

Welfare-Based Evaluation of Real Exchange Rate Stabilization in the Presence of News about the Future*

- Job Market Paper -

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October 2007

(First version: September 2, 2007)

Abstract

This paper studies the effect of news shocks about the future technology level and performs the welfare-based policy evaluation of real exchange rate stabilization in a two-country open economy model. When prices of consumption goods across countries are sticky in the local currency, the consumption-based real exchange rate moves closely with the nominal exchange rate whose movements reflect changes in expectations of future fundamentals caused by news about the future. Consequently, the movement of the real exchange rate correctly informs the monetary policy authority of the impact of news shocks on the economy. In the sticky price economy, we show that the optimal policy rule in the presence of news shocks requires real exchange rate stabilization. When both sticky wages and prices are taken into account, the inflation-targeting policy alone amplifies the response of the economy to news shocks, creating a large welfare loss. In this case, either real exchange rate stabilization or output gap stabilization is needed to prevent the economy from overreacting to news shocks. Under the optimal policy rule, however, the role of real exchange rate stabilization in dampening the impact of news shocks is dominated by output gap stabilization because the movement of the output gap is more informative about the impact of news shocks. Nevertheless, our specification of real exchange rate stabilization implies that it is viewed as a legitimate goal of monetary policy to target news shocks in the economy with sticky wages. In addition, we show that the real exchange rate exhibits hump-shaped dynamics in response to a positive news shock and that both the real exchange rate and the terms-of-trade can either appreciate or depreciate in response to such a news shock, depending on how far into the future the shock will actually be realized.

JEL Classification: F41; F42; E52

Keywords: real exchange rate stabilization, welfare-based policy evaluation, news shocks

*I am greatly indebted to my advisor, Charles Engel for useful discussion and constant encouragement. All errors are mine.

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1 Introduction

The debate whether the nominal interest rate as the monetary policy instrument should react to the real exchange rate in an open economy has continued for a long time without reaching a conclusion. One of the arguments opposing the reaction of the nominal interest rate to the real exchange rate is based on its contribution to the stability of the economy. For instance, John Taylor (2001) states: "monetary-policy rules that react directly to the exchange rate, as well as to inflation and output, do not work much better in stabilizing inflation and real output and sometimes work worse than policy rules that do not react directly to the exchange rate." Such a conclusion has been reached in the setting where aggregate fluctuations are driven only by contemporaneous shocks, but news shocks about future economic conditions have recently been explored as the driving force of boom-bust business cycles (among others, Beaudry and Portier (2004) and Jaimovich and Rebelo (2006)). In this paper, we consider news shocks about the future technology level as well as contemporaneous technology shocks in a fully developed two-country open economy model with nominal rigidities and then quantitatively perform the welfare-based evaluation of real exchange rate stabilization.

News about future economic conditions leads to changes in expectations of the future, an essential element in determining the dynamics of aggregate variables of the economy in modern macroeconomics. News about the future has different effects than new information in the form of a contemporaneous shock, so under rational expectations, the dynamics of the economy in response to a news shock cannot be the same as in response to a contemporaneous shock. For instance, while the inflation rate falls immediately in response to an unexpected technology improvement which comes as a contemporaneous shock, it can rise in response to a news shock that the technology will improve in the near future because more investment and consumption occur immediately without a change in the current productivity level. In addition, different evolutions of the inflation rate in response to such contemporaneous and news shocks also affect forward-looking decisions made in the current period by agents with rational expectations in different ways. Even though contemporaneous and news shocks are the same driving force of aggregate fluctuations, they yield different dynamic responses from the economy and thus have different implications for monetary policy.

In the presence of news shocks about future economic conditions, we attempt to answer the question of what monetary policy responds efficiently to news shocks. In other words, how should the monetary policy authority design its policy so as to transmit news shocks to the economy in a welfare-improving way? We show that a monetary policy rule that directly targets real exchange rate fluctuations can improve welfare and contribute to the stability of the economy as a whole. When prices of consumption goods are set in the local currency and are sticky, the consumption-based real exchange rate, the relative price of consumption goods across different countries denominated in one currency, is very close to the nominal exchange rate, which is consistent with the empirical finding on the relation between real and nominal exchange rates. The nominal exchange rate is primarily affected by changes in expectations of future fundamentals relevant for determining its value, which implies that the nominal exchange rate movement captures the effect of news

shocks about the future immediately and consequently, the real exchange rate does so. In the general equilibrium framework, real exchange rate movements correctly inform the monetary policy authority of the effect of news shocks on the economy. Thus, the monetary policy rule that reacts to the real exchange rate would work better in predicting the dynamics of aggregate variables in response to news shocks than a policy rule that does not react to the real exchange rate.

In particular, explicit consideration of news shocks about future economic conditions has a direct implication for exchange rate policy, which is first addressed by Devereux and Engel (2006a and 2007); news shocks are the source of the misalignment of the current relative prices of goods across countries, which distorts the allocation of resources.¹ Their insight is based on the dual role of the nominal exchange rate in the asset and goods markets. On the one hand, the nominal exchange rate is an asset price of two currencies as durable goods in the asset market, so its movement is primarily affected by changes in expectations of its relevant future fundamentals caused by news about the future. On the other hand, it plays a significant role in determining the relative prices of goods across countries when prices of goods adjust slowly to real shocks and are set in different currencies. Thus, with sticky prices of goods, the relative goods prices across countries can be misaligned by news about the future altering the nominal exchange rate in the sense that they reflect future, not current, economic conditions. Such a misalignment of relative prices of goods across countries creates a welfare loss different from the one resulting from the price stickiness of goods.

For instance, given news about a future technology improvement in the home country relative to the foreign country, it is expected that the inflation rate in the home country will be relatively low in the future. With an inflation-targeting monetary authority in the home country, the market expects that it will cut the nominal interest rate in the future and thereby the home country currency will depreciate. In the asset market equilibrium, holding the interest rate differential fixed, the expected depreciation of the home country currency immediately leads to an increase in the nominal exchange rate.² With sticky prices of traded goods across countries which are set in the producer's currency, the current domestic terms-of-trade as the relative prices of traded goods across countries is worsened by such a movement of the nominal exchange rate and depends on the future technology level. In such a situation, real exchange rate stabilization would prevent the terms-of-trade from being misaligned by the nominal exchange rate movement due to news about future technology in the home country. Under sticky prices of consumption goods, the increase in the nominal exchange rate due to such news contributes to the real exchange rate depreciation, which implies that the movement of the real exchange rate is a measure of the misalignment of the terms-of-trade made by the nominal exchange rate movement due to news about future technology. So a monetary policy that reacts to the real exchange rate depreciation eliminates the impact of news about future technology on the nominal exchange rate. Consequently, real exchange rate

¹For example, the terms-of-trade defined as the ratio of prices of imported goods to prices of exported goods in terms of one currency shows the relative price of traded goods across countries. As mentioned above, the real exchange rate is the relative price of consumption goods across countries.

²The nominal exchange rate is defined as the home country currency price of a unit of the foreign country currency.

stabilization prevents the misalignment of the terms-of-trade.

While in the line of the research of Devereux and Engel (2006a and 2007), our study of real exchange rate stabilization has several different dimensions. First, our welfare-based evaluation of real exchange rate stabilization is performed in the presence of both contemporaneous and news shocks, as real exchange rate stabilization creates a welfare loss by not allowing the flexibility of the nominal exchange rate, which is needed for the adjustment of the relative prices goods across countries such as the terms-of-trade to contemporaneous shocks, even while simultaneously eliminating the impact of news shocks on the nominal exchange rate.³ So our evaluation of real exchange rate stabilization demonstrates a trade-off between its desirability to target news shocks and its inefficient response to contemporaneous shocks. Second, we consider several types of news shocks in terms of their distance into the future: that is, how many periods in advance the future technology level is known. Such a consideration help us evaluate the severity of the misalignment of the relative prices of goods caused by the movement of the nominal exchange rate due to news shocks. Thinking of the nominal exchange rate as an asset price, it can be expressed by the discounted expected present value of the relevant current and future fundamentals.⁴ For a news shock with a given impact on future fundamentals, its impact on the nominal exchange rate in the current period depends on its distance into the future because news shocks about the more distant future is more heavily discounted, lessening its impact on the current nominal exchange rate. Thus, it is hard to say that every news shock should be targeted only because it is the source of the misalignment of the relative goods prices across countries at the current period. Moreover, our consideration of different lengths of news shocks is not only based on the simple conjecture explained above, but also on the possibility of different transitional dynamics of macroeconomic fundamentals from the current period to the future period at which the news shock is realized. The length of news shocks affects the transitional dynamics of the economy and thus plays a role in determining changes in expectations of future fundamentals. Consequently, it has an influence on the way the nominal exchange rate is altered by news shocks.⁵ In addition, the study of different lengths of news shocks suggests several possibilities for the instantaneous response of the relative prices of goods across countries to a news shock.⁶ Finally, we consider sticky wages in addition to sticky prices. With sticky nominal wages, it is expected that the dynamics of the real wage during periods before a news shock is realized is not efficient when compared to the case of flexible nominal wages. Even though the instantaneous response of the real wage to a news shock is close to the efficient one, when forward-looking firms that use labor as input in their production re-optimize their prices, these prices will be distorted by firms' expectations of the inefficient evolution of factor prices. On impact of a news shock, the relative prices of goods across countries can be misaligned by the interaction between sticky wages and the sticky price decision made by forward-looking firms

³Refer to Devereux and Engel (2006b) and Wang (2007) for details on undesirability of real exchange rate stabilization in the presence of contemporaneous shocks only, which will also be discussed below.

⁴Refer to Engel, Mark, and West (2007) and Engel and West (2005).

⁵The design of monetary policy is also important in determining the transmission mechanism of news shocks, so it also affects the nominal exchange rate determination.

⁶This will be discussed in more detail in Section 4.

even when prices can adjust quickly to a news shock.

Another related literature to our study is Christiano, Ilut, Motto, and Rostagno (2007). They address the effect of news shocks about future technology in the closed economy, arguing that the dynamics of the whole economy in response to news shocks is amplified by the interaction between sticky nominal wages and an inflation-targeting monetary policy, two important characteristics of the U.S. economy. With sticky wages (as well as sticky prices), an inflation-targeting monetary policy reduces welfare in the presence of news shocks. The intuition behind their finding is based on the dynamics of the real wage, as the real wage rises in response to a positive news shock about the future technology level. When nominal wages are slow to adjust to such a news shock, a rise in the real wage requires that the inflation rate be allowed to drift down. Consequently, an inflation-targeting authority would cut the nominal interest rate, thereby making the economic expansion much bigger than is socially optimal. In such a situation, their monetary policy recommendation is to integrate credit growth into the inflation-targeting policy; since credit growth rises in response to a positive news shock, leaning against the wind when credit growth increases helps prevent the economic expansion caused by a positive news shock from being amplified by the inflation-targeting policy. Instead, we consider real exchange rate stabilization in the presence of news shocks, a welfare-improving policy that has long been debated in the open economy monetary policy literature. When the inflation rate drifts down in response to a positive news shock, the consumption-based real exchange rate rises, and the reaction of the nominal interest rate to the real exchange rate depreciation can help prevent the economy from overreacting to a positive news shock under the inflation-targeting policy. In this sense, we discuss monetary policy in the presence of news shocks in a more conventional framework than Christiano et al. (2007). More importantly, our monetary policy evaluation is based on the welfare measure, not just on the study of the dynamics of aggregate variables in response to news shocks.

We use a model similar to Devereux and Engel (2006b) and Wang (2007). In our model, intermediate goods are produced by using capital and labor and are traded across countries. Their prices are sticky in the producer's currency (PCP). Then, both domestic and foreign-made intermediate goods are used to produce final consumption goods in each country. The prices of final goods are sticky in the local currency (LCP). This price stickiness structure in both sectors is consistent with the empirical evidence that while exchange rate pass-through to prices of imported goods is high, pass-through to prices of consumer goods is weak. In this setting, however, there is a trade-off shown in Devereux and Engel (2006b): in response to contemporaneous shocks, the flexibility of the nominal exchange rate is needed to facilitate the terms-of-trade adjustment, but leads to an undesirable change in the CPI real exchange rate that causes goods to be allocated inefficiently across countries. In contrast, Wang (2007) shows that when the production of final goods is biased toward domestic intermediate goods, the baskets of consumption goods are not identical across countries, so real exchange rate fluctuations do not necessarily allocate goods inefficiently across countries. With home bias, our model predicts that real exchange rate stabilization responds inefficiently to contemporaneous technology shocks. When news shocks are modeled as news about the future

technology level, the movement of the nominal exchange rate due to news shocks can misalign both the real exchange rate and the terms-of-trade, so real exchange rate stabilization improve welfare by eliminating the impact of news shocks on the nominal exchange rate. Hence, in our model, real exchange rate stabilization presents a trade-off between its ability to target news shocks and its inefficient response to contemporaneous shocks. Sticky wages are also considered. In addition, our model features the habit formation in consumption, investment adjustment costs in terms of the flow specification, and prices and wages indexed to the long-run CPI inflation rate.

The monetary policy we consider is a modified interest rate feedback rule in which the nominal interest rate reacts to the real exchange rate depreciation from the previous period, deviations of the CPI inflation rate and the inflation rate of the nominal wage index from their target values, and the output gap. We define our welfare measure as the conditional expectation of the weighted average of individual lifetime utilities. Thus, the optimal monetary policy rule is found by ranking the conditional welfare associated with each policy regime, which we define as a set of policy parameters in the interest rate feedback rule. In the economy with sticky prices only, we find that the optimal policy rule requires that the real exchange rate be stabilized while putting zero weight on real exchange rate fluctuations in the absence of news shocks. This implies that the welfare gain from real exchange rate stabilization in response to news shocks dominates the welfare loss from its inefficient response to contemporaneous shocks. Moreover, as news shocks are further into the future and home bias gets higher, there is more welfare gain from real exchange rate stabilization. Based on these findings in the sticky price economy, real exchange rate stabilization is a legitimate goal of monetary policy in the presence of news shocks in the sense that it is needed to correct the misalignment of both the real exchange rate and the terms-of-trade which results from the impact of news shocks on the nominal exchange rate.

In the economy with sticky wages and prices, the optimal policy rule takes a much weaker stance against the CPI inflation rate than it does in the case without considering news shocks. Output gap stabilization is emphasized because it is the best policy to prevent the impact of news shocks on the economy from being amplified by an inflation-targeting policy rule. When a policy rule without output gap stabilization takes as strong a stance against the CPI inflation rate as it does under the optimal policy rule in the absence of news shocks, there is a large welfare loss. This is in contrast to the conventional view that output gap stabilization can destabilize the economy.⁷ Regarding real exchange rate stabilization, the optimal policy rule does not seem to require that the real exchange rate be stabilized because strong output gap stabilization under the optimal policy rule dominates the role of real exchange rate stabilization in eliminating the impact of news shocks. However, this does not mean that real exchange rate stabilization is no longer a legitimate goal of monetary policy once we consider the possibility of news shocks. McCallum (2001) discusses the issue of policy-rule

⁷Regarding output gap stabilization, McCallum (2001) raises two issues: one is the trade-off between inflation and output gap variability and the other is the availability of the data on the natural-rate level of output in actual estimation of the output gap. For the former, output gap stabilization contributes enormously to the stability of the whole economy by dampening the response of employment to news shocks, a response amplified by the interaction between sticky wages and an inflation-targeting policy. The latter is discussed below.

operationality in stabilizing the output gap in practice, namely the unobservability of the natural-rate level of output by central banks. Our specification of real exchange rate stabilization is the real depreciation from the previous period, so real exchange rate stabilization is more operational than output gap stabilization. If the output gap is not stabilized, the welfare gain from real exchange rate stabilization is monotonically increasing when the policy authority takes a moderately strong stance against the CPI inflation rate. In addition, it contributes to the stability of the economy by reducing the volatilities of aggregate variables, something which does not occur in the absence of news shocks. Real exchange rate stabilization can be a goal of monetary policy in the presence of news shocks in an economy with sticky wages (and sticky prices) and the inflation-targeting policy that many central bankers uses.⁸

Finally, by looking at the response of aggregate variables to a positive news shock under a simple inflation-targeting rule, we find that the real exchange rate exhibits the hump-shaped dynamics in response to a positive news shock and this shape is invariant to the exclusion of habit formation in consumption. Moreover, both the real exchange rate and the terms-of-trade can appreciate over periods of one and two years, respectively. These findings suggest that news shocks can reconcile the observed dynamics of the relative prices across countries in the data with those generated by contemporaneous shocks in standard general equilibrium open economy models.

