{M(s^t)}\right\}_{n=1}^{N}\right].$$

We solve the stationary equilibrium dynamics by first log-linearizing the equilibrium conditions around a balanced-trade steady state, then solve the resulting linear rational-expectations equilibrium system using standard solution methods.

In what follows, we focus on a symmetric equilibrium in which all firms in the same price-setting cohort at the same stage of production and trade in the same country make identical pricing decisions. In such an equilibrium, firms are identified by the country in which they operate, the stage at which they produce and trade, and the time at which they can change prices.

3. Calibration and some measurement issues

We now describe our procedure of calibrating the key parameters for our quantitative exercises. We also discuss some issues concerning the appropriate measures of gross domestic products (GDP) in this open economy with trade in intermediate inputs.

3.1. Calibration

The parameters to be calibrated include the subjective discount factor β, the preference parameters b, v, ξ, and σ, the technology parameters α, γ, and θ, the capital depreciation rate δ, the adjustment cost parameter ψ, the number of processing stages N, the share of material input at each stage ϕ, and the monetary policy parameters ρ_μ and σ_μ. The calibrated parameter values are summarized in Table 1.

We assume that each model period corresponds to a quarter of a year in the data. Under this assumption, a typical price contract in our model lasts for two quarters. This relatively short contract duration seems to be supported by recent evidence (e.g., Bils and Klenow, 2004).[5] We set $\beta = 0.99$, so that the steady-state annualized real interest rate is equal to 4%, as suggested by the standard business cycle literature. The parameter ξ is chosen so that, in the steady state, a household devotes $\frac{1}{4}$ of its time endowment to market activity. The parameter σ corresponds to the inverse elasticity of intertemporal substitution (EIS), and we set $\sigma = 3$ so that the EIS is about $\frac{1}{3}$, which lies in the range of estimates reported by Vissing-Jorgensen (2002) for stock holders. To assign values for b and v, we use the equilibrium money demand equation

$$\ln\left(\frac{M(s^t)}{\bar{P}_N(s^t)}\right) = -\frac{1}{1-v}\ln\left(\frac{b}{1-b}\right) + \ln(C(s^t)) - \frac{1}{1-v}\log\left(\frac{r(s^t)-1}{r(s^t)}\right),$$

[5] In this sense, we put a relatively small weight on exogenous price rigidity in our model, and rely more heavily on trade in intermediate goods across various stages of processing to confront the stylized facts of international business cycles.

Table 1
Calibrated parameters

Preferences	$\beta = 0.99$, $b = 0.94$, $v = -1.56$, $\xi = 1.6$, $\sigma = 3$
Technologies	$\alpha = 1/3$, $\theta = 13$, $\gamma = 0.9$, $\phi = 0.9$
Capital accumulation	$\delta = 0.02$, ψ adjusted
Money growth process	$\rho_\mu = 0.68$, $\sigma_\mu = 0.0092$

where $r(s^t) = (\sum_{s^{t+1}} D(s^{t+1}|s^t))^{-1}$ is the gross nominal interest rate. The regression of this equation using U.S. data, as performed in CKM (2000), suggests that $v = -1.56$ and $b = 0.94$.

We set $\alpha = \frac{1}{3}$ and $\delta = 0.02$, so that the model predicts an annualized capital–output ratio of 2.6 and an investment–output ratio of 0.2. We vary the capital adjustment cost parameter ψ when computing the equilibrium dynamics for different values of N, so that the standard deviation of consumption relative to GDP is 0.83, as in the data. In a balanced-trade steady state, $\gamma = Y_H/Y$ corresponds to the share of domestically produced goods in real GDP. We set $\gamma = 0.9$, so that the import share in GDP is 10%. The parameter θ determines the steady-state markup at each stage of processing. Based on the work of Basu (1996) and Basu and Fernald (2002), we set $\theta = 13$, corresponding to a markup of $\mu = 1.08$.

