International trade in intermediate inputs and the welfare gains from monetary policy cooperation

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Abstract

This paper introduces international trade in intermediate inputs into Clarida et al.(2002) to examine the welfare gains from monetary policy cooperation when the world is hit by cost-push shocks. We find that Clarida et al.(2002)'s prediction is right. Specifically, the introduction of the international trade in intermediate inputs opens a new channel through which the terms of trade at the stage of intermediate-goods production produce the spillover effect. In Clarida et al. (2002), the risk sharing effect and the terms of trade effect cancel out and the welfare gains from monetary policy cooperation disappear when the utility function of consumption is logarithmic. By contrast, in our model, the new channel still works. By internalizing the spillover effect produced through the new channel, the cooperative monetary policymaker achieves the welfare gains which are substantially larger than those found in the literature. In addition, we find that the welfare gains increase with the degree of intermediate-goods trade openness.

Key words: International trade in intermediate inputs, Monetary policy cooperation, Welfare gains

JEL classification: E5, F3, F4

1. Introduction

In an increasingly interdependent world, whether central banks need to cooperate or not has been a classical question in the open economy macroeconomics literature.[1] Especially, the recent financial turmoil rekindled the discussion about the spillovers from monetary policy among policymakers and researchers (Blanchard et al., 2013; Ostry and Ghosh, 2016). However, traditionally, the old-Keynesian analyses find that the welfare gains from monetary policy cooperation are quantitatively small (Hamada, 1976; Oudiz and Sachs, 1984; Canzoneri and Gray, 1985). By incorporating

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[1] See Engel (2016a) for a review of the recent literature on international monetary policy cooperation.

optimizing households and other Keynesian features, the New-Keynesian approach takes the welfare loss function obtained by doing a second-order approximation to the representative household' utility function as a metric to evaluate the monetary policy, and finds that, though the welfare gains from monetary policy cooperation exist, they are still small and have little monetary policy relevance (Obstfeld and Rogoff, 2002; Pappa, 2004; Fujiwara and Wang, 2017). Thus there is a gap between the policy discussion and what the literature tells us.

Over the past decades, the international trade in intermediate goods has been growing faster than that in final goods, and more and more countries are increasingly integrated together by vertical production and trade (Feenstra, 1998; Hummels et al., 1998, 2001; Yi, 2003, 2010; Koopman, et al., 2014; Antras, 2016). Some researchers find that the international trade in intermediate goods greatly changes the monetary policy prescriptions (Devereux and Engel, 2007; Monacelli, 2013; Gong et al., 2016; Wei and Xie, 2019; Xia, 2020). In addition, Clarida et al. (2002) predict that the international trade in intermediate goods can provide an additional effect of openness on marginal cost, thereby producing new welfare gains from monetary policy cooperation. Building on Clarida et al. (2002), Gong et al. (2016) introduce the international trade in intermediate goods to examine the optimal monetary policy in the cooperative case only, thus has nothing to say about Clarida et al. (2002)'s prediction. By contrast, Xia (2020) finds that the welfare gains from monetary policy cooperation decrease with the degree of intermediate-goods trade openness, which is entirely opposite to what is predicted by Clarida et al. (2002). The disagreement between Clarida et al. (2002)'s prediction and Xia (2020)'s conclusion calls for new studies to settle the dispute.

In this paper, we introduce the international trade in intermediate goods into Clarida et al. (2002) to examine the welfare gains from monetary policy cooperation when the world economy is buffeted by cost-push shocks. [2]A novel feature of our model is that the production in both countries is integrated vertically in two stages, from intermediate goods to final goods. At the stage of final-goods production, a representative producer in each country inputs domestic and imported intermediate goods to produce a final good which is consumed by the households in both countries, while at the stage of intermediate-goods production, a representative producer in each country employs domestic labor to produce a differentiated intermediate input which is used as input by the home and foreign final-goods producers.