The rest of the paper is organized as follows. Section 2 describes the structure of our two-country open economy model and the representation of news shocks about future technology. Section 3 introduces our welfare measure under a monetary policy regime and the welfare cost of a particular monetary regime relative to a reference regime. In Section 4, we analyze the equilibrium response of aggregate variables of interest to contemporaneous and news shocks under a simple policy rule. In Section 5, we provide results on the welfare evaluation of monetary policy. Section 6 has concluding remarks.

2 Structure of the model⁹

Our model is a two-country model with traded intermediate goods and non-traded final goods. The structure of the model is similar to Devereux and Engel (2006b). Prices of both intermediate and final goods are sticky a la Calvo (1983) and Yun (1996). The labor market is modeled as in Erceg et al. (2000) and wages are sticky in the same way as goods prices. Asset markets are complete at both domestic and international levels. Each household supplies its labor and rents capital to intermediate goods firms, whose prices are set in the producer's currency (PCP). In the

⁸We are not saying that the real exchange rate should be stabilized. In the presence of news shocks and sticky wages, it should be considered by central banks as a part of monetary policy like Christiano et al.'s policy recommendation of monitoring credit growth. Note that in the Taylor rule Christiano et al. (2007) use in their simulation, the specification on the reaction to output is the deviation of output from its nonstochastic steady state growth path. While we use the deviation of output from its nonstochastic steady state value in our model, the optimal policy rule does not put a positive weight on it, implying that the role of the reaction to output fluctuations around its steady state value is not the same as that of output gap stabilization. However, real exchange rate stabilization still prevents the response of the whole economy to news shocks from being amplified by an inflation-targeting policy.

⁹In this section, we provide the basic structure of our model. Refer to the technical appendix for details.

final goods sector, firms produce their own differentiated consumption goods by using composites of domestic and foreign intermediate goods and set their prices in the consumer's currency (LCP). The monetary policy is designed as an interest rate feedback rule in which the nominal interest rate reacts to deviations of the CPI inflation rate and the inflation rate of the nominal wage index from their target values, the GDP output gap, and the depreciation of the real exchange rate from the past period. We follow Christiano et al. (2007) and Devereux and Engel (2006a) to model news shocks as a part of technology shocks that is known in advance.

2.1 Households

There is a continuum of households indexed by h over the unit interval $[0, 1]$.¹⁰ Each household consumes a composite of final goods. It also supplies its differentiated labor of type h and rents capital to intermediate goods firms. Asset markets are assumed to be complete both domestically and internationally. Even though households set their nominal wage and supply different amounts of labor, they are homogeneous in every other respect due to the complete asset market assumption.¹¹ The lifetime utility of each household h is

$$E_0 \sum_{t=0}^{\infty} \beta^t [U(C_t - bC_{t-1}) - V(L_t(h))], \quad (1)$$

where C_t is the composite of consumption goods and $L_t(h)$ is hours worked. The functional forms are given by

$$U(C_t - bC_{t-1}) = \frac{(C_t - bC_{t-1})^{1-\rho}}{1-\rho} \quad \text{and} \quad V(L_t(h)) = \frac{L_t^{1+\eta}(h)}{1+\eta},$$

where we assume internal habit formation of degree b , $0 \leq b < 1$. The consumption good is assumed to be a composite made of a continuum of differentiated final goods via the following aggregator:

$$C_t = \left(\int_0^1 C_t(f)^{\frac{\theta_F-1}{\theta_F}} df \right)^{\frac{\theta_F}{\theta_F-1}},$$

where $\theta_F > 1$ is the elasticity of substitution between a variety of final goods f on the interval $[0, 1]$. The intratemporal optimal demand for each final good is given by

$$C_t(f) = \left(\frac{P_t(f)}{P_t} \right)^{-\theta_F} C_t,$$

where $P_t(f)$ is the price of final good f and the price index of the composite of consumption goods is

$$P_t = \left(\int_0^1 P_t(f)^{1-\theta_F} df \right)^{\frac{1}{1-\theta_F}}.$$

¹⁰Throughout the paper, we preserve three lower-case letters h , f , and i for home country households, final good firms, and intermediate good firms, respectively. These letters with asterisks indicate their respective foreign country counterparts.

¹¹For notational convenience, this homogeneity is reflected in what follows.

Each household is assumed to be a monopolistic supplier of labor of type h . Taking the wage index W_t and the total demand for the labor composite L_t^d as exogenous and given the wage $W_t(h)$ it charges, each household is assumed to supply enough labor $L_t(h)$ to satisfy the demand for its labor:

$$L_t(h) = \left(\frac{W_t(h)}{W_t} \right)^{-\theta_w} L_t^d = \left(\frac{w_t(h)}{w_t} \right)^{-\theta_w} L_t^d, \quad (2)$$

where $\theta_w > 1$ is the elasticity of substitution between types of labor on the interval $[0, 1]$, $w_t(h) = W_t(h)/P_t$ is the real wage of labor of type h in terms of the composite of final goods (i.e. consumption goods), and $w_t = W_t/P_t$ is the real wage index.¹² Each household is also assumed to own physical capital K_t and rent it to intermediate goods firms. Capital accumulates according to its law of motion:

$$K_{t+1} = (1 - \delta) K_t + I_t \left(1 - S \left(\frac{I_t}{I_{t-1}} \right) \right), \quad (3)$$

where δ is the rate of capital depreciation. The function S introduces investment adjustment costs which are modeled in terms of the change in the flow of investment as in Christiano et al. (2007), and its functional form is given by

$$S \left(\frac{I_t}{I_{t-1}} \right) = \frac{\kappa}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2,$$

where κ is a scale parameter for investment adjustment costs. Note that capital and investment are in the form of the consumption goods composite and the total demand for the composite of consumption goods is given by

$$Y_t^d = C_t + I_t. \quad (4)$$

The budget flow at period t is expressed in terms of the composite of consumption goods:

$$\begin{aligned} & C_t + I_t + E_t \left[\frac{Q_{t,t+1} B_{t+1}}{P_t} \right] + S_t E_t \left[\frac{Q_{t,t+1}^* B_{t+1}^*}{P_t} \right] \\ = & (1 + \tau_w) w_t(h) \left(\frac{w_t(h)}{w_t} \right)^{-\theta_w} L_t^d + r_t^k K_t + \frac{B_t}{P_t} + \frac{S_t B_t^*}{P_t} + \phi_{Ft} + \phi_{It} - \tau_t^L, \end{aligned} \quad (5)$$

where S_t is the nominal exchange rate in period t , defined as the home country currency price of a unit of foreign country currency, $Q_{t,t+1}$ ($Q_{t,t+1}^*$) is the home (foreign) country currency price of a nominal state-contingent claim which pays one unit of the home (foreign) currency in period $t + 1$, B_{t+1} (B_{t+1}^*) is the number of such nominal state-contingent claims held, $\tau_w \geq 0$ is the real labor subsidy, r_t^k is the real rental rate per unit of capital, τ_t^L is a lump-sum tax, and ϕ_{Ft} (ϕ_{It}) is real profits from final (intermediate) goods firms. Then, each household's problem is to maximize (1) subject to (2), (3), and (5). The first-order conditions with respect to C_t , I_t , K_{t+1} , $L_t(h)$, B_{t+1} ,

¹²In what follows, real quantities are expressed in terms of the composite of final goods.

B_{t+1}^* , and $w_t(h)$ imply

$$\lambda_t = U_C(C_t - bC_{t-1}) - b\beta E_t[U_C(C_{t+1} - bC_t)], \quad (6)$$

$$\lambda_t = \lambda_t \mu_t^q \left(1 - S\left(\frac{I_t}{I_{t-1}}\right) - \left(\frac{I_t}{I_{t-1}}\right) S'\left(\frac{I_t}{I_{t-1}}\right) \right) + \beta E_t \left[\lambda_{t+1} \mu_{t+1}^q \left(\frac{I_{t+1}}{I_t}\right)^2 S'\left(\frac{I_{t+1}}{I_t}\right) \right], \quad (7)$$

$$\lambda_t \mu_t^q = \beta E_t \left[\lambda_{t+1} \left(r_{t+1}^k + \mu_{t+1}^q (1 - \delta) \right) \right], \quad (8)$$

$$V_L(L_t(h)) = \frac{\lambda_t w_t}{\tilde{\mu}_t^w(h)}, \quad (9)$$

$$Q_{t,t+1} = \beta \frac{\lambda_{t+1}}{\lambda_t} \frac{P_t}{P_{t+1}} \text{ and } Q_{t,t+1}^* = \beta \frac{\lambda_{t+1}}{\lambda_t} \frac{S_{t+1} P_t}{P_{t+1} S_t}, \quad (10)$$

for all states of the nature at period $t + 1$, and

$$w_t(h) = \begin{cases} \tilde{w}_t(h) & \text{if } W_t(h) \text{ is set optimally at period } t \\ w_{t-1}(h) \frac{\bar{\Pi}}{\bar{\Pi}_t} & \text{otherwise} \end{cases}, \quad (11)$$

where $\tilde{w}_t(h)$ denotes the real wage of labor type h if household h has the chance to re-optimize its nominal wage with probability $1 - \alpha_w$ in period t .¹³ Note that if a household does not have the chance to re-optimize its nominal wage, it will index its nominal wage to the long-run gross CPI inflation rate $\bar{\Pi}$. It follows from Eq. (10) that the gross nominal interest rate R_t of a one period risk-free bond is

$$R_t^{-1} = E_t[Q_{t,t+1}] = \beta E_t \left[\frac{\lambda_{t+1}}{\lambda_t} \frac{1}{\bar{\Pi}_{t+1}} \right]. \quad (12)$$

Regarding the optimal wage $\tilde{w}_t(h)$, s periods after the last wage re-optimization the real wage and the demand for labor of type h are given, respectively, by:

$$\tilde{w}_t(h) \prod_{k=1}^s \frac{\bar{\Pi}^s}{\bar{\Pi}_{t+k}} \text{ and } \left(\frac{\tilde{w}_t(h)}{w_{t+s}} \prod_{k=1}^s \frac{\bar{\Pi}^s}{\bar{\Pi}_{t+k}} \right)^{-\theta_w} L_{t+s}^d.$$

Then, the part of the household's Lagrangian that is relevant for the optimal wage setting is expressed as

$$\mathcal{L}_w(h) = E_t \sum_{s=0}^{\infty} (\alpha_w \beta)^s \lambda_{t+s} L_{t+s}^d \left(\frac{1}{w_{t+s}} \prod_{k=1}^s \frac{\bar{\Pi}^s}{\bar{\Pi}_{t+k}} \right)^{-\theta_w} \left\{ \begin{array}{l} (1 + \tau_w) \tilde{w}_t^{1-\theta_w} \prod_{k=1}^s \frac{\bar{\Pi}^s}{\bar{\Pi}_{t+k}} \\ - \tilde{w}_t^{-\theta_w} \frac{V_L(L_{t+s})}{\lambda_{t+s}} \end{array} \right\}.$$

Note that because every household faces the same labor demand function, it follows that all households re-optimizing wages in a given period will choose to set the same nominal wage, so we drop the index h from $\tilde{w}_t(h)$ and $L_{t+s}(h)$ and use the first-order condition with respect to its labor

¹³Note that $\beta^t \lambda_t w_t / \tilde{\mu}_t^w(h)$, $\beta^t \lambda_t \mu_t^q$, and $\beta^t \lambda_t$ are Lagrange multipliers associated with constraints (2), (3), and (5), respectively. Refer to the technical appendix for details.

supply (i.e. Eq. (9)). Then, the household's first-order condition with respect to \tilde{w}_t implies

$$(1 + \tau_w) \left(\frac{\theta_w - 1}{\theta_w} \right) x_{wt}^1 = x_{wt}^2, \quad (13)$$

where the recursive forms of x_{wt}^1 and x_{wt}^2 are given by

$$x_{wt}^1 = \lambda_t \tilde{w}_t \left(\frac{\tilde{w}_t}{w_t} \right)^{-\theta_w} L_t^d + (\alpha_w \beta) E_t \left[\left(\frac{\tilde{w}_t}{\tilde{w}_{t+1}} \frac{\bar{\Pi}}{\Pi_{t+1}} \right)^{1-\theta_w} x_{wt+1}^1 \right], \quad (14)$$

$$x_{wt}^2 = \left(\frac{\tilde{w}_t}{w_t} \right)^{-\theta_w(1+\eta)} L_t^{d(1+\eta)} + (\alpha_w \beta) E_t \left[\left(\frac{\tilde{w}_t}{\tilde{w}_{t+1}} \frac{\bar{\Pi}}{\Pi_{t+1}} \right)^{-\theta_w(1+\eta)} x_{wt+1}^2 \right]. \quad (15)$$

The wage index given as $W_t = \left(\int_0^1 W_t(h)^{1-\theta_w} dh \right)^{1/(1-\theta_w)}$ implies

$$1 = (1 - \alpha_w) \left(\frac{\tilde{w}_t}{w_t} \right)^{1-\theta_w} + \alpha_w \left(\frac{w_{t-1} \bar{\Pi}}{w_t \Pi_t} \right)^{1-\theta_w}. \quad (16)$$

Before ending our discussion of wage-setting, we introduce the measure of the wage dispersion which is involved in the weighted average of individual lifetime utilities:

$$\Delta_{wt}^{1+\eta} \equiv \int_0^1 \left(\frac{w_t(h)}{w_t} \right)^{-\theta_w(1+\eta)} dh,$$

whose law of motion is expressed as:

$$\Delta_{wt}^{1+\eta} = (1 - \alpha_w) \left(\frac{\tilde{w}_t}{w_t} \right)^{-\theta_w(1+\eta)} + \alpha_w \left(\frac{w_{t-1} \bar{\Pi}}{w_t \Pi_t} \right)^{-\theta_w(1+\eta)} \Delta_{wt-1}^{1+\eta}. \quad (17)$$

For the foreign country, similar equations hold. It follows from the complete international asset market assumption that the international risk-sharing condition holds:

$$\frac{\lambda_t^*}{\lambda_t} = kRS_t, \quad (18)$$

where $RS_t \equiv S_t P_t^* / P_t$ is the consumption-based real exchange rate and $k = \frac{\lambda_{-1}^*}{\lambda_{-1}} \frac{1}{RS_{-1}}$ is a constant.