A simple autoregression using quarterly M1 data in the postwar U.S. economy results in an AR(1) coefficient of $\rho_\mu = 0.68$ in the money growth process. From the same regression, we obtain the standard deviation of ε_t equal to $\sigma_\mu = 0.0092$. We impose no correlations between the two countries' money growth shocks, for two reasons. First, the data in the U.S. and Europe do not support systematic correlations in the money growth rates. Second, we would like to isolate the role of trade in intermediates in accounting for the observed international business cycle facts.

The remaining parameters to be calibrated are ϕ and N, which jointly determine the contribution of intermediate goods to production. According to the BEA's 1997 benchmark input–output tables, the share of intermediate goods in total manufacturing output is about 0.7. Let η denote the steady-state share of total intermediate inputs (across all stages of processing) in gross sales. From the steady-state relations, we obtain

$$\frac{1}{1-\eta} = \sum_{n=1}^{N} \frac{\bar{P}_n \bar{Y}_n}{\bar{P}_N Y_N} = \frac{1-(\phi/\mu)^N}{1-\phi/\mu}. \tag{19}$$

Clearly, in addition to the condition that $\eta = 0.7$, we need a second condition to jointly identify ϕ and N. For this purpose, we rely on the empirical evidence produced by Barsky et al. (2003), which suggests that a lower bound for the cumulative markup across different stages of production and distribution in the U.S. is about 1.4. In the model, the cumulative markup across all processing stages is given by μ^N. Given our calibrated value of the markup $\mu = 1.08$ at each stage and that $\mu^N = 1.4$, the implied value of N is about 4. We thus view $N = 4$ as a reasonable benchmark value. The relation in (19) then implies that $\phi = 0.9$.

3.2. Measuring GDP

The value of final output $\bar{P}_{Nt} Y_{Nt}$ is a measure of nominal aggregate demand (for final goods) in the home country. It does not correspond to nominal GDP. Instead, nominal

GDP is the value of finished goods produced by domestic firms, sold domestically or exported. Let $X_N(s^t)$ denote real GDP. We have

$$\bar{P}_N(s^t)X_N(s^t) = \bar{P}_{N\mathrm{H}}(s^t)\bar{Y}_{N\mathrm{H}}(s^t) + e(s^t)\bar{P}^*_{N\mathrm{H}}(s^t)\bar{Y}^*_{N\mathrm{H}}(s^t), \quad (20)$$

where $\bar{Y}_{N\mathrm{H}}$ and $\bar{Y}^*_{N\mathrm{H}}$ are aggregate demand for home finished goods by households in the home country and in the foreign country, respectively. Nominal GDP so measured is not equal but related to nominal aggregate demand for finished goods. To see the relation, we first integrate and then sum up Eqs. (5) and (6) to obtain $\bar{P}_N Y_N = \bar{P}_{N\mathrm{H}}\bar{Y}_{N\mathrm{H}} + \bar{P}_{N\mathrm{F}}\bar{Y}_{N\mathrm{F}}$. This reveals that the difference between nominal GDP and nominal aggregate demand is simply the net exports of finished goods

$$\bar{P}_N(s^t)NX_N(s^t) = e\bar{P}^*_{N\mathrm{H}}\bar{Y}^*_{N\mathrm{H}} - \bar{P}_{N\mathrm{F}}\bar{Y}_{N\mathrm{F}} = \bar{P}_N(s^t)X_N(s^t) - \bar{P}_N(s^t)Y_N(s^t), \quad (21)$$

where $NX_N(s^t)$ denotes the net exports. Note that, since aggregate demand is the sum of consumption and investment, the relation in (21) simply reflects the national income and product identity:

$$X_N(s^t) = Y_N(s^t) + NX_N(s^t) = C(s^t) + I(s^t) + NX_N(s^t), \quad (22)$$

where the second equality follows from (3), and $I(s^t)$ denotes the gross investment (inclusive of capital adjustment costs).