We find that Clarida et al. (2002)'s prediction is right. To be specific, the vertical production and trade structure amplifies the spillover effect produced by the terms of trade at the stage of intermediate-goods production, thereby generating the welfare gains from monetary policy cooperation which are substantially greater than the findings in the literature. Unlike Xia (2020), we find that the welfare gains from monetary policy cooperation increase with the degree of intermediate-goods trade openness. In addition, in the knife-edge case of logarithmic utility from consumption, Clarida et al. (2002) find that the terms of trade and risk sharing effects cancel out and the welfare gains from monetary policy cooperation disappear. By contrast, substantial welfare gains still exist in our model.

In Clarida et al. (2002), the spillover effect of the economic activity in one country on the

[2]Clarida et al. (2002) find that, as in a closed economy, cost-push shocks generate a tradeoff between the output gap and inflation in open economies. However, Clarida et al. (2002) do not study the effect of cost-push shocks on the welfare gains from monetary policy cooperation. Though Benigno and Benigno (2006), Coenen et al. (2010) and Xia (2020) examine the welfare gains from monetary policy cooperation when cost-push costs occur, their models are different from Clarida et al. (2002). By contrast, we directly build our model on Clarida et al. (2002) thus can verify whether Clarida et al. (2002)'s prediction is true or false.

real marginal cost in the other country is the source of the welfare gains from monetary policy cooperation. By contrast, the introduction of the international trade in intermediate inputs in our model opens a new channel through which the terms of trade at the stage of intermediate-goods production produce the spillover effect. Specifically, the final-goods output and the relative price of intermediate goods in terms of final goods in one country can influence the real marginal costs at both stages of production via the terms of trade at the stage of intermediate-goods production. Thus, even if the risk sharing effect and the terms of trade effect produced at the stage of final-goods production cancel out when the utility function of consumption is logarithmic, the new channel still works, thus generating the spillover effect. Furthermore, when the central bank in each country conducts the monetary policy strategically, the real marginal cost gaps affect home and foreign welfare loss functions oppositely. The central bank in each country has the incentive to manipulate the real marginal cost gaps in its favor, thereby producing the welfare losses. The cooperative monetary policymaker, however, will choose to internalize the spillover effects, thereby generating the welfare gains. Since the magnitude of the spillover effect produced through the new channel is governed by the input share of imported intermediate goods, the welfare gains from monetary policy cooperation increase with the degree of intermediate-goods trade openness.

Our research is closed related to the literature on the optimal monetary policy in open economies.[3] Friedman (1953) advocates the flexible exchange rate to achieve the desired adjustment of the relative price between home and foreign countries when the prices are sticky. The implication of Friedman (1953)'s monetary policy prescription is that the central bank in the home country does not need to cooperate with its counterpart in the foreign country, the flexible exchange rate can achieve the efficient allocation by adjusting domestic economy to cope with foreign shocks. The studies based on ad hoc Keynesian model use game-theoretic approach to examine monetary policy cooperation but find that the welfare gains from monetary policy cooperation are quantitatively small (Hamada, 1976; Oudiz and Sachs, 1984; Canzoneri and Gray, 1985).

Due to the fact that the ad hoc Keynesian models are criticized for the lack of microfoundations, recent studies mainly examine the question of whether there exist the welfare gains from monetary policy cooperation or not in two-country New-Keynesian models. According to the duration of the nominal stickiness, the literature is classified into two strands, with the first strand using one-period in advance price setting while the second using staggered price setting in the spirit of Calvo (1983).

The first stand of literature is pioneered by Obstfeld and Rogoff (2002), which examine the optimal monetary policy in a two-country New-Keynesian model with producer-currency pricing (PCP). [4] When a global shock occurs, Obstfeld and Rogoff (2002) find that there are no welfare gains from monetary policy cooperation. By contrast, there exist the welfare gains from monetary policy cooperation when the world is hit by idiosyncratic shocks. However, the quantitative analysis shows that the welfare gains are small thus having no monetary policy relevance. Devereux and Engel (2003) extend Obstfeld and Rogoff (2002) to allow for local-currency pricing (LCP) to revisit the optimal monetary policy.[5] They conclude that the optimal monetary policy requires a fixed exchange rate and there are no welfare gains from monetary policy cooperation. By assuming that the productivity shocks are imperfectly correlated across traded and non-traded good sectors, Canzoneri et al. (2005) find that the welfare gains from monetary policy cooperation may be larger than those found in the old-Keynesian models.