2.2 Firms

2.2.1 Final goods firms

In the final goods sector, each firm produces its differentiated good by using composites of domestic and foreign intermediate goods. When a firm sets its price, it is denominated in the local currency

(LCP). The composite of differentiated final goods is made via the following aggregator:

$$Y_t = \left(\int_0^1 y_t(f)^{\frac{\theta_F-1}{\theta_F}} df \right)^{\frac{\theta_F}{\theta_F-1}},$$

where $y_t(f)$ is a final good of type f on the unit interval $[0, 1]$. The technology of final goods is the same across firms and is given by:

$$y_t^s(f) = \left[\omega^{\frac{1}{\psi}} Y_{Ht}^{\frac{\psi-1}{\psi}}(f) + (1-\omega)^{\frac{1}{\psi}} Y_{Ft}^{\frac{\psi-1}{\psi}}(f) \right]^{\frac{\psi}{\psi-1}},$$

where $Y_{Ht}(f)$ and $Y_{Ft}(f)$ are composites of domestic and foreign intermediate goods demanded by a final good firm f and ψ is the elasticity of substitution between composites. Given the production function, its real marginal cost is expressed by:

$$mc_t = \left[\omega (p_{Ht})^{1-\psi} + (1-\omega) (p_{Ft}^* R S_t)^{1-\psi} \right]^{\frac{1}{1-\psi}}, \quad (19)$$

where $p_{Ht} \equiv P_{Ht}/P_t$, $p_{Ft}^* \equiv P_{Ft}^*/P_t^*$, and $R S_t = S_t P_t^*/P_t$. Note that P_{Ht} and P_{Ft}^* are price indices of composites of domestic and foreign intermediate goods, respectively. The intratemporal optimal aggregate demands for composites of domestic and foreign intermediate goods are given by:

$$Y_{Ht}^d = \omega \left(\frac{p_{Ht}}{mc_t} \right)^{-\psi} \Delta_t Y_t^d, \quad Y_{Ft}^d = (1-\omega) \left(\frac{p_{Ft}^* R S_t}{mc_t} \right)^{-\psi} \Delta_t Y_t^d, \quad (20)$$

where $Y_{Ht}^d \equiv \int_0^1 Y_{Ht}^d(f) df$, $Y_{Ft}^d \equiv \int_0^1 Y_{Ft}^d(f) df$, and $\Delta_t \equiv \int_0^1 \left(\frac{P_t(f)}{P_t} \right)^{-\theta_F} df$ is the measure of the price dispersion of final goods.

When a final good firm f re-optimizes its price with probability $1 - \alpha_F$, it maximizes the discounted expected present value of profits subject to its demand schedule:

$$\begin{aligned} E_t \sum_{s=0}^{\infty} (\alpha_F)^s Q_{t,t+s} P_{t+s} \left[(1 + \tau_F) \frac{\tilde{P}_t(f)}{P_{t+s}} \bar{\Pi}^s - mc_{t+s} \right] y_{t+s}^d(f) \\ s.t. \ y_{t+s}^d(f) = \left(\frac{\tilde{P}_t(f)}{P_{t+s}} \bar{\Pi}^s \right)^{-\theta_F} Y_{t+s}^d, \end{aligned}$$

where $Q_{t,t+s} = \beta^s \frac{\lambda_{t+s}}{\lambda_t} \frac{P_t}{P_{t+s}}$ is the nominal stochastic discount factor and $\tau_F \geq 0$ is the real subsidy to final good firms. Note that when firms do not have the chance to reset their prices, prices are indexed to the long-run CPI inflation rate $\bar{\Pi}$. Then, the first-order condition with respect to $\tilde{P}_t(f)$ implies

$$(1 + \tau_F) \frac{\theta_F - 1}{\theta_F} x_{Ft}^1 = x_{Ft}^2, \quad (21)$$

with the recursive forms of x_{Ft}^1 and x_{Ft}^2 given by:

$$x_{Ft}^1 = \tilde{p}_t^{-\theta_F} Y_t^d + (\alpha_F \beta) E_t \left[\left(\frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{\tilde{p}_t}{\tilde{p}_{t+1}} \right)^{-\theta_F} \left(\frac{\bar{\Pi}}{\bar{\Pi}_{t+1}} \right)^{1-\theta_F} x_{Ft+1}^1 \right], \quad (22)$$

$$x_{Ft}^2 = \tilde{p}_t^{-\theta_F-1} Y_t^d m c_t + (\alpha_F \beta) E_t \left[\left(\frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{\tilde{p}_t}{\tilde{p}_{t+1}} \right)^{-\theta_F-1} \left(\frac{\bar{\Pi}}{\bar{\Pi}_{t+1}} \right)^{-\theta_F} x_{Ft+1}^2 \right], \quad (23)$$

where $\tilde{p}_t \equiv \tilde{P}_t(f)/P_t$ is the optimal new price deflated by the price index of the composite of final consumption goods. Moreover, the price index of the composite of final goods implies

$$1 = (1 - \alpha_F) \tilde{p}_t^{1-\theta_F} + \alpha_F \left(\frac{\bar{\Pi}}{\bar{\Pi}_t} \right)^{1-\theta_F}, \quad (24)$$

and the law of motion of the measure of the price dispersion of final goods Δ_t is

$$\Delta_t = (1 - \alpha_F) \tilde{p}_t^{-\theta_F} + \alpha_F \left(\frac{\bar{\Pi}}{\bar{\Pi}_t} \right)^{-\theta_F} \Delta_{t-1}. \quad (25)$$

For foreign final goods firms, similar equations hold. However, home bias is allowed: the technology of foreign final goods is given by

$$y_t^s(f^*) = \left[(1 - \omega)^{\frac{1}{\psi}} Y_{Ht}^{*\frac{\psi-1}{\psi}}(f^*) + \omega^{\frac{1}{\psi}} Y_{Ft}^{*\frac{\psi-1}{\psi}}(f^*) \right]^{\frac{\psi}{\psi-1}},$$

where $\omega > \frac{1}{2}$ indicates home bias in the production of final goods toward domestic intermediate goods. The foreign aggregate demands $Y_{Ht}^{d*} \equiv \int_0^1 Y_{Ht}^{d*}(f^*) df^*$ and $Y_{Ft}^{d*} \equiv \int_0^1 Y_{Ft}^{d*}(f^*) df^*$ for composites of domestic and foreign intermediate goods are given by:

$$Y_{Ht}^{d*} = (1 - \omega) \left(\frac{p_{Ht} R S_t^{-1}}{m c_t^*} \right)^{-\psi} \Delta_t^* Y_t^{d*}, \quad Y_{Ft}^{d*} = \omega \left(\frac{p_{Ft}^*}{m c_t^*} \right)^{-\psi} \Delta_t^* Y_t^{d*}. \quad (26)$$

2.2.2 Intermediate goods firms

In the intermediate goods sector, firms use labor and capital to produce their own differentiated goods that are traded across countries and set their prices in the producer's currency (PCP). The composite of intermediate goods are used to produce consumption goods in the final goods sector. In both countries, composites of domestic and foreign intermediate goods are made via the following aggregator:

$$Y_{Ht}(Y_{Ht}^*) = \left(\int_0^1 y_t(i)^{\frac{\theta_I-1}{\theta_I}} di \right)^{\frac{\theta_I}{\theta_I-1}}, \quad Y_{Ft}(Y_{Ft}^*) = \left(\int_0^1 y_t(i^*)^{\frac{\theta_I-1}{\theta_I}} di^* \right)^{\frac{\theta_I}{\theta_I-1}},$$

where $y_t(i)$ ($y_t(i^*)$) is a domestic (foreign) intermediate good i (i^*) on the unit interval $[0, 1]$ and $\theta_I > 1$ is the elasticity of substitution between a variety of intermediate goods. The total demand

for i (i^*) is given by:

$$y_t^{td}(i) = \left(\frac{P_t(i)}{P_{Ht}} \right)^{-\theta_I} Y_{Ht}^w, \quad y_t^{td}(i^*) = \left(\frac{P_t^*(i^*)}{P_{Ft}^*} \right)^{-\theta_I} Y_{Ft}^w,$$

where $P_t(i)$ ($P_t^*(i^*)$) is the price of a domestic (foreign) intermediate good i (i^*) denominated in the producer's currency, $Y_{Ht}^w \equiv Y_{Ht}^d + Y_{Ht}^{d*}$ ($Y_{Ft}^w \equiv Y_{Ft}^d + Y_{Ft}^{d*}$) is the total demand for the composite of domestic (foreign) intermediate goods, and P_{Ht} (P_{Ft}^*) is the price index of the composite of domestic (foreign) intermediate goods:

$$P_{Ht} = \left(\int_0^1 P_t(i)^{1-\theta_I} di \right)^{\frac{1}{1-\theta_I}}, \quad P_{Ft}^* = \left(\int_0^1 P_t^*(i^*)^{1-\theta_I} di^* \right)^{\frac{1}{1-\theta_I}}.$$

Note that Y_{Ht}^d , Y_{Ht}^{d*} , Y_{Ft}^d , and Y_{Ft}^{d*} are given in Eqs. (20) and (26). The technology of intermediate goods is the same across firms i and is given by

$$y_t^s(i) = A_t K_t^\varphi(i) L_t^{1-\varphi}(i),$$

where A_t is the country-specific technology shock and $K_t(i)$ and $L_t(i)$ are the capital and labor demanded by firm i . So the real marginal cost mc_{It} is expressed by:

$$mc_{It} = \varphi^{-\varphi} (1 - \varphi)^{-(1-\varphi)} A_t^{-1} (r_t^k)^\varphi (w_t)^{1-\varphi}. \quad (27)$$

When a firm i has a signal to reset its price $\tilde{P}_t(i)$ with probability $1 - \alpha_I$, its problem is to maximize the following:

$$\mathcal{L}_I(i) = E_t \sum_{s=0}^{\infty} (\alpha_I)^s Q_{t,t+s} Y_{Ht+s}^w P_{Ht+s} \left(\prod_{k=1}^s \frac{\bar{\Pi}^s}{\Pi_{Ht+k}} \right)^{-\theta_I} \left\{ (1 + \tau_I) \left(\frac{\tilde{P}_t(i)}{P_{Ht}} \right)^{1-\theta_I} \left(\frac{\bar{\Pi}^s}{\Pi_{Ht+k}} \right) \right. \\ \left. - mc_{It+s} \left(\frac{\tilde{P}_t(i)}{P_{Ht}} \right)^{-\theta_I} \frac{P_{t+s}}{P_{Ht+s}} \right\},$$

where $\Pi_{Ht} \equiv P_{Ht}/P_{Ht-1}$ is the inflation rate of the price index of the intermediate goods composite and $\tau_I \geq 0$ is the real subsidy. Note that when firms do not re-optimize their prices in period t , they index prices to the long-run CPI inflation rate $\bar{\Pi}$. Then, the first-order condition with respect to $\tilde{P}_t(i)$ implies

$$(1 + \tau_I) \frac{\theta_I - 1}{\theta_I} x_{It}^1 = x_{It}^2, \quad (28)$$

where the recursive forms of x_{It}^1 and x_{It}^2 are as follows:

$$x_{It}^1 = \tilde{p}_{Ht}^{-\theta_I} Y_{Ht}^w + (\alpha_I \beta) E_t \left[\left(\frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{\tilde{p}_{Ht}}{\tilde{p}_{Ht+1}} \right)^{-\theta_I} \Pi_{Ht+1}^{\theta_I} \bar{\Pi}^{1-\theta_I} \Pi_{t+1}^{-1} x_{It+1}^1 \right], \quad (29)$$

$$x_{It}^2 = \tilde{p}_{Ht}^{-\theta_I - 1} Y_{Ht}^w mc_{It} \tilde{p}_{Ht}^{-1} + (\alpha_I \beta) E_t \left[\left(\frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{\tilde{p}_{Ht}}{\tilde{p}_{Ht+1}} \right)^{-\theta_I - 1} \Pi_{Ht+1}^{1+\theta_I} \bar{\Pi}^{-\theta_I} \Pi_{t+1}^{-1} x_{It+1}^2 \right], \quad (30)$$

where $\tilde{p}_{Ht} \equiv \tilde{P}_t(i)/P_{Ht}$ and $p_{Ht} \equiv P_{Ht}/P_t$. The price index of the composite of domestic intermediate goods evolves according to:

$$1 = (1 - \alpha_I) \tilde{p}_{Ht}^{1-\theta_I} + \alpha_I \left(\frac{\bar{\Pi}}{\Pi_{Ht}} \right)^{1-\theta_I}. \quad (31)$$

In addition, from definitions of Π_{Ht} and Π_t , we have the following identity:

$$p_{Ht} = \frac{\Pi_{Ht}}{\Pi_t} p_{Ht-1}. \quad (32)$$

The aggregate demands for capital and labor are given by:

$$K_t^d = \varphi \left(\frac{r_t^k}{mc_{It}} \right)^{-1} \Delta_{It} Y_{Ht}^w, \quad L_t^d = (1 - \varphi) \left(\frac{w_t}{mc_{It}} \right)^{-1} \Delta_{It} Y_{Ht}^w, \quad (33)$$

where $K_t^d \equiv \int_0^1 K_t^d(i) di$, $L_t^d \equiv \int_0^1 L_t^d(i) di$, and $\Delta_{It} \equiv \int_0^1 \left(\frac{P_t(i)}{P_{Ht}} \right)^{-\theta_I} di$ is the measure of the price dispersion of intermediate goods which evolves according to

$$\Delta_{It} = (1 - \alpha_I) \tilde{p}_{Ht}^{-\theta_I} + \alpha_I \left(\frac{\bar{\Pi}}{\Pi_{Ht}} \right)^{-\theta_I} \Delta_{It-1}. \quad (34)$$

For foreign intermediate goods firms, similar equations hold.

2.3 Government and Monetary policy

The government subsidizes suppliers of labor, final goods firms, and intermediate goods firms with real subsidies τ_{wt} , τ_{Ft} , and τ_{It} , and imposes lump-sum taxes τ_t^L . It is assumed that the government budget is balanced at all times: $\tau_{wt} + \tau_{Ft} + \tau_{It} = \tau_t^L$.

In a competitive equilibrium, the monetary policy is designed as an interest-rate feedback rule: for the domestic and foreign monetary authorities,

$$\log(R_t/\bar{R}) = \Theta_\pi \log(\Pi_t/\bar{\Pi}) + \Theta_w \log(\Pi_t^w/\bar{\Pi}^w) + \Theta_Y y_t^g + \Theta_{RS} \log(RS_t/R_{S_{t-1}}) + \epsilon_{mt}, \quad (35)$$

$$\log(R_t^*/\bar{R}^*) = \Theta_\pi \log(\Pi_t^*/\bar{\Pi}^*) + \Theta_w \log(\Pi_t^{w*}/\bar{\Pi}^{w*}) + \Theta_Y y_t^{g*} - \Theta_{RS} \log(RS_t/R_{S_{t-1}}) + \epsilon_{mt}^* \quad (36)$$

where a bar over a variable denotes its target value, i.e. its nonstochastic steady state value, $\Pi_t^w \equiv W_t/W_{t-1}$ is the gross inflation rate of the nominal wage index, y_t^g is the output gap defined as the logarithmic difference between the actual GDP output and its counterpart under the flexible economy, and ϵ_{mt} denotes monetary policy shocks. It is assumed that coefficients in the monetary policy rule are the same across countries. In other words, we consider the international monetary cooperative equilibrium in which both domestic and foreign monetary authorities cooperate to choose a set of coefficients in their policy rules that maximizes the sum of the weighed averages of domestic and foreign individual utilities. Note that when nominal wages are flexible, the coefficient

Θ_w on the inflation rate of the nominal wage index is set to zero.