Another way to measure GDP is to use aggregate value added across all stages of processing. The value added is the sum of the country's wage income, capital rental income, and profit income. Inspecting the budget equation for the home representative household reveals that the country's nominal income from these three sources can be deflated consistently by its consumer price index $\bar{P}_N(s^t)$. Thus, real GDP in the home country can also be measured by

$$X_N(s^t) = [W(s^t)L(s^t) + R(s^t)K(s^{t-1}) + \Pi(s^t)]/\bar{P}_N(s^t). \quad (23)$$

The two measures of GDP in (20) and (23) are equivalent. We choose the first measure for ease of computation.

4. International monetary transmission: some intuition

We now provide some intuition about how the model works. We do this with the aid of impulse response functions computed using the calibrated parameter values. To compute the impulse responses, we assume that there is a one-time unilateral monetary expansion in the home country. Specifically, we set $\varepsilon_0 = (1-\rho_\mu)/(1-\rho_\mu^4)$, $\varepsilon_t = 0$ for all $t \geqslant 1$, and $\varepsilon_t^* = 0$ for all $t \geqslant 0$, so that the home money stock rises by 1% one year after the shock, and the foreign money stock remains unchanged for all periods.

To understand the model's transmission mechanism, it is essential to understand the patterns of price adjustment following the shock. For this purpose, we plot in Fig. 1 the impulse responses of the price indices to the shock. The figure reveals some interesting patterns of price adjustment. When the total number of processing stages is fixed at $N = 4$, the prices at a more advanced stage adjust less in both countries, and complete adjustments take more periods of time (see the upper panel of the figure). As we vary N from 1 to 4, the initial rise in the price levels (i.e., the price indices of finished goods) becomes smaller, and subsequent adjustments of the price levels become more gradual and longer lasting (see the lower panel).