[3] For a recent review, see Corsetti et al. (2011).

[4] Producer-currency pricing or PCP means that all exporters set prices in terms of their own currency.

[5] Local-currency pricing means that all exporting firms set prices in the consumers' currency.

After introducing the elasticity of exchange rate pass-through, Corsetti and Pesenti (2005) find that there are no welfare gains from monetary policy cooperation in three cases, which correspond to a global shock, PCP, and LCP, respectively.[6] In the general case other than PCP and LCP, Corsetti and Pesenti (2005) Conclude that there exist the welfare gains from monetary policy cooperation, but they do not answer the question of whether the welfare gains from monetary policy cooperation are sizable or not. Cui et al. (2020) introduce the dollar standard as in Devereux et al. (2007), and prove that the welfare gains from monetary policy cooperation exist, even if the world is hit by a global shock.

The second strand of literature is initiated by Clarida et al. (2002), which assume PCP and staggered price setting. As reviewed previously, the terms of trade and risk sharing effects cancel out and there are no welfare gains from monetary policy cooperation when the elasticity of intertemporal substitution is unity, while the welfare gains exist when it is not equal to unity. But Clarida et al. (2002) do not show how sizable the welfare gains are. Benigno and Benigno (2003) show that the central bank may have either an inflationary or deflationary bias in the noncooperative case, depending on model's structural characteristics. The cooperative monetary policymaker will eliminate the biases, thereby generating the welfare gains from monetary policy cooperation. Pappa (2004) finds that the welfare gains from monetary policy cooperation are related to the elasticity of substitution between home and foreign goods, the intertemporal elasticity of substitution, and the degree of trade openness, but the gains are quantitatively small.

Benigno and Benigno (2006) show that the welfare gains from monetary policy cooperation exist in the general case and examine how to design simple targeting rules for the central banks in the noncooperative case to implement the cooperative outcome. Liu and Pappa (2008) find that, after introducing asymmetric trading structures, the welfare gains from monetary policy cooperation reach a maximum of 0.62% of the steady state consumption. Coenen et al. (2010) quantify the welfare gains from monetary policy cooperation and find that they are an order of magnitude larger for the markup shocks than those for other shocks. Rabitsch (2012) and Engel (2016b) explore the optimal monetary policy in the cooperative and noncooperative cases when the financial markets are incomplete. Fujiwara and Wang (2017) extend Engel (2011) to the noncooperative case and find that the welfare gains are not sizable. Xia (2020) investigates the optimal monetary policy in a two-country model with input-output structure and shows that the cooperative policymaker can achieve the maximal welfare gains of 1.03% of the steady state consumption. But Xia (2020) draws a surprising conclusion that the welfare gains decrease with the degree of intermediate-goods trade openness.

The rest of the paper is organized as follows. Section 2 lays out the model. Section 3 derives model's equilibrium. Section 4 arrives at the welfare loss functions in the cooperative and noncooperative cases and discusses model's mechanism. Section 5 performs quantitative analysis of the welfare gains. Section 6 concludes.

2. The model

We first adapt Gong et al. (2016) to introduce cost-push shocks in the spirit of Clarida et al. (2002) and Engel (2011), then examine monetary policies in both cooperative and noncooperative policy game cases. It turns out that the introduction of the trade in intermediate inputs can generate

[6] The elasticity of exchange rate pass-through in PCP is 1, while it is 0 in LCP case.

the gains from monetary policy cooperation which are much larger than those found in the literature (Obstfeld and Rogoff, 2002; Pappa, 2004; Rabitsch, 2012; Fujiwara and Wang, 2017). In addition, contrary to Xia (2020), we find that the gains from monetary policy cooperation increase with the degree of intermediate-goods trade openness, which accords with what is predicted in Clarida et al. (2002). The underlying model is similar to Gong et al. (2016), thus we only outline the essential features.