2.4 Representation of news shocks

We have two types of shocks: technology shocks and monetary policy shocks. Monetary shocks, ϵ_{mt} and ϵ_{mt}^* in the policy rules, are white noise. The processes for technology shocks, A_t and A_t^* , are given as:

$$\log A_t = \rho_a \log A_{t-1} + \rho_a^c \log A_{t-1}^* + \xi_{t-p} + \epsilon_{at}, \quad (37)$$

$$\log A_t^* = \rho_a^c \log A_{t-1} + \rho_a^* \log A_{t-1}^* + \xi_{t-p}^* + \epsilon_{at}^* \quad (38)$$

where ρ_a^c reflects technology spillover, $p \geq 1$ is called the length of news shocks, and ϵ_{mt} , ϵ_{mt}^* , ϵ_{at} , ϵ_{at}^* , ξ_t , and ξ_t^* are uncorrelated over time and with each other. This representation embodies news about the future technology level. For instance, $p = 1$ means that part of a technology shock is known one period in advance. That is, the technology level of $\log A_t$ at period t depends on the realized value of ξ_{t-1} at period $t - 1$ so that in period $t - 1$, the expectation of the period t technology level depends on news about the technology known at time $t - 1$, i.e. ξ_{t-1} . When evaluating different monetary policies, we consider three lengths of news shocks, i.e. $p = 4, 8,$ and 12 . Our approach is motivated by the empirical finding in Beaudry and Portier (2006) that it takes several years for news about future technology to have its eventual impact on the productivity level. Note that since the time unit of our model is one quarter, these values of p correspond to one, two, and three years, respectively.

3 Welfare measure and cost

Our policy evaluation is based on welfare. We measure the weighted average of individual lifetime utilities that is associated with a set of policy parameters in the monetary policy rule, i.e. a policy regime. In period 0, the weighted average of individual lifetime utilities is expressed as

$$V_0 \equiv E_0 \sum_{t=0}^{\infty} \beta^t \left[U(C_t - bC_{t-1}) - \int_0^1 V(L_t(h)) dh \right] = E_0 \sum_{t=0}^{\infty} \beta^t \left[U(C_t - bC_{t-1}) - V(\Delta_{wt} L_t^d) \right], \quad (39)$$

where

$$\int_0^1 V(L_t(h)) dh = \left(\int_0^1 \left(\frac{w_t(h)}{w_t} \right)^{-\theta_w(1+\eta)} dh \right) \frac{L_t^{d1+\eta}}{1+\eta} = \frac{(\Delta_{wt} L_t^d)^{1+\eta}}{1+\eta},$$

and Δ_{wt} is the measure of the wage dispersion defined in Section 2.1. That is, V_0 is the conditional expectation of the weighted average of individual lifetime utilities.¹⁴ It is assumed that in period 0, the economy is in the nonstochastic steady state.¹⁵ Therefore, we find the value of V_0 conditional

¹⁴Under flexible nominal wages, the weighted average of individual lifetime utilities is equal to the lifetime utility of the representative household.

¹⁵We consider the symmetric nonstochastic steady state in which the long-run CPI inflation rate is equal to a non-zero value, $\bar{\Pi}$.

on the initial state being the nonstochastic steady state. Since the steady state is the same across all policy regimes we consider, the first-order approximation to V_0 is always equal to its steady state value. So in order to study the effect of news shocks on the welfare level under a particular policy regime, we need the second-order accurate approximation to V_0 . The recursive form for this conditional welfare measure in period t is

$$V_t = U(C_t - bC_{t-1}) - V(\Delta_{wt}L_t^d) + \beta E_t[V_{t+1}],$$

so the second-order accurate approximation to V_t can be obtained by putting this form into the system of equilibrium equations and calculating the second-order approximation of the solution to the system around the nonstochastic steady state.¹⁶ Based on this conditional welfare measure, we find the optimal cooperative monetary policy rule that maximizes the sum of domestic and foreign conditional welfare levels, so the optimal monetary policy is defined as the set of values of coefficients in the monetary policy rule, $(\Theta_\pi, \Theta_w, \Theta_Y, \Theta_{RS})$, that maximizes

$$V_t^W \equiv V_t + V_t^*.$$

We also compute the welfare cost of a particular monetary regime relative to a reference regime. The welfare cost of a particular monetary regime is defined as the fraction of the consumption process under a reference regime that households would be willing to give up to be equally well off under a particular regime as they are under the reference regime. Let the reference policy regime be denoted by *opt* and an alternative policy regime by *a*. The welfare levels associated with policy regimes *opt* and *a* are defined as:

$$V_0^{opt} \equiv E_0 \sum_{t=0}^{\infty} \beta^t \left[U(C_t^{opt} - bC_{t-1}^{opt}) - V(\Delta_{wt}^{opt}L_t^{d,opt}) \right],$$

$$V_0^a \equiv E_0 \sum_{t=0}^{\infty} \beta^t \left[U(C_t^a - bC_{t-1}^a) - V(\Delta_{wt}^aL_t^{d,a}) \right],$$

where $\{C_t^k, \Delta_{wt}^k, L_t^k\}$ denotes the equilibrium process under regime $k = opt, a$. Thus, let us define

¹⁶Regarding the calculation of the second-order accurate approximation to the solution of the system, we do not use the package of computer codes provided by Schmitt-Grohé and Uribe (2004). For the purpose of our search for the optimal policy rule, it is not possible to calculate the second-order approximation to a large system like our model by using their package. This is because for a second-order approximation, their algorithm suffers from the curse of dimensionality, i.e. problems with a large number of state variables. For instance, when we study the effect of news shocks with $p = 12$, 12 auxiliary state variables must be added to implement their package. Instead, we use Dynare, which adopts the Anderson-Moore algorithm as in Levin et al. (2005). Note that in order to calculate the output gap, another set of equilibrium equations under the flexible economy must be added to the system of equations under the competitive equilibrium with nominal rigidities.

the welfare cost λ^c as follows:

$$\begin{aligned} V_0^a &= U\left((1-\lambda^c)C_0^{opt} - bC_{-1}^{opt}\right) - V\left(\Delta_{w0}^{opt}L_0^{d,opt}\right) + E_0 \sum_{t=1}^{\infty} \beta^t \left[\begin{array}{c} U\left((1-\lambda^c)\left(C_t^{opt} - bC_{t-1}^{opt}\right)\right) \\ -V\left(\Delta_{wt}^{opt}L_t^{d,opt}\right) \end{array} \right] \\ &= \log\left((1-\lambda^c)C_0^{opt} - bC_{-1}^{opt}\right) + \frac{\beta}{1-\beta} \log(1-\lambda^c) - \log\left(C_0^{opt} - bC_{-1}^{opt}\right) + V_0^{opt}, \end{aligned}$$

which we rewrite as¹⁷

$$V_0^a - V_0^{opt} = \log\left((1-\lambda^c)C_0^{opt} - bC_{-1}^{opt}\right) + \frac{\beta}{1-\beta} \log(1-\lambda^c) - \log\left(C_0^{opt} - bC_{-1}^{opt}\right) + V_0^{opt}.$$

Following Schmitt-Grohé and Uribe (2004 and 2006b), the second-order approximation to the welfare cost λ^c is expressed by the percentage:

$$\lambda^c = \left(-\frac{g_{\sigma\sigma}^{v,a}(x,0) - g_{\sigma\sigma}^{v,opt}(x,0)}{\frac{1}{1-b} + \frac{\beta}{1-\beta}} \frac{1}{2} \right) \times 100, \quad (40)$$

where for each regime $k = a, opt$, $g_{\sigma\sigma}^{v,k}(x,0)$ is the second derivative of the solution of the conditional welfare with respect to σ evaluated at the nonstochastic steady state. Note that σ is a parameter scaling the standard deviation of the exogenous shocks and x is the steady state value of the vector of state variables.¹⁸

4 Dynamics under a simple rule

In this section, we analyze the equilibrium response of aggregate variables of interest to positive contemporaneous and news shocks under a simple inflation-targeting policy rule in order to develop our intuition for the dynamics of the economy under the optimal policy rule which we will find in the next section. More importantly, this analysis helps us understand how a change in expectations of future fundamentals caused by news about a future technology improvement affects the nominal exchange rate as an asset price and consequently determines the instantaneous responses of the real exchange rate and the terms-of-trade to such a news shock. To avoid some difficulties in forming this intuition, we first consider the sticky price economy before turning our attention to the economy with sticky prices and wages. Before conducting such an exercise, we calibrate our model by choosing the time unit of our model to be one quarter, and we assume that the nominal interest rate responds only to the deviation of the CPI inflation rate from its target value with a coefficient of 1.5.

The calibrated parameter values are listed in Table 1. The discount factor takes the value of 4 percent per annum. Following Altig et al. (2005) and Christiano et al. (2005), the degree of habit formation measured by b is set at 0.69 and the value of η is set to one, implying a unit Frisch

¹⁷Our baseline calibration uses logarithmic utility in consumption.

¹⁸Refer to the technical appendix for details.

elasticity of labor supply. The share of capital in value added is 36 percent. The depreciation rate of capital is set at 10 percent per year. The investment adjustment cost parameter κ is set to 2.79. The elasticity of substitution between varieties of goods in both the final and intermediate goods sectors is set to 6, implying a markup of 20 percent. The elasticity of substitution between differentiated labor is 21, implying a markup of 5 percent. The values of real subsidies are set such that they offset the distortions caused by monopolistic power in the labor and goods markets, so the allocation under the flexible economy is the first-best one. As in Wang (2007), we set ψ , the elasticity of substitution between composites of domestic and foreign intermediate goods, to 1.1 and ω , the value of home bias, to 0.85. The degrees of price stickiness for final and intermediate goods are set to 0.75 and 0.5, respectively. These values reflect the fact that prices of finished goods are less flexible than prices of intermediate goods. The degree of wage stickiness is set at 0.6, slightly lower than estimates in the literature. However, this choice of value is still consistent with the fact that wages are less flexible than prices of intermediate goods produced by labor and capital in our model. As in Schmitt-Grohé and Uribe (2006b), we assume that the inflation rate at the nonstochastic steady state is 4.2 percent per annum, the average growth rate of the U.S. GDP deflator between 1960 and 1998. For the technology shock process, we set ρ_a and ρ_a^* at 0.89 and ρ_a^c at 0.02. We will consider alternative values of the home bias, the elasticity of substitution between composites of intermediate goods, the degree of price stickiness in the intermediate goods sector, and the degree of wage stickiness in the next section.

4.1 Economy with sticky prices

Figures 1-1 and 1-2 show the response of aggregate variables of interest to positive contemporaneous and news shocks, respectively.¹⁹ In Figure 1-1, we show that the responses of aggregate variables to a contemporaneous shock qualitatively tracks their responses under the flexible economy well. So in the presence of contemporaneous shocks only, a strict CPI-inflation-targeting policy alone can be optimal as it eliminate price dispersion. Before proceeding to the response of aggregate variables to a news shock, it is worth explaining the instantaneous responses of the real exchange rate and the terms-of-trade to a contemporaneous shock: on impact, they both increase. Due to the immediate technology improvement in the intermediate goods sector of the home country, new prices set by intermediate goods firms that have the chance to re-optimize their prices fall and the terms-of-trade deteriorates. Because production in the final goods sector is biased toward domestic intermediate goods, the composite of consumption goods in the home country is also cheap relative to the corresponding composite in the foreign country, so the CPI-based real exchange rate depreciates. In addition, the movement of the nominal exchange rate contributes to the instantaneous movements of the real exchange rate and the terms-of-trade under sticky prices. The inflation-targeting monetary authority cuts the nominal interest rate in the current period,

¹⁹In the legend of our figures, FLEX represents the flexible economy, SPH the sticky price economy with habit formation, and SWH the economy with sticky wages and prices and habit formation. A vector next to either SPH or SWH indicates a set of coefficients in the monetary policy rule.

as the CPI inflation rate has decreased. In the asset market equilibrium, *ceteris paribus*, this cut makes the home country currency depreciate immediately.²⁰ On impact, the nominal exchange rate depreciation contributes to depreciation of the real exchange rate and deterioration of the terms-of-trade.

Figure 1-2 shows the response of the economy to a positive news shock. It is assumed that such a news shock is known 4 periods in advance (i.e. as of period 1, it is expected that the technology level will be higher in period 5 than without such a news shock). In response to a positive news shock, output, consumption, and investment all rise and decline gradually. Employment and real wages also rise until period 4, just before a news shock known in period 1 is actually realized, and then drop sharply in period 5. Except for the real wage, their responses are qualitatively similar to those under the flexible economy. The terms-of-trade (i.e. the relative prices of traded goods) also track its response under the flexible prices well. Furthermore, it appears not to respond to a news shock immediately.²¹ However, while the real exchange rate under the flexible economy does not respond to a news shock until period 4 and jumps in period 5, it moves up immediately and exhibits hump-shaped dynamics under sticky prices. Thus, there is a noticeable difference in the dynamics of the real exchange rate in response to a news shock between the flexible and sticky price economies. With sticky prices, the short-run response of the real exchange rate to a news shock reduces the welfare level. It is well-known that when monetary policy takes a strong stance against inflation, aggregate fluctuations in response to contemporaneous shocks are close to those in the efficient allocation, as in Figure 1-1. However, it is not obvious that a strict inflation-targeting policy alone makes the response of the economy to news shocks under sticky prices close to the one in the efficient allocation, particularly if there is a qualitatively significant difference in the dynamics of the real exchange rate. In this sense, real exchange rate stabilization can improve welfare by dampening real exchange rate fluctuations in the presence of news shocks, but on the other hand, it could respond inefficiently to contemporaneous shocks to create a welfare loss. When prices of traded intermediate goods are less sticky, the short-run misalignment of the terms-of-trade due to news shocks is not as severe as in Figure 1-2, so the welfare benefit from real exchange rate stabilization for correcting such a misalignment may not be large. However, there is still the welfare loss from real exchange rate stabilization obstructing the terms-of-trade adjustment to contemporaneous shocks. These conjectures call for the welfare-based evaluation of real exchange rate stabilization in the presence of both contemporaneous and news shocks.

It is worth discussing the shape of the dynamics of each variable in response to a news shock in Figure 1-2. Investment exhibits hump-shaped dynamics. Intuitively, the strategy of cutting investment now and raising it in the future when the technology is high is inefficient because it entails heavy investment adjustment costs in the future. So in both the flexible economy and

²⁰Our model implies that the uncovered interest parity (UIP) condition holds.