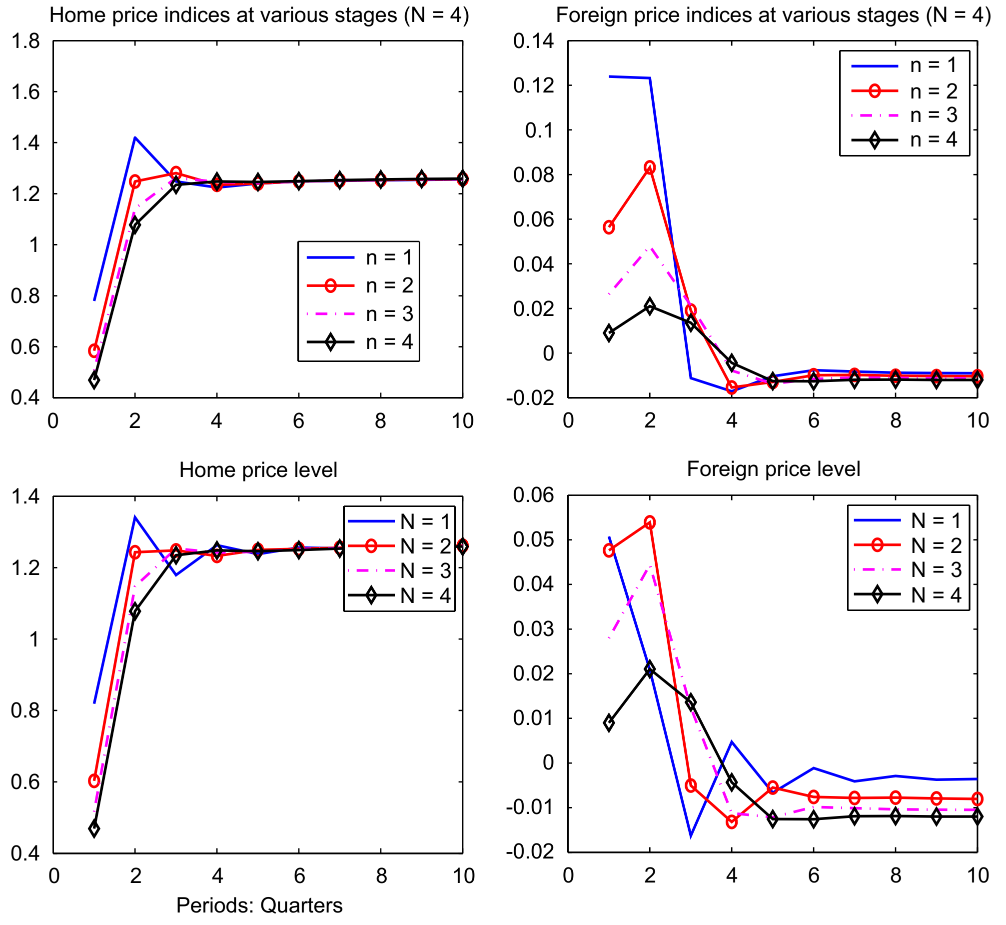

Fig. 1. Impulse responses of sectoral price indices (for $N = 4$ fixed) and of the price levels (as N varies) to home monetary shock.

The reason why the upward adjustment in the home price level can be attenuated and stretched out across time in our benchmark model is similar to that in a closed-economy version of the model (e.g., Huang and Liu, 2001). Briefly, following a monetary expansion, the costs of primary factors (labor and capital) rise immediately, so does the marginal cost facing firms at the first stage of production (i.e., the raw material producers). These firms will raise their prices fully whenever it is their turn to set prices. Firms producing intermediate goods at the second stage do not face a full rise in their marginal cost immediately, because their marginal cost is determined in part by the price index of raw materials that records both prices newly adjusted and prices fixed by previous contracts. These firms thus do not have incentives to raise their prices fully even when they get the chance to set prices. Since some firms at the second stage cannot adjust prices, and those that can adjust choose partial adjustments, firms at the third stage face an even smaller rise in their marginal cost and thus have even less incentives to raise their prices, and so forth.

What is new in this open-economy framework is that the upward adjustment in the foreign price level can also be attenuated through the production and trading chain. Foreign prices tend to go up, since the shock raises demand for foreign goods, forcing foreign firms to produce more. This raises the demand for primary factors and drives up foreign factor prices and marginal costs. For similar reasons described above for the home country, the adjustments in foreign marginal costs and prices can be attenuated and stretched out across time as the shock works its way through different stages of processing.

More importantly, foreign marginal cost and price adjustments can be further contained through trade in intermediate goods. This is so because marginal costs facing foreign firms at an advanced stage depend in part on home exporting prices at an earlier stage which, under local currency pricing, are determined by home marginal costs in units of the foreign currency. At a more advanced stage, home marginal costs not only rise less in units of the home currency as explained above, but, due to the home currency's depreciation, they would rise even less and may actually fall in units of the foreign currency. So do home exporting prices. In consequence, the upward adjustments in foreign marginal costs and prices would be further contained at more advanced stages. With a greater number of stages, the rise in the foreign price level can also be attenuated.

These patterns of price adjustments are a manifestation of how the model's transmission mechanism functions. To put it into perspective, recall that most new open-economy macro models feature two channels through which a monetary shock gets transmitted across countries: an aggregate-demand externality and a terms-of-trade externality. The aggregate demand externality means that, with sticky prices, a unilateral monetary expansion tends to raise real aggregate demand in both countries (e.g., Obstfeld and Rogoff, 1995). The terms-of-trade externality refers to the phenomenon that a unilateral monetary expansion and the associated currency depreciation tend to change the terms of trade in favor of one country against the other. The aggregate demand externality helps propagate the monetary shock to generate positive international quantity comovements, whereas the terms of trade externality tends to offset the aggregate demand effect, as it hurts the foreign country's purchasing power.[6]

The patterns of price adjustment illustrated above suggest that the production and trading chain tends to magnify the aggregate demand externality and to attenuate the terms-of-trade externality. This tendency has implications for the responses of real variables and, in particular, for international comovements of aggregate quantities.