The world economy consists of two countries, Home and Foreign, each of which is inhabited with a continuum of households with population size normalized to unity. There are two types of tradable goods, the final goods and the intermediate inputs. Final-goods producers input domestic and imported intermediate inputs to produce the consumption goods for the home and foreign households. By contrast, intermediate-goods producers only employ domestic labor to produce the intermediate inputs, which are transported to the home and foreign final-goods producers as inputs. Following Obstfeld and Rogoff (2000, 2002), Clarida et al. (2002), and Gali and Monacelli (2005), we assume that all exporters set prices in terms of their own currency (denoted producer-currency pricing or PCP). Households in both countries can trade in a complete set of state-contingent claims denominated in the home currency to achieve risk sharing. Labor is immobile across countries and households are monopolistic suppliers of their unique form of labor services to domestic intermediate-goods producers. Throughout this paper, foreign variables are marked with an asterisk.

2.1. Households

The representative household $h \in [0,1]$ in the home country maximizes the following utility function

$$\mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t U\left(C_t\left(h\right), N_t\left(h\right)\right) = \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \left\{ \frac{C_t\left(h\right)^{1-\sigma}}{1-\sigma} - \frac{N_t\left(h\right)^{1+\varphi}}{1+\varphi} \right\}, \tag{1}$$

subject to the following budget constraint

$$P_{ft} C_t\left(h\right) + \sum_{s_{t+1} \in \Omega_{t+1}} Z\left(s_{t+1} | s_t\right) D\left(h, s_{t+1}\right) = W_t\left(h\right) N_t\left(h\right) + D\left(h, s_t\right) - T_t + \Gamma_t, \tag{2}$$

in which $\beta \in (0,1)$ is the discount factor, the consumption aggregate $C_t\left(h\right)$ is a composite of home and foreign final goods:

$$C_t(h) = \left(C_{Ht}\left(h\right)\right)^{\frac{\upsilon}{2}} \left(C_{Ft}\left(h\right)\right)^{1-\frac{\upsilon}{2}}, 0 \leq \upsilon \leq 2. \tag{3}$$

Following Engle (2011) and Gong et al. (2016), we allow the households in both countries to have home bias in their consumption preferences, which happens when $\upsilon > 1$. The foreign representative household has a symmetric consumption preference with the weight $\upsilon/2$ on domestic goods. The home and foreign consumption indices are the aggregates of the differentiated final goods produced in their respective countries,

$$C_{Ht}\left(h\right) = \left(\int_0^1 C_{Ht}\left(h, j_f\right)^{\frac{\xi_f - 1}{\xi_f}} dj_f\right)^{\frac{\xi_f}{\xi_f - 1}}, C_{Ft} = \left(\int_0^1 C_{Ft}\left(h, j_f^*\right)^{\frac{\xi_f - 1}{\xi_f}} dj_f^*\right)^{\frac{\xi_f}{\xi_f - 1}}, \tag{4}$$

where $\xi_f > 1$ is the elasticity of substitution between the differentiated final goods. In equation (1), $N_t\left(h\right)$ is the labor supply, σ is the coefficient of relative risk aversion, and φ denotes the inverse of the Frisch elasticity of labor supply. In equation (2), $P_{ft} = k^{-1} P_{Hft}^{\nu/2} P_{Fft}^{1-\nu/2}$,where $k = (\upsilon/2)^{\nu/2} (1-\upsilon/2)^{1-\nu/2}$, is home consumption price index; $D(h, s_{t+1})$ is the nominal payoffs on state-contingent claims purchased at time t, if state s_{t+1} is realized; $Z(s_{t+1}|s_t)$ is the state-s_t price of a claim that will generate one unit of home currency in state $s_{t+1}; \Omega_{t+1}$ is the set of all time $t+1$ states; $W_t(h)$ is the nominal wage; T_t is the lump-sum tax levied by the government; and Γ_t represents the profit from the ownership of domestic firms.

Different from Gong et al. (2016), the first order condition for the labor supply