²¹This observation seems to be against the argument that the terms-of-trade is misaligned by the short-run movement of the nominal exchange rate due to news about future economic conditions. However, that is because prices of intermediate goods are less sticky and thus they are more likely to adjust to news shocks immediately. The instantaneous response of the terms-of-trade will be discussed below.

the sticky price economy, the gradual increase in investment is efficient during periods before the technology improvement is actually realized. The dynamics of consumption and output in response to a news shock are also hump-shaped, but under the flexible economy, their hump-shaped dynamics depend on the inclusion of habit formation in consumption.²² In the case of habit formation, the efficient response of consumption under the flexible economy is that when a higher technology level is expected and consumption is also expected to increase in the future, the dependence of consumption on its own past level smooths the higher consumption in the future during the periods before the higher level of technology is actually realized. Otherwise, consumption is unlikely to rise until the technology improvement is actually realized. With sticky prices, however, the hump-shaped dynamics of consumption and investment in response to a news shock are invariant to the exclusion of habit formation, which is in contrast to their responses to a contemporaneous shock. Note that as in Figure 1-1, under the economy with nominal rigidities, the hump-shaped dynamics of consumption and output in response to a contemporaneous shock result from habit formation. Most importantly, the real exchange rate exhibits its hump-shaped dynamics in response to a news shock, which is invariant to the inclusion of habit formation. In theoretical models in the open economy literature, it is known that it is difficult to generate the hump-shaped dynamics of the real exchange rate in response to (contemporaneous) shocks, but its estimated impulse response function from the data is hump-shaped. Thus, news shocks can reconcile the dynamics of the real exchange rate in theoretical models with its observed dynamics in the data.²³

Now, we analyze the instantaneous impact of a positive news shock on the real exchange rate and terms-of-trade in light of the nominal exchange rate movement by changes in expectations of future fundamentals. In Figure 1-2, even when the nominal interest rate goes up on impact of a new shock, the real exchange rate depreciates immediately, implying that with sticky prices of consumption goods in the local currency, the home country currency depreciates. This seems to be at odds with the increase in the nominal interest rate of the home country when the nominal exchange rate rises. However, this is consistent with the view of the nominal exchange rate as an asset price. On impact of a positive news shock, the market expects that the inflation-targeting monetary authority of the home country will cut its nominal interest rate in the near future, as in Figure 1-1 (i.e. its response to a positive contemporaneous shock). This is equivalent to a bad news shock for the home country currency and its effect on the nominal exchange rate dominates the effect of the increase in the home country's nominal interest rate in the current period. So

²²To save space, the impulse response functions under no habit formation are not provided. They are available on request.

²³Steinsson (2007) addresses this issue to understand the persistence of the real exchange rate. His empirical work shows that the estimated impulse response function of the real exchange rate from an univariate AR modeling is hump-shaped. Based on the high correlation between the nominal and real exchange rates, it is reasonable to agree that the driving force of their fluctuations is the same. In addition, most of the variability of nominal exchange rates is attributed to non-contemporaneous movements in fundamentals (see Devereux and Engel (2006a)). Thus, the driving force of real exchange rate fluctuations can be news shocks such as those identified by Beaudry and Portier (2006). Hence, as in our model, sticky price models can easily generate the hump-shaped dynamics of the real exchange rate when news shocks are incorporated. However, it is not obvious that news shocks generate the observed volatility of the real exchange rate. This is an area for future research.

both the nominal and real exchange rates will depreciate immediately in response to such a news shock on the technology level. This is illustrated in the first two rows of Figure 1-3, which show the dynamics of the interest rate, inflation rate, real exchange rate, and terms-of-trade in response to a positive news shock for all shock lengths. On impact, the real exchange rate can move either up or down depending on the magnitude of the effect of the news shock on the nominal exchange rate. For all lengths of news shocks we consider, the nominal interest rate increases on impact, which contributes to the appreciation of the nominal exchange rate and consequently leads to the appreciation of the real exchange rate as well. For instance, the increase in the nominal interest rate for $p = 8$ is much greater than for $p = 12$, implying that the nominal exchange rate appreciates more for $p = 8$. So it is natural that with sticky prices of consumption goods, the real exchange rate appreciates much more when $p = 8$ than when $p = 12$. In the second row of Figure 1-3, however, we see that the real exchange rate appreciates more for $p = 12$ than for $p = 8$. This is because the nominal exchange rate determination is the discounted expected present value of the current and future fundamentals. For both $p = 8$ and $p = 12$, the expectation of the interest rate cut in the future contributes to the depreciation of the nominal exchange rate immediately, but because in the case of $p = 12$ the cut will occur further in the future than if $p = 8$, its effect for $p = 12$ is discounted more and thus has less impact on the exchange rate determination. Even in the case that there is less increase in the nominal interest rate (i.e. $p = 12$) in the current period, the nominal exchange rate will appreciate more due to the small magnitude of the impact of a (bad) news shock on it.²⁴ In this sense, when real exchange rate stabilization is evaluated in the presence of news shocks, it is reasonable to consider several potential lengths.²⁵

The instantaneous impact of a positive news shock on the terms-of-trade is shown in the last two rows of Figure 1-3. From our calibrated values of the degrees of price stickiness, prices of intermediate goods can adjust to a news shock more quickly than prices of final goods. Thus, the instantaneous response of the terms-of-trade seems not to be dominated by the nominal exchange rate movement due to news shocks. The second row of Figure 1-3 shows the responses under our baseline calibration. In this case, there is the depreciation of the real exchange rate for $p = 4$, which

²⁴Our explanation is simplified because the nominal exchange rate determination is also affected by changes in expectations of the nominal interest rate during periods before a news shock is realized.

²⁵In Corsetti et al. (2006), their empirical work shows heterogeneity in the short-run response to the productivity gain in the manufacturing sector. They find that among the G7 countries they consider, there is a short-run appreciation of the real exchange rate in the US and Japan and a depreciation in the UK and Italy. They rely on the Balass-Samuelson hypothesis and incomplete asset markets to explain their empirical findings. However, even under the complete asset market assumption in our model, our study of the short-run responses of the real exchange rate and the terms-of-trade in response to a positive news shock in total factor productivity suggests several possibilities for their signs and short-run movements on impact. Note that TFP in our model represents productivity shocks in the traded goods sector. Corsetti et al. cast doubt on the ability of standard general equilibrium open-economy models to explain episodes such as the strong (real) US dollar and the US terms-of-trade appreciation in the second half of the 1990s, which accompanied the productivity boom in the US. That episode is also motivation for the expectations-driven real business cycle literature. Our discussion of the terms-of-trade movement shows that it can appreciate along with the appreciation of the real exchange rate. In this sense, the news shocks identified by Beaudry and Portier (2006) (is) are emphasized once again, and the nominal exchange rate movement in response to changes in expectations of future fundamentals is a promising explanation for understanding the relative prices of goods across countries. News shocks may be the key element in understanding the observed dynamics of aggregate variables. This is an area for future research.

results from the nominal exchange rate depreciation explained above. On impact, however, the terms-of-trade does not move. For this to happen, prices of intermediate goods made domestically must be higher than prices of those made in the foreign country to offset the depreciation of the nominal exchange rate. On impact of a positive news shock, many monopolistic intermediate firms re-optimize their prices by maximizing their discounted expected present value of profits subject to the demand schedule for their goods. Loosely speaking, new prices set by firms are equal to the markup over the discounted expected present value of marginal costs. Given news that the technology level will be high in period 5, marginal cost is expected to be low in period 5. However, it is also expected that the real wage will be rising until period 4, as is shown in Figure 1-2.²⁶ In the last row of Figure 1-3, where the degree of price stickiness of intermediate goods is equal to that of final goods (i.e. $\alpha_I = \alpha_F = 0.75$), we see that the instantaneous response of the terms-of-trade to a news shock is almost the same as that of the real exchange rate. Here, they are both determined by the movement of the nominal exchange rate which reflects the change in expectations of the future. Note that in the last row of Figure 1-3, where $p = 12$, there is appreciation of the real exchange rate and improvement in the terms-of-trade for more than one year and two years, respectively. In sum, the instantaneous responses of the real exchange rate and the terms-of-trade to a news shock can be different in the sticky price economy, which is in contrast to their responses to a contemporaneous shock. As expected, the short-run misalignment of the terms-of-trade caused by the nominal exchange rate fluctuations due to news shocks is more severe when prices of traded goods are slower to adjust to news shocks. So the optimal sticky price set by intermediate goods firms increases immediately and the relative price of home country intermediate goods also increases in terms of the producer's currency. Consequently, the terms-of-trade does not move immediately while the real exchange rate depreciates.

4.2 Economy with sticky wages and prices

We turn our attention to the dynamics of the economy with sticky wages and its implications for monetary policy. Figure 1-1 also shows the dynamics of the economy with sticky wages in response to a positive contemporaneous shock. Under a simple inflation-targeting rule, it tracks the flexible economy well. Figure 1-2 shows the dynamics of the economy in response to a positive news shock with length 4. Compared with the dynamics of the sticky price economy (i.e. nominal wages are flexible), output, consumption, investment, employment, the real exchange rate, and the terms-of-trade respond to such a news shock more strongly than they do under the sticky price economy. More importantly, there is a noticeable difference in the dynamics of the real wage: in response to a news shock, the real wage rises and falls very slowly over time and its dynamics is not as volatile under flexible wages because nominal wages cannot adjust quickly to a news shock. With sticky nominal wages, a rise in the real wage requires that the inflation rate drift down, so an inflation-targeting monetary authority of the type we consider in this section would cut the nominal interest

²⁶When prices of final consumption goods are sticky and nominal wages are flexible, a rise in the real wage implies a rise in the nominal wage.

rate. This cut makes the expansion of the economy bigger than it would be under the sticky price economy and much bigger than under the flexible economy: the responses of output, consumption, investment, and employment are amplified by the inflation-targeting policy under sticky wages and prices, which we see more clearly when considering news shocks of length 12.²⁷

Based on the theoretical background on the optimal monetary policy in the presence of sticky wages and contemporaneous shocks only (e.g. Erceg et al. (2000)), an inflation-targeting policy alone is not optimal in the sense that it cannot achieve the Pareto optimal allocation and therefore cannot maximize social welfare. Our study of the dynamics of the economy with sticky wages implies that the inflation-targeting policy is not optimal because it reduces welfare by making the impact of a positive news shock more expansionary. With sticky wages, the optimal monetary policy in the presence of news shocks must be one which prevents the impact of news shocks from being amplified. When a monetary policy rule that responds to both the CPI inflation rate and the inflation rate of the nominal wage index is considered, we must question whether the welfare loss from the interaction between sticky wages and the inflation-targeting policy in the presence of news shocks is prevented by such a specification of the monetary policy rule and whether the optimal policy rule requires an additional specification such as output gap stabilization or real exchange rate stabilization. These questions cannot be answered by studying the dynamics of aggregate variables in response to shocks. Nevertheless, with sticky wages, it is obvious that a strict inflation-targeting policy alone amplifies the impact of news shocks, reducing welfare.

In Figure 1-2, we show that the instantaneous response of the terms-of-trade to a news shock under sticky wages, where it deteriorates immediately, is different than the response under the sticky price economy. This is because new prices set by intermediate goods firms are distorted by the change in expectations of inefficient future real wages. When firms have the chance to re-optimize their prices, they expect a lower real wage in the near future than they would under the sticky price economy where nominal wages are flexible, so their new prices, which represent the discounted expected present value of marginal costs, drop immediately. Consequently, the terms-of-trade moves up on impact of a positive news shock. Such a short-run misalignment of the relative prices of traded intermediate goods results from the inefficient response of factor prices when they are more easily adjustable.²⁸

5 Welfare-based monetary policy evaluation

In this section, we find the optimal cooperative monetary policy rule. To do this, we adopt a grid search method over the range of each parameter in the policy rule and follow two requirements for

²⁷To save space, the figure is not provided in this paper. It is available upon request.

²⁸When prices of intermediate goods are stickier, there are fewer firms that have the chance to re-optimize their prices, so in any given period the instantaneous movement of the terms-of-trade is less likely to be distorted by the change in expectations of inefficient future marginal costs. With stickier prices, however, the terms-of-trade is more likely to be misaligned by the nominal exchange rate movement caused by the change in expectations of future fundamentals.

a rule to be operational as suggested in the literature (e.g. Schmitt-Grohé and Uribe (2006)).²⁹ For a policy rule to be operational, it must induce a locally unique rational expectations equilibrium and satisfy the zero-bound constraint on the nominal interest rate. The second-order perturbation approach we use in our numerical work is ill-equipped to deal with binding constraints, so we instead require that the target value of the nominal interest rate be greater than or equal to twice the standard deviation of the nominal interest rate, i.e. $\log \bar{R} \geq 2\sigma_{\hat{R}_t}$. This guarantees that the (logarithmic) nominal interest rate will be positive 98 percent of the time if the equilibrium nominal interest rate is normally distributed around its target value.³⁰

5.1 Optimal monetary policy rule

The results on the optimal monetary policy rule are provided in this section. As in the previous section, we first discuss the optimal policy rule under the sticky price economy and then consider an economy with sticky wages and prices. Moreover, in each economy, the optimal policy rule is found for three lengths of news shocks, i.e. $p = 4, 8,$ and $12,$ as well as the case with only contemporaneous shocks, where $p = 0.$

Table 2-1 provides the optimal policy rule in our baseline model with sticky prices only, where the home bias parameter ω is equal to 0.85. In the first row, we see that in the absence of news shocks (i.e. $p = 0$), the optimal policy rule takes a strong stance against both the CPI inflation rate and the output gap, but it does not require that the real exchange rate be stabilized. In this case, there is a trade-off between real exchange rate stabilization for allocating goods efficiently across countries and the flexibility of the nominal exchange rate that facilitates the terms-of-trade adjustment. With home bias, however, the baskets of consumption goods are not identical across countries, so the consumption-based real exchange rate in the efficient allocation (i.e. under the flexible economy) is not constant and real exchange rate fluctuations do not necessarily allocate goods inefficiently across countries. In the presence of contemporaneous shocks only, real exchange rate stabilization obstructs the terms-of-trade adjustment and may prevent the real exchange rate from fluctuating as much as it does in the flexible economy.

In the rest of rows in Table 2-1 (i.e. $p = 4, 8, 12$ in the case of $\omega = 0.85$), we see that the optimal policy rule requires real exchange rate stabilization in the presence of both contemporaneous and news shocks. Based on the interaction between sticky prices of final and intermediate goods and the dual role of the nominal exchange rate under the sticky price economy, news shocks can misalign both the real exchange rate and the terms-of-trade. As shown in the previous section, since prices of intermediate goods are not as sticky as prices of final goods, the misalignment of the terms-of-trade

²⁹Basically, the range of coefficients on deviations of the CPI inflation rate and the inflation rate of the nominal wage index from their target values, Θ_π and Θ_w , is $[0, 3]$ with a step size of 0.2. The range of the coefficient on the GDP output gap, Θ_Y , is $[0, 3]$ with a step size of 0.2, and the range of the coefficient on the real exchange rate depreciation from the past period, Θ_{RS} , is $[0, 0.3]$ with a step size of 0.02. For computational purposes, the step size of each range is a little large and the ranges of Θ_Y and Θ_{RS} under sticky wages are reduced to $[0, 2]$ and $[0, 0.2]$, respectively, which we think is innocuous for the purpose of finding the optimal policy rule.