In the absence of trade in intermediate goods, that is, when all production and trade occur at a single stage of processing, price adjustments would be large and rapid. In such an economy, the negative terms-of-trade effect tends to dominate the positive aggregate demand effect, so that the rise in foreign aggregate demand would be small, and international comovements would be weak. Does this happen when we calibrate the model and impose $N = 1$? The impulse response functions plotted in Fig. 2 suggest that the answer is affirmative. The figure shows that, in the case with $N = 1$, international quantity comovements appears weak or even negative: increases in foreign output and consumption are small, and foreign investment actually falls. Investment falls because much of the increase in production goes to exports, while consumption does not fall because of

[6]Under local currency pricing, the home currency's depreciation tends to worsen the foreign country's terms of trade since foreign exporting prices are sticky in the (weaker) home currency.

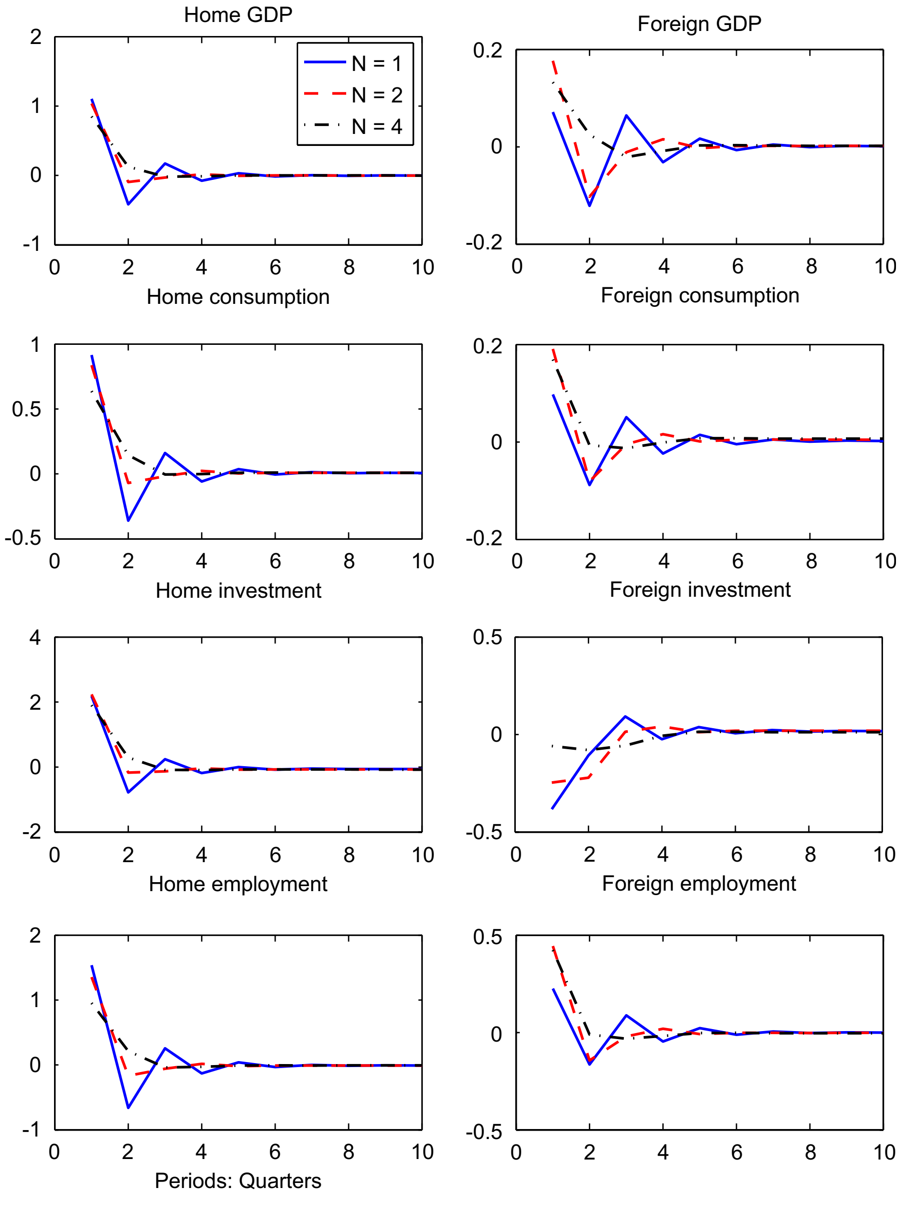

Fig. 2. Impulse responses of quantity variables to home monetary shock.

international risk sharing. Foreign employment rises because foreign firms need to increase production to meet the higher exporting and domestic demand.

When we allow trade in intermediate goods produced at multiple stages of processing, the adjustments in prices would be attenuated in both countries. As such, the aggregate demand effect would be magnified, while the terms-of-trade effect would be muted. This helps raise foreign aggregate quantities and put them more in line with their home

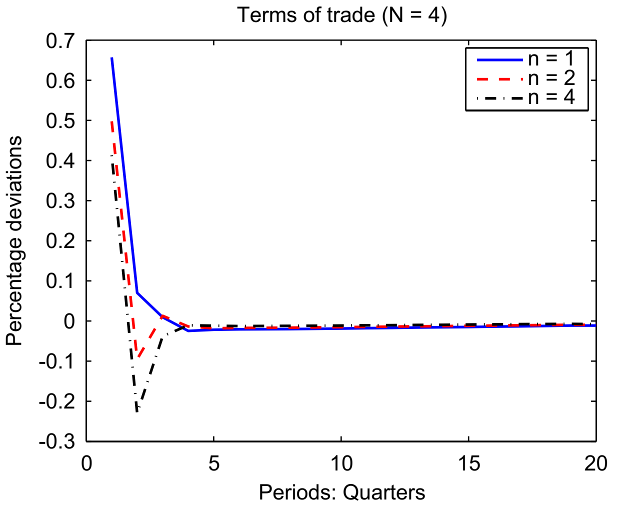

Fig. 3. Impulse responses of home terms of trade to home monetary shocks in the benchmark model with $N = 4$.

counterparts. The impulse response functions in Fig. 2 confirm this possibility: compared to the case with $N = 1$, foreign aggregates become more in line with home aggregates in our benchmark economy with $N = 4$, suggesting stronger international quantity comovements. To see how the terms-of-trade effect gets muted, we plot the impulse responses of the terms of trade in Fig. 3. The figure reveals that the terms of trade at a more advanced stage (for N fixed at 4) not only rise less in the impact period of the shock but can even be reversed in subsequent periods. This result obtains essentially because trade in intermediate goods across multiple stages of processing effectively reduces the segmentation of the international goods market, so that the two countries behave more like a single economy.

The patterns of price adjustments described above also have implications for the behavior of the real exchange rate. To see this, we plot the impulse response of the real exchange rate in Fig. 4. In an economy with $N = 1$, the response of the real exchange rate shows no persistence: it actually oscillates around the steady state. As N becomes larger, not only does the initial response of the real exchange rate become larger, but it takes more periods for the exchange rate to return to the steady state. This result arises because the real exchange rate is determined by the ratio of the marginal utilities of consumption across countries, and the marginal utilities become more volatile and more persistent as price adjustments become smaller and more gradual. In this sense, incorporating trade in intermediate goods into a sticky-price model helps, at least in principle, to improve the model's ability to generate volatile and persistent real exchange rate movements.

The impulse response functions presented here suggest that incorporating staggered prices and trade in intermediate goods into a standard NOEM model can potentially help us to understand the international transmission of monetary shocks. In particular, it may help explain some of the stylized facts about international business cycles and the cyclical behavior of the real exchange rate. This raises a natural question: how close can the model's equilibrium predictions come to the observed business cycle statistics? As we show below through numerical simulations, our benchmark model does quite well in explaining