³⁰We also consider the alternative requirement that the second-order accurate approximation for the unconditional mean of the nominal interest rate be greater than or equal to twice its standard deviation, i.e. $E[\log R_t] \geq 2\sigma_{\hat{R}_t}.$

is not severe. Thus, the welfare benefit of real exchange rate stabilization results from correcting the misalignment of the real exchange rate caused by news shocks. However, the welfare gain from real exchange rate under the optimal rule is small. For instance, when $p = 12$, its welfare gain is 0.0028 % of the consumption process under the policy rule without real exchange rate stabilization (i.e. $(\Theta_\pi, \Theta_Y, \Theta_{RS}) = (3, 3, 0)$), but the welfare gain from inflation-targeting under the optimal rule is 0.2107 % of consumption relative to the policy with $(\Theta_\pi, \Theta_Y, \Theta_{RS}) = (1.1, 3, 0.3)$, which is shown in Table 2-2. Nevertheless, when the monetary policy rule takes a weak stance against the inflation rate, the welfare gain from real exchange rate stabilization increases. In Table 2-2, we set the coefficient on the CPI inflation at 1.1 and the coefficient on the output gap at 3 and then, we calculate its welfare gain relative to the policy rule setting Θ_{RS} at zero by increasing Θ_{RS} from 0.05 to 0.3 with a step size of 0.05. We see that when the coefficient on the real exchange rate takes on its highest value, 0.3, the welfare gain from real exchange rate is now 0.0524 % of the consumption process under the rule without real exchange rate stabilization.³¹

Figures 2-1 and 2-2 show the dynamics of aggregate variables in response to positive contemporaneous and news shocks when $p = 12$ under the optimal policy rule, the policy rule that sets the coefficient on the real exchange rate depreciation to zero [Simple 1], and the strict inflation-targeting rule with the coefficient on the CPI inflation set to 3 [Simple 2], and the flexible economy. Under the optimal policy rule, while real exchange rate stabilization responds inefficiently to a contemporaneous shock by obstructing the movement of both the terms-of-trade and the real exchange rate, it makes the dynamics of the real exchange rate in response to a news shock close to the corresponding response under the flexible economy. This implies that the welfare gain from correcting the misalignment of the real exchange rate dominates the welfare loss from obstructing the responses of the terms-of-trade and the real exchange rate to a contemporaneous shock. In addition, it is worth discussing the effects of output gap stabilization and the strict inflation-targeting rule posited above. In Figures 2-1 and 2-2, we see that the strict inflation-targeting policy rule [Simple 2] alone seems not to respond to a news shock efficiently, while output gap stabilization appears to be more important in the presence of news shocks than without them. This is inconsistent with the conventional view on strict inflation-targeting policies and the need for output gap stabilization: when price dispersion is the only distortion in the economy, a strict inflation-targeting policy can achieve the maximum welfare level, so there is no need to stabilize the output gap to eliminate the price dispersion.³² Finally, in Table 2-1 where the value of the home bias parameter increases from 0.85 to 0.95, we see that as home bias gets higher and news shocks are further into the future, there is more welfare gain from real exchange rate stabilization.

We now consider the optimal policy rule in the economy with sticky wages and prices. Table 3-1

³¹In the search for the optimal policy rule, we set the upper bound of the range of the CPI inflation rate at 3. So one might guess that under a strict inflation-targeting policy with its value larger than 3, there is no need for real exchange rate stabilization in the presence of news shocks. When the range of Θ_π is extended to $[0, 6]$ and the coefficient on the output gap is fixed at 3, we find the optimal rule in the model with home bias, $\omega = 0.85$; in this case, the coefficient on the real exchange under the optimal rule takes on 0.08, 0.18, and 0.24 for $p = 4, 8,$ and $12,$ respectively. Note that the coefficient of 0.08 for $p = 4$ is the same as when the range of Θ_π is equal to $[0, 6]$.

³²We will discuss the need for output gap stabilization more in the economy with sticky wages below.

shows the optimal policy rule for two cases of the degree of wage stickiness: $\alpha_w = 0.6$ as our baseline calibrated value and $\alpha_w = 0.8$. First, when compared against the optimal rule in the absence of news shocks (i.e. $p = 0$), the optimal policy rule in the presence of news shocks takes a weak stance against the CPI inflation rate. As shown in the previous section, a rise in the real wage in response to a positive news shock requires that the inflation rate must drift down if nominal wages are sticky, so an inflation-targeting policy makes the impact of such a news shock more expansionary by cutting the interest rate. Hence, a strong stance against the inflation rate cannot be optimal. Second, the optimal policy rule does not require real exchange rate stabilization even in the presence of news shocks, which stands in contrast to the optimal rule in the sticky price economy. Note that in the case of $\alpha_w = 0.8$, the optimal rule puts a positive weight on the depreciation of the real exchange rate, but the resulting welfare gain is very trivial. This is because in the economy with sticky wages the output gap movement is more informative about the impact of news shocks than the real exchange rate movement, so output gap stabilization dominates the role of real exchange rate stabilization in targeting news shocks. However, this does not mean that real exchange rate stabilization is no longer a legitimate goal of monetary policy in the presence of news shocks, which is discussed below.

For the high degree of wage stickiness (i.e. $\alpha_w = 0.8$), Figures 3-1 and 3-2 show the dynamics of the economy in response to positive contemporaneous and news shocks, respectively, under the optimal policy rule, the policy rule with the coefficient on the real exchange rate depreciation equal to zero [Simple 1], and the strict inflation-targeting rule with the same values of the coefficients on the CPI inflation rate and the inflation rate of the nominal wage index as under the optimal rule in the absence of news shocks and without output gap stabilization [Simple 2]. First, the responses of aggregate variables to a contemporaneous shock are nearly identical under the three rules we consider. Second, without output gap stabilization and real exchange rate stabilization, a strict inflation-targeting policy, even with a strong stance against the inflation rate of the nominal wage index (i.e. Simple 2), responds inefficiently to news shocks. This implies that either output gap stabilization or real exchange rate stabilization is needed to prevent the impact of news shocks on the economy from being amplified by the inflation-targeting policy. In Table 3-2, we provide the welfare gain from real exchange rate stabilization and output gap stabilization relative to the policy regime, [Simple 2]. We see that they both improve welfare, but the welfare gain from output gap stabilization is much larger than from real exchange rate stabilization. In Table 3-3, we also provide the percentage change in the standard deviation of aggregate variables of interest under real exchange rate stabilization (output gap stabilization) relative to [Simple 2]. Note that the minus sign indicates the volatility gain. Compared with their roles in reducing volatilities of the CPI inflation rate, output, consumption, investment, employment, the nominal interest rate, and the real exchange rate in the absence of news shocks, both real exchange rate stabilization and output gap stabilization contribute enormously to the stability of the economy. In sum, both real exchange rate stabilization and output gap stabilization improve welfare and contribute to the stability of the economy when the monetary policy authority takes a moderately strong stance

against inflation. However, it is difficult to stabilize the output gap in practice (see McCallum 2001), so our specification of real exchange rate stabilization is more operational than output gap stabilization. Thus, real exchange rate stabilization is still a legitimate goal of monetary policy in the presence of news shocks.

5.2 Robustness³³

Without habit formation in consumption, consumption and output under the flexible economy do not exhibit hump-shaped dynamics in response to a positive news shock. This implies that under the sticky price economy, the role of output gap stabilization could be of more significance without habit formation than with habit formation. Consequently, there may be no need for real exchange rate stabilization in the optimal policy rule if there is no habit formation. Our results on the optimal policy rule, however, are robust to the exclusion of habit formation: the coefficient on the real exchange rate depreciation in the optimal rule takes on the highest value of its range in the presence of news shocks and is zero in the absence of news shocks. The exclusion of habit formation also does not change our results on the optimal policy rule in the economy with sticky wages and prices. We also perform robustness analysis on the value of the elasticity of substitution between composites of domestic and foreign intermediate goods by considering alternative values: $\psi = 0.5$ and 2. We see that as ψ gets smaller, the response of the terms-of-trade gets increasingly volatile. The results on the optimal rule are invariant to these alternatives under sticky prices. As expected, there is more welfare gain from real exchange rate stabilization for $\psi = 0.5$ than for its baseline calibrated value, $\psi = 1.1$; while there is less welfare gain for $\psi = 2$, the coefficient on the real exchange rate depreciation takes on its highest value in the optimal policy rule.

6 Conclusion

This paper has provided a comprehensive monetary policy evaluation and studied the dynamics of the economy in the presence of news shocks about the future technology level. Our focus was on real exchange rate stabilization as a legitimate goal of monetary policy and on the dynamics of relative prices across countries, with our analysis based on the interaction between sticky prices of goods and the dual role of the nominal exchange rate when news about future economic conditions leads to changes in expectations of future economic fundamentals. While real exchange rate stabilization is needed to target news shocks in the sticky price economy, its role in eliminating the impact of news shocks is dominated by strong output gap stabilization under an optimal monetary policy in the economy with sticky wages and prices. However, as long as there is an issue of operationality with output gap stabilization in practice, real exchange rate stabilization can be viewed as a legitimate goal of monetary policy even in an economy with sticky wages. Furthermore, once we recognize that the nominal exchange rate moves primarily in response to changes in expectations of the future

³³To save space, the results of our robustness analysis are not provided. They are available upon request.

caused by news shocks and that the real exchange rate moves closely with the nominal exchange rate, real exchange rate stabilization is desirable to target the impact of news shocks correctly.

Under a simple inflation-targeting rule, our study of the dynamics of the economy in response to a news shock suggested several possibilities for the movement of relative prices across countries, such as the real exchange rate and the terms-of-trade, which is difficult to explain with only contemporaneous shocks in standard general equilibrium open economy models. The relative price movement shown in this paper is consistent with the dual role of the nominal exchange rate in asset and goods markets and with the empirical evidence on its movement: most of variability in the nominal exchange rate is accounted for by changes in expectations of future fundamentals. Thus, this paper provides evidence that news shocks about the future reconcile the observed dynamics of relative prices across countries with that generated by contemporaneous shocks in standard theoretical models.³⁴ This is an area for future research.

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³⁴We do not emphasize the role of news about the future as a driving force of aggregate fluctuations as is common in the expectations-driven real business cycle literature. The consensus in the literature on the role of the nominal exchange rate in determining the relative prices across countries suggests that news shocks should be taken into account at least to explain the observed movements in relative prices.

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Appendix A: Tables

Table 1

Parameter	Value	Description
β	0.9902	Subjective discount factor
ρ	1	Degree of relative risk aversion
η	1	Inverse of elasticity of labor supply
b	0.69	Degree of habit formation
φ	0.36	Share of capital in value added
δ	0.025	Depreciation rate of capital
κ	2.79	Parameter scaling investment adjustment costs
ψ	1.1	Elasticity of substitution between home and foreign intermediate goods
ω	0.85	Home bias toward intermediate goods of each own country in production of final goods
θ_F	6	Elasticity of substitution between final goods
θ_I	6	Elasticity of substitution between intermediate goods
θ_w	21	Elasticity of substitution between labors
α_F	0.75	Degree of final goods price stickiness
α_I	0.5	Degree of intermediate goods price stickiness
α_w	0.6	Degree of wage stickiness
$\bar{\Pi}$	1.0103	Steady state value of inflation rate
ρ_a	0.89	AR(1) coefficient of technology shocks
ρ_a^c	0.02	Coefficient for technology spillover
$\sigma_{\varepsilon_a} = \sigma_{\xi}$	0.0064	Standard deviations of contemporaneous and news shocks
σ_{ε_m}	0.0025	Standard deviations of monetary shocks

The Sticky Price Economy

Table 2-1: the optimal policy rule in the sticky price economy

	$\omega = 0.85$					$\omega = 0.95$				
	Θ_π	Θ_Y	Θ_{RS}	Gain	Welfare	Θ_π	Θ_Y	Θ_{RS}	Gain	Welfare
$p = 0$	3.0	3.0	0.00		-135.3700	3.0	3.0	0.00		-135.3740
$p = 4$	3.0	3.0	0.08	0.0002	-135.3917	3.0	3.0	0.22	0.0030	-135.3969
$p = 8$	3.0	3.0	0.28	0.0018	-135.3985	3.0	3.0	0.30	0.0067	-135.4034
$p = 12$	3.0	3.0	0.30	0.0028	-135.3998	3.0	3.0	0.30	0.0089	-135.4047

ω : the home bias parameter.

p : the length of news shocks; $p = 0$ indicates the case without news shocks.

Welfare: the conditional welfare level.

Gain: the welfare gain of the optimal rule (as a particular regime) relative to a rule with $\Theta_{RS} = 0$ (as a reference regime); the fraction of the consumption process in percentage under the reference regime that households would be willing to pay to achieve the welfare level of the particular regime.

Table 2-2: the welfare gain of real exchange rate stabilization and inflation-targeting in the sticky price economy with home bias, $\omega = 0.85$ and the length of news shock, $p = 12$.

Welfare gain from real exchange stabilization			Welfare gain from inflation-targeting		
Θ_{RS}	$\Theta_\pi = 1.1,$ $\Theta_Y = 3$	$\Theta_\pi = 3,$ $\Theta_Y = 3$	Θ_π	$\Theta_{RS} = 0,$ $\Theta_Y = 3$	$\Theta_{RS} = 0.3,$ $\Theta_Y = 3$
	Gain	Gain		Gain	Gain
0.05	0.0134	0.0008	1.5	0.1986	0.1555
0.10	0.0250	0.0014	2.0	0.2364	0.1869
0.15	0.0348	0.0019	2.5	0.2510	0.2015
0.20	0.0426	0.0023	3.0	0.2603	0.2107
0.25	0.0484	0.0026			
0.30	0.0524	0.0028			

Gain: the welfare gain of a given rule relative to the rule with $\Theta_{RS} = 0$.

Note that the coefficient on the CPI inflation rate takes on either 1.1 or 3 and the coefficient on the output gap is fixed at 3.

Gain: the welfare gain of the given policy relative to the rule with $\Theta_\pi = 1.1$.

Note that the coefficient on the real exchange rate takes on either 0 or 0.3 and the coefficient on the output gap is fixed at 3.

The Economy with Sticky Wages and Prices

Table 3-1: the optimal policy rule in the economy with sticky wages and prices

	$\alpha_w = 0.6$							$\alpha_w = 0.8$						
	Θ_π	Θ_w	Θ_Y	Θ_{RS}	Gain 1	Gain 2	Welfare	Θ_π	Θ_w	Θ_Y	Θ_{RS}	Gain 1	Gain 2	Welfare
$p = 0$	1.6	3.0	2.0	0.00			-135.4189	2.4	3.0	2.0	0.00			-135.4112
$p = 4$	0.4	3.0	2.0	0.00	0	0.0019	-135.4094	0.8	3.0	2.0	0.02	0.0000	0.0019	-135.4019
$p = 8$	0.4	3.0	2.0	0.00	0	0.0016	-135.4058	0.8	3.0	2.0	0.04	0.0000	0.0017	-135.3986
$p = 12$	0.6	3.0	2.0	0.00	0	0.0015	-135.4038	0.8	3.0	2.0	0.02	0.0000	0.0016	-135.3967

α_w : the degree of wage stickiness.

p : the length of news shocks; $p = 0$ indicates the case without news shocks.

Gain 1: the welfare gain of the optimal rule relative to a rule with $\Theta_{RS} = 0$.

Gain 2: the welfare gain of the optimal rule relative to a rule that is the same as the optimal rule when $p = 0$.

Note that the notion of the welfare gain is described in Table 2-1.

Table 3-2: the welfare gain of output gap stabilization and real exchange rate stabilization in the economy with sticky wages, where the degree of wage stickiness, $\alpha_w = 0.8$ and the length of news shocks, $p = 12$.

Welfare gain from real exchange stabilization		Welfare gain from output gap stabilization	
$(\Theta_\pi, \Theta_w) = (2.4, 3) \ \& \ \Theta_Y = 0$		$(\Theta_\pi, \Theta_w) = (2.4, 3) \ \& \ \Theta_{RS} = 0$	
Θ_{RS}	Gain	Θ_Y	Gain
0.05	0.0260	0.5	0.3182
0.10	0.0502	1.0	0.3384
0.15	0.0723	1.5	0.3438
0.20	0.0925	2.0	0.3460

Gain: the welfare gain of a given rule relative to the rule with $\Theta_{RS} = 0$.

Gain: the welfare gain of a given rule relative to the rule with $\Theta_Y = 0$.

Note that values of coefficients on the CPI inflation rate and the inflation rate of the nominal wage index, (i.e. $(\Theta_\pi, \Theta_w) = (2.4, 3)$) correspond to their values in the optimal policy rule in the absence of news shocks, i.e. $p = 0$.

Table 3-3: the volatility gain of output gap stabilization and real exchange rate stabilization in the economy with sticky wages, where the degree of wage stickiness, $\alpha_w = 0.8$ and the length of news shocks, $p = 12$.

Volatility gain from real exchange rate stabilization

In the presence of news shocks, $p = 12$

$$(\Theta_\pi, \Theta_w) = (2.4, 3) \text{ \& } \Theta_Y = 0$$

Θ_{RS}	π	Y	C	I	L	R	RS
0.05	-2.28	-6.81	-6.99	-6.67	-9.38	-4.05	-7.76
0.10	-4.29	-11.96	-12.17	-11.76	-16.78	-6.95	-13.02
0.15	-6.02	-15.76	-15.94	-15.52	-22.58	-8.91	-16.48
0.20	-7.47	-18.52	-18.66	-18.26	-27.12	-10.19	-18.73

In the absence of news shocks (i.e. $p = 0$)

$$(\Theta_\pi, \Theta_w) = (2.4, 3) \text{ \& } \Theta_Y = 0$$

Θ_{RS}	π	Y	C	I	L	R	RS
0.05	-0.67	1.05	0.82	1.15	2.29	-3.34	-1.64
0.10	-1.28	2.06	1.57	2.29	4.89	-5.61	-3.49
0.15	-1.78	2.99	2.21	3.36	7.70	-7.15	-5.66
0.20	-2.16	3.77	2.69	4.28	10.58	-8.28	-8.20

The number represents the percentage change in the standard deviation of a variable under a given policy regime relative to under the policy regime with $\Theta_{RS} = 0$.

π : CPI inflation rate; Y : output; C : consumption; I : investment; L : employment; R : nominal interest rate; RS : real exchange rate.

The standard deviation is calculated by HP-filtering simulated series for a long period.

The minus sign indicates that the standard deviation of each variable decreases relative to under the policy regime with $\Theta_{RS} (\Theta_Y) = 0$.

Note that we provide the percentage change in SD in the absence of news shocks for the comparison of the role of real exchange rate (output gap) stabilization in stabilizing the economy.

Volatility gain from output gap stabilization

In the presence of news shocks, $p = 12$

$$(\Theta_\pi, \Theta_w) = (2.4, 3) \text{ \& } \Theta_{RS} = 0$$

Θ_Y	π	Y	C	I	L	R	RS
0.5	-12.49	-24.93	-24.83	-24.59	-40.64	-11.44	-22.49
1.0	-15.58	-26.30	-25.91	-25.96	-47.35	-7.90	-21.75
1.5	-16.90	-26.29	-25.67	-25.98	-50.04	-3.55	-20.60
2.0	-17.64	-26.13	-25.34	-25.86	-51.62	0.72	-19.67

In the absence of news shocks (i.e. $p = 0$)

$$(\Theta_\pi, \Theta_w) = (2.4, 3) \text{ \& } \Theta_{RS} = 0$$

Θ_Y	π	Y	C	I	L	R	RS
0.5	-0.95	2.02	2.80	1.58	-4.90	5.91	2.80
1.0	-1.62	2.50	3.82	1.77	-7.43	9.42	4.32
1.5	-2.11	2.92	4.55	2.02	-9.06	12.12	5.40
2.0	-2.45	3.24	5.09	2.23	-10.27	14.35	6.20

The number represents the percentage change in the standard deviation of a variable under a given policy regime relative to under the policy regime with $\Theta_Y = 0$.

Appendix B: Figures

Figure #	Description
Figures 1-1, 1-2, & 1-3	Figures on dynamics under a simple rule in Section 4
Figures 3-1 & 3-2	Figures under optimal monetary policy rule in model with sticky prices in Section 5
Figures 4-1 & 4-2	Figures under optimal monetary policy rule in model with sticky wage & prices in Section 5

Figure 1-1: Dynamics in response to a positive contemporaneous shock under a simple inflation-targeting rule

Output in response to a contemporaneous shock
 $\omega = 0.85$; $\alpha W = 0.6$, $(\alpha F, \alpha I) = (0.75, 0.5)$; $p = 4$

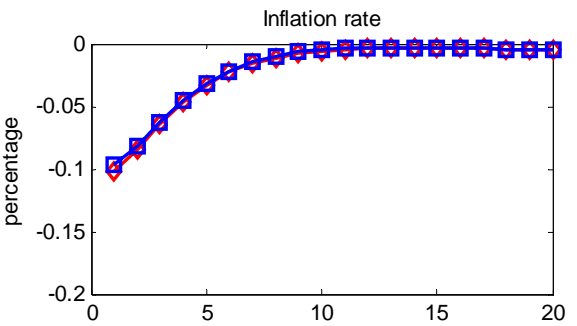
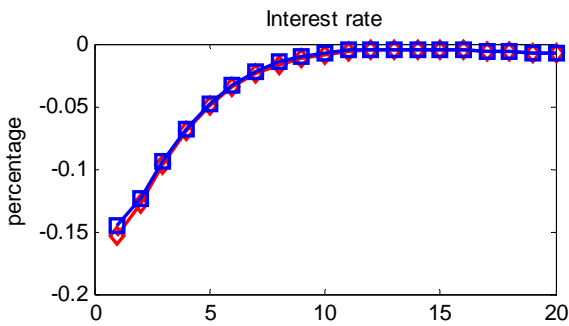
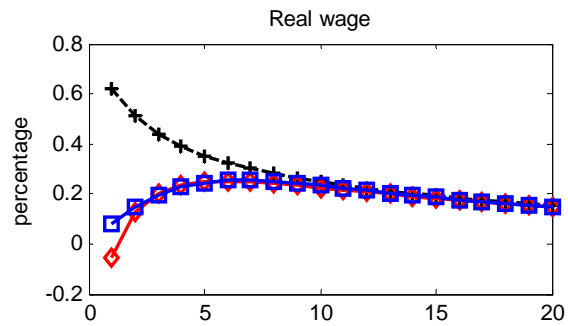
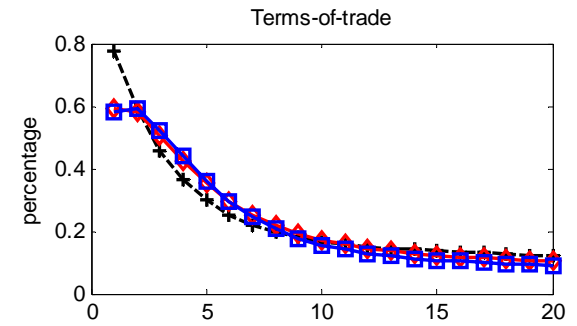
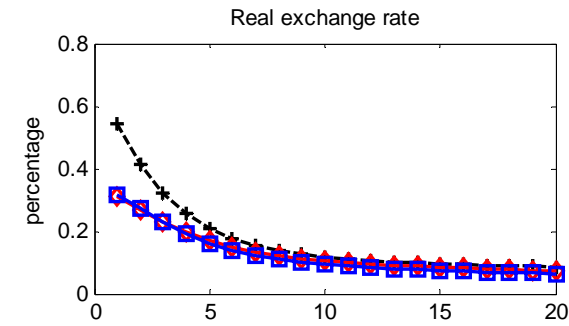
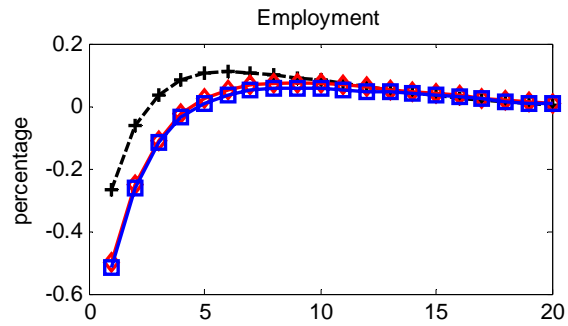
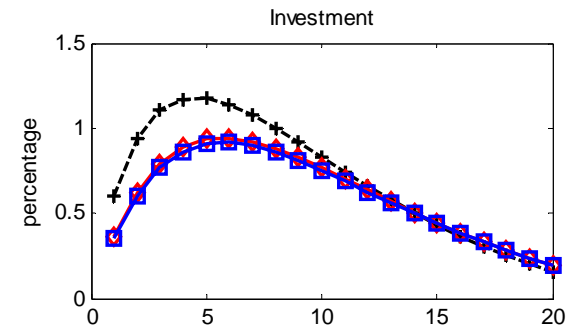
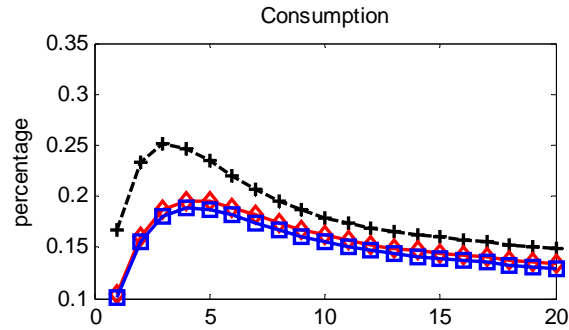
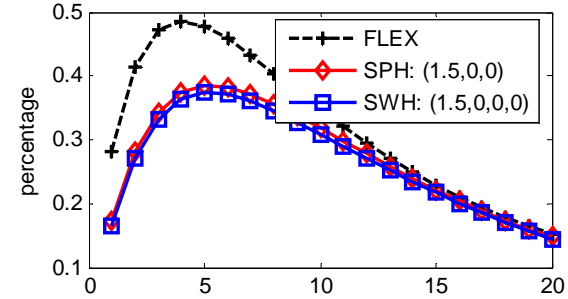


Figure 1-2: Dynamics in response to a positive news shock whose length is equal to 4 under a simple inflation-targeting rule

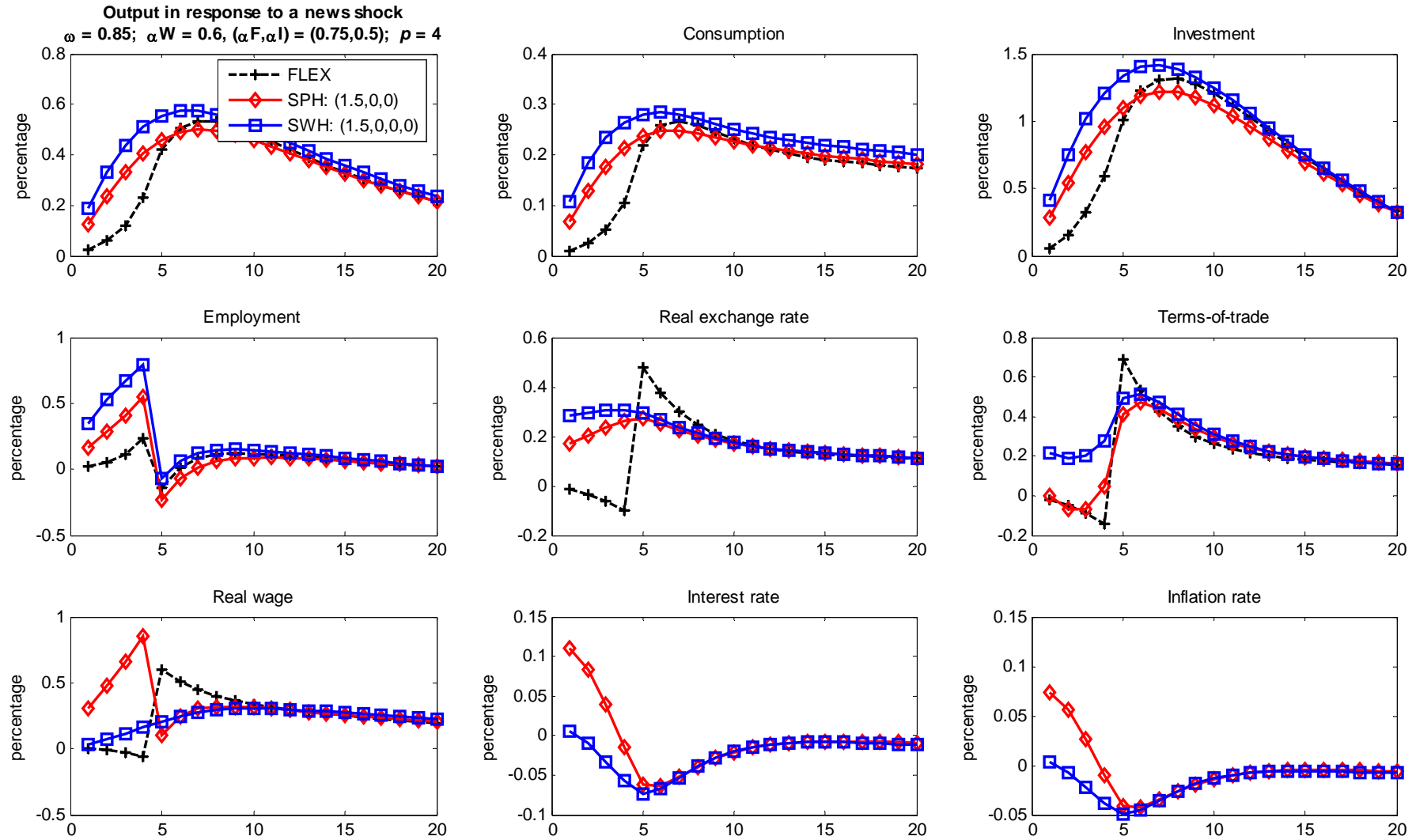


Figure 1-3: Responses of Real Exchange Rate & Terms-of-Trade to a new shock with its different length under SPH & simple rule

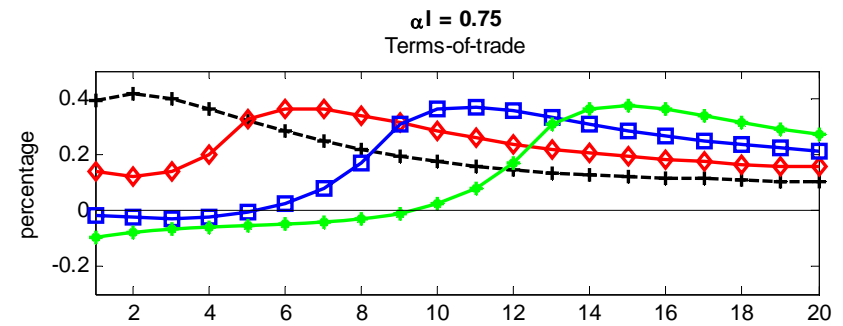
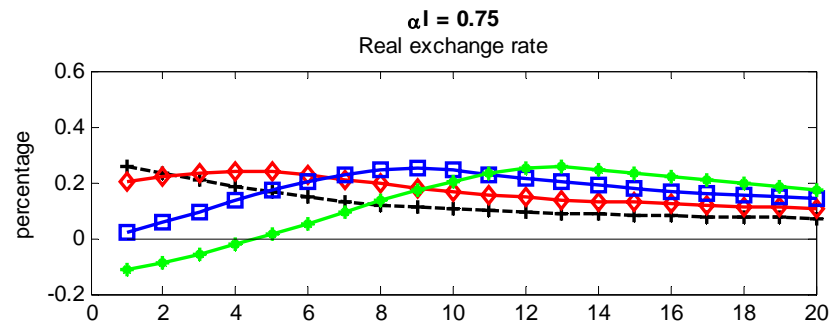
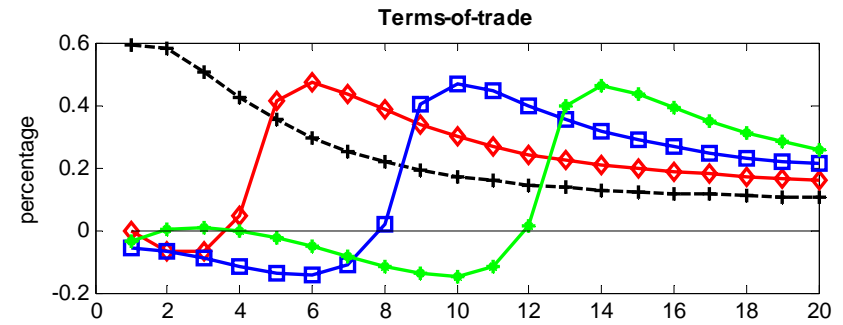
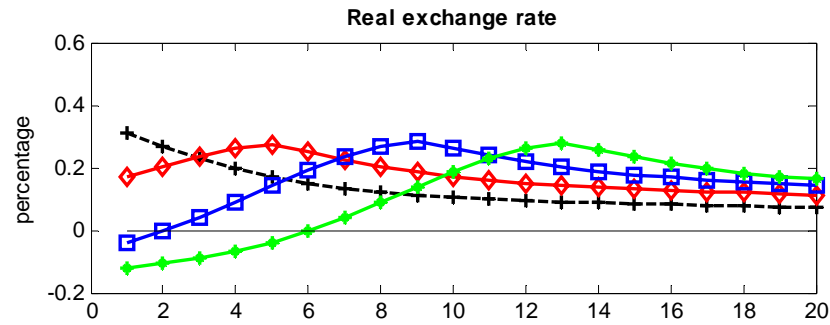
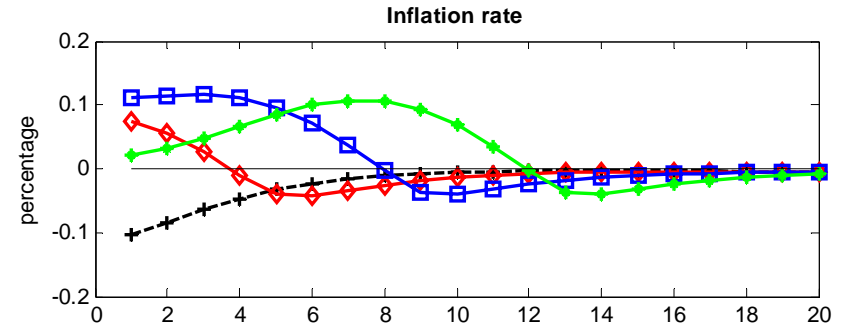
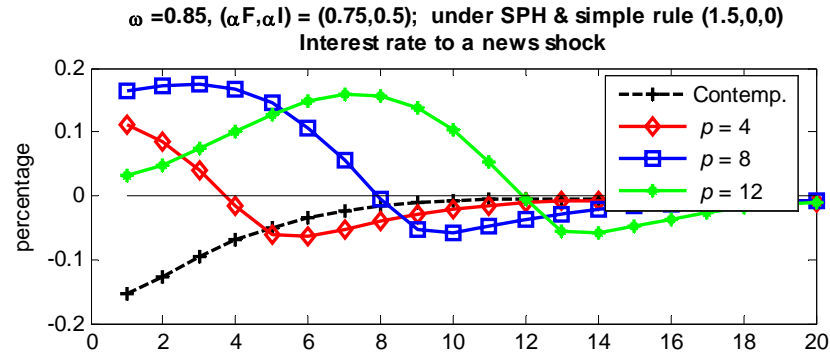


Figure 2-1: Dynamics in response to a positive contemporaneous shock under the optimal rule & SPH

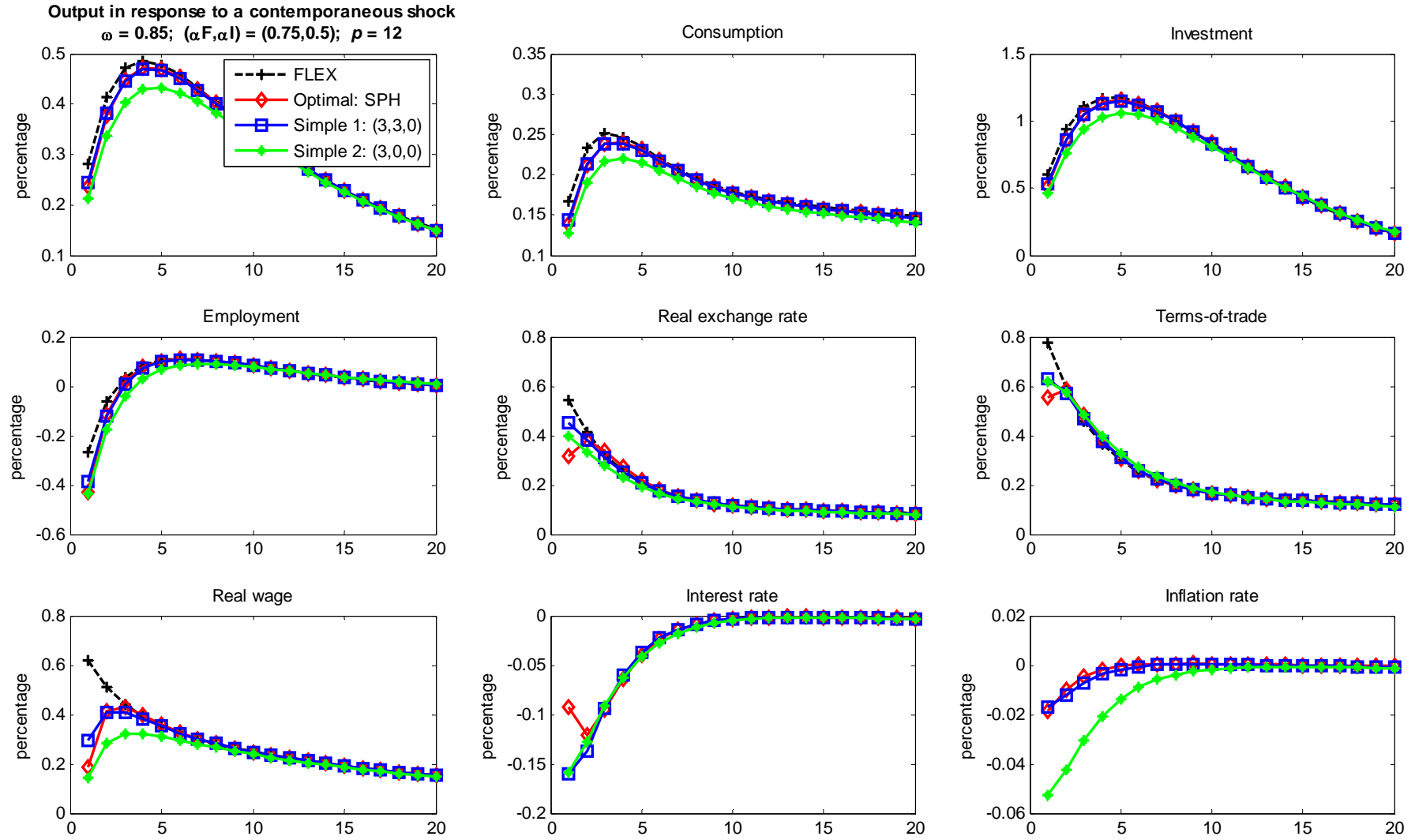


Figure 2-2: Dynamics in response to a positive news shock under the optimal rule & SPH

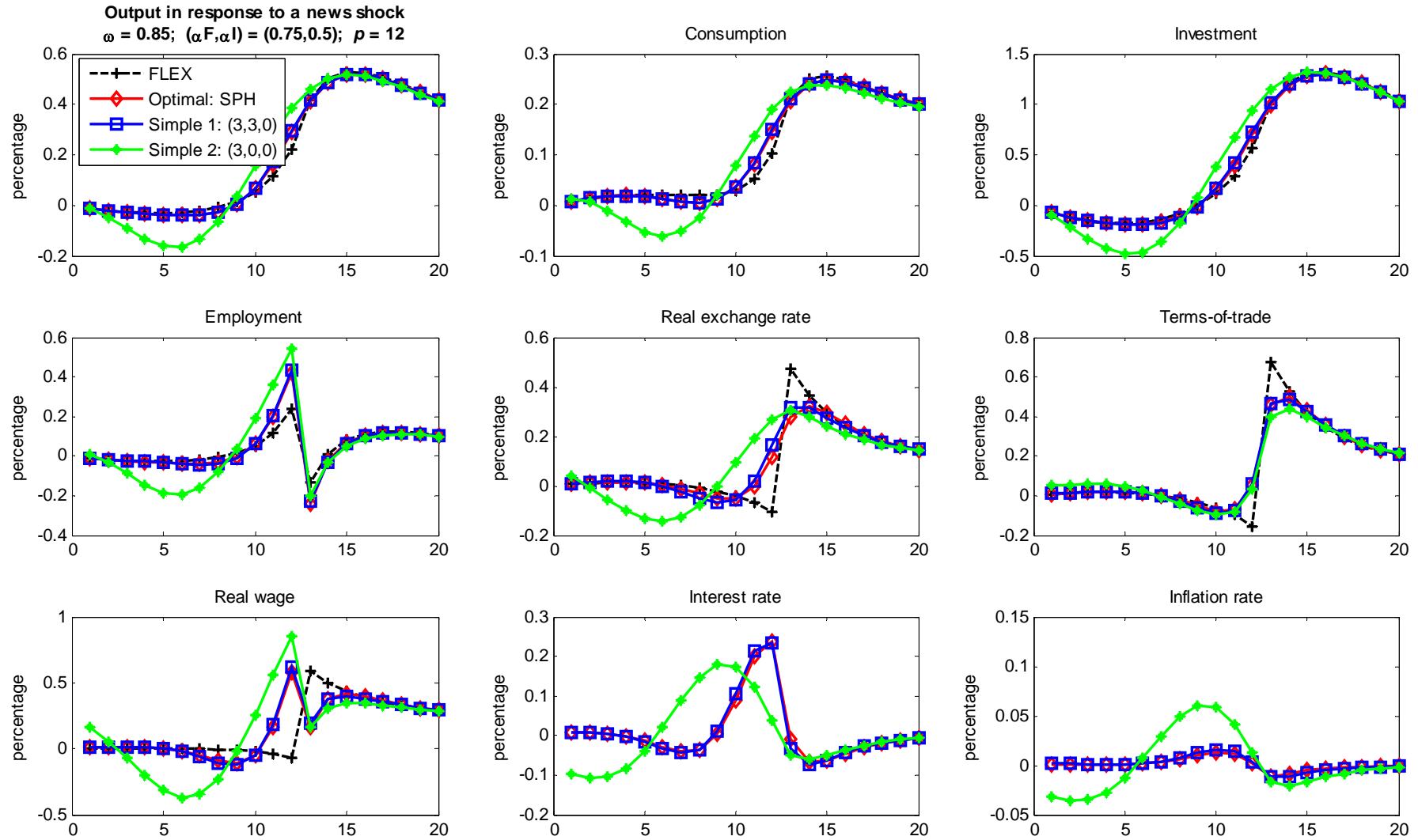


Figure 3-1: Dynamics in response to a positive contemporaneous shock under the optimal rule & SWH

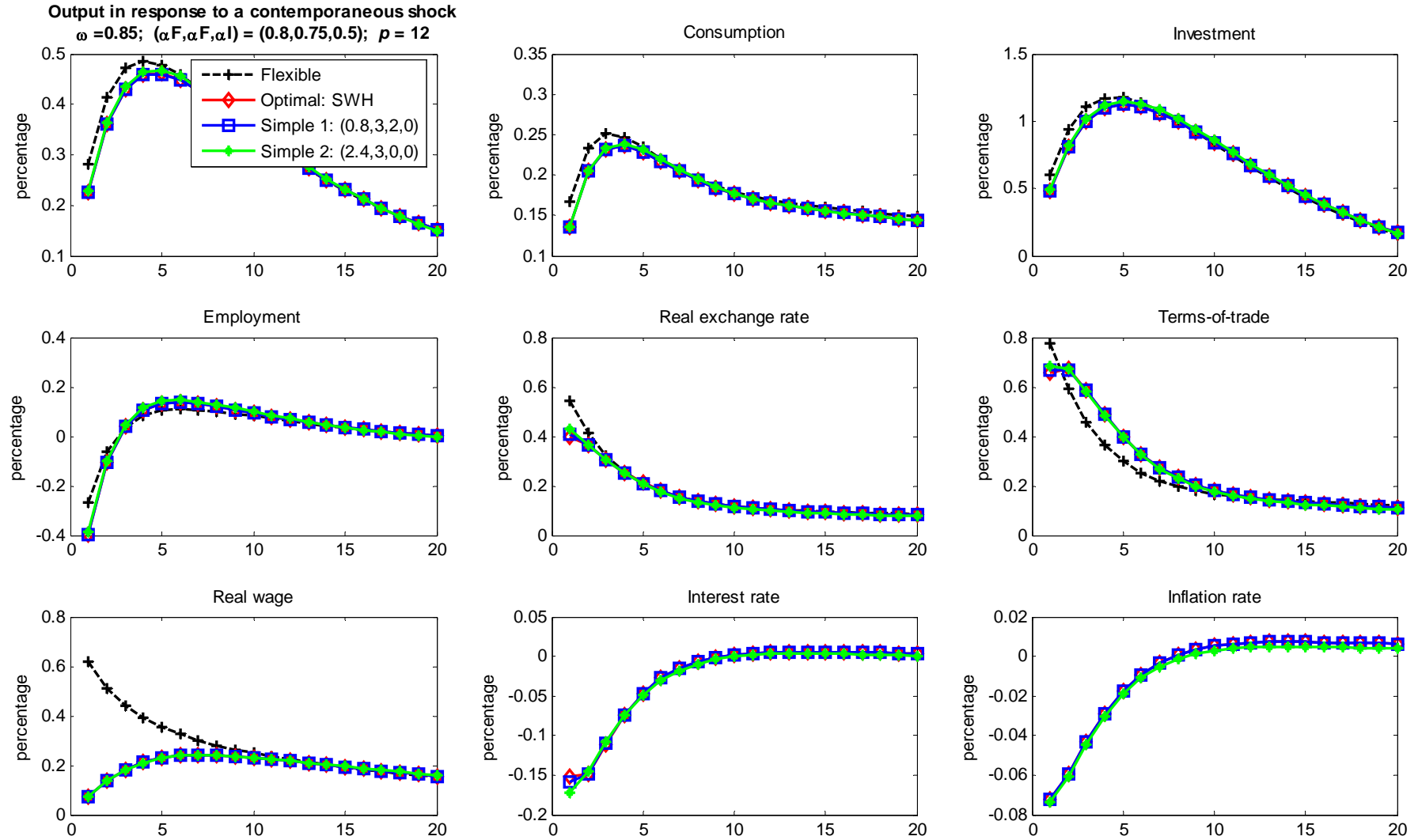


Figure 3-2: Dynamics in response to a positive news shock under the optimal rule & SWH