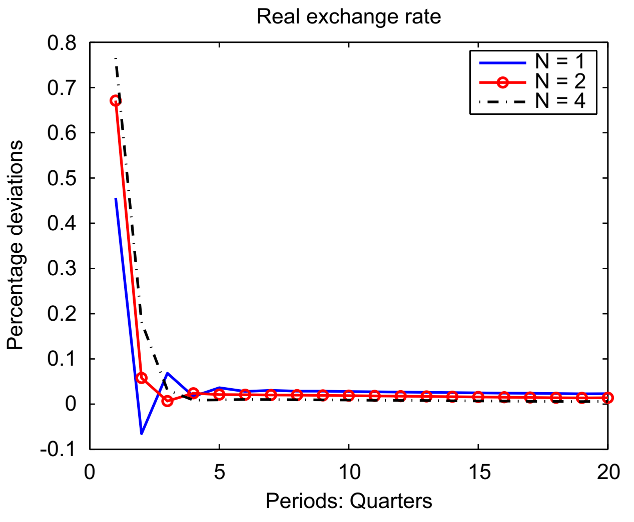

Fig. 4. Impulse responses of real exchange rate to home monetary shocks.

international business cycle correlations, but it does not fully account for the volatility and persistence in the real exchange rate, nor does it explain the low (or even negative) correlation between the real exchange rate and relative consumption. These deficiencies, as we explain below, do not have much to do with the model's production and trading structure, but might rather be related to the specifications of preferences and asset market structures.

5. Quantitative implications

We assess the model's quantitative performance by confronting its equilibrium predictions against two sets of stylized facts about international business cycles. The first set of facts concerns the cross correlations of aggregate quantities between major industrialized countries, including the "quantity anomaly" suggested by BKK (1992, 1995) and Baxter (1995). The second set of facts concerns the cyclical behavior of the real exchange rate.

5.1. International business cycle correlations

In the data, correlations in aggregate output, consumption, investment, and employment between major industrialized countries are generally positive and fairly high, and output correlations are in general higher than consumption correlations. Most models of international business cycles have difficulties explaining these correlation patterns, especially the order between output correlations and consumption correlations. This discrepancy between theories and the observations is known as the "quantity anomaly."

Table 2 displays some business cycle statistics from the data and from the benchmark model with four stages of processing. For purposes of comparison, we also display the model's predictions as N takes other values (from 1 to 3).

Table 2
Business cycle statistics for the model[a]

Statistics	Data[b]	Benchmark	Number of processing stages		
		($N = 4$)	$N = 1$	$N = 2$	$N = 3$
Cross-correlations between foreign and domestic					
GDP	0.60	0.46	0.12	0.28	0.33
Consumption	0.38	0.42	0.06	0.24	0.30
Investment	0.33	0.49	−0.01	0.21	0.33
Employment	0.39	0.26	0.06	0.19	0.20
Correlations of real exchange rates and					
GDP	0.08	0.51	0.65	0.58	0.55
Net export	0.14	−0.07	−0.98	−0.90	−0.49
Relative consumption	−0.35	0.96	1.00	0.99	0.98
Standard deviation of real exchange rate relative to GDP					
	4.36	1.07	0.88	0.98	1.07
Standard deviations relative to GDP					
Consumption	0.83	0.83	0.83	0.83	0.83
Investment	2.78	1.88	1.87	1.85	1.86
Employment	0.67	1.61	1.55	1.57	1.59
Net exports	0.11	0.02	0.06	0.03	0.02

[a]The model's statistics are computed based on HP-filtered artificial time series and are averages over 200 simulations of 100 periods each.

[b]The statistics are taken from Chari et al. (2002), which are based on HP-filtered data for the U.S. and those for a European aggregate with France, Italy, the U.K., and Germany. The sample period covers 1973:1–1994:4.

The top panel of the table reports the cross-country correlations in aggregate quantities. The benchmark model does quite well in predicting these correlations. Trade in intermediates seems to make a big difference. As $N = 1$, there is no trade in intermediate inputs and the cross-country correlations are small or even negative; as N rises, the correlations become more sizable and move in the right directions; as N takes the benchmark value of 4, the model comes quite close to the data.

A notable feature is that, under our benchmark calibration, the model's predicted correlation in consumption is lower than that in output (0.42 versus 0.46), as in the data (0.38 versus 0.60). In this aspect, our model does much better than many other models of international business cycles. Our results here suggest that incorporating staggered prices and trade in intermediate inputs should be a promising avenue for resolving the quantity anomaly.

5.2. The cyclical behavior of the real exchange rate

The middle panel of Table 2 displays the cyclical behavior of the real exchange rate. Here, the model is less successful. One discrepancy between the model and the data is that the model generates a modestly procyclical real exchange rate, but this variable is essentially acyclical in the data (0.51 versus 0.08). A second and somewhat minor discrepancy is that, in the data, the real exchange rate is weakly correlated with net exports, but in the model, they are essentially uncorrelated (0.14 versus −0.07). With no trade in intermediate goods (i.e., with $N = 1$), the model does much worse, as it predicts a strongly negative correlation (−0.98). In other words, introducing trade in intermediate inputs helps explain the weak correlation between the real exchange rate and net exports. A third and much bigger discrepancy between the model and the data is that the model's predicted correlation between the real exchange rate and the relative consumption is close to unity, while the data suggest a modestly negative correlation (0.96 versus −0.35). It has been shown in the literature that this discrepancy is quite robust to alternative specifications of model environments and is called the "consumption-real exchange rate anomaly" by CKM (2002). Varying N here does not help resolve this anomaly. Further, although the standard deviation of the real exchange rate in the model is much lower than that in the data (1.07 versus 4.36), it improves over the case with no trade in intermediate inputs (1.07 versus 0.88).

5.3. Other business cycle statistics

A further question is: what are the model's implications for other business cycle properties? This question is important because our model belongs to the class of stochastic dynamic general equilibrium models pioneered by Kydland and Prescott (1982). In this literature, an important criterion for evaluating a model's performance is to look at a fairly comprehensive set of business cycle facts within the model.

The bottom panel of Table 2 shows that, compared to the data, our model predicts a smaller volatility of investment (1.88 versus 2.78) but a larger volatility of employment (1.61 versus 0.67). It also slightly understates the volatility of net exports (0.02 versus 0.11). These results are not sensitive to variations in the number of processing stages and arise for reasons similar to those for a single-stage model such as that in CKM (2002). Briefly, with $\sigma = 3$, a large capital adjustment cost parameter is required to make consumption equally volatile as in the data (with a standard deviation of 0.83). A large adjustment cost parameter gives rise to a small volatility of investment. Employment volatility is higher than output volatility mainly because our model is driven by demand shocks only.[7]

6. Conclusion

International trade in intermediate inputs and, increasingly, in goods produced at multiple stages of processing has become an important component of modern world trade. This feature has been extensively studied in the real trade literature, but largely overlooked in business cycle theories. In this paper, we have studied the role of this feature of modern world trade in the transmission of international business cycles. Our model that incorporates this feature into a standard new open-economy macro model with staggered prices does quite well in explaining the observed international quantity correlations, and the model performs much better than a version without trade in intermediate goods. We have also confronted the model against some stylized facts concerning the cyclical behavior of the real exchange rate and, in particular, the large and persistent deviations from the

[7]One way to reduce the volatility of employment relative to that of output is to introduce productivity shocks. Since our goal is to examine the role of staggered prices and trade in intermediate goods in a stereotypical new open-economy macro model, we focus on monetary shocks rather than technology shocks.

purchasing power parity and the disconnect between the real exchange rate and aggregate quantities, such as relative consumption. There, the model falls short in explaining the facts, but it moves in the right direction as trade in intermediate goods is incorporated.

Our findings suggest that trade in intermediate goods, a feature much emphasized in real trade theories, can be an important element in building international business cycle models. The model's inability to fully account for the observed exchange-rate behaviors should not be viewed as evidence against the importance of trade in intermediates. As we have shown in the paper, incorporating trade in intermediate goods moves the model in the right direction along these dimensions. What is needed is perhaps some asset-market frictions or non-time-separable preferences, which may help break the tight link between the real exchange rate and relative consumption. Exploring these frictions in a model that incorporates trade in intermediate goods should be a promising avenue for resolving some of the puzzles concerning the behaviors of the real exchange rate. It should also further our understanding of the international transmission of business cycles.

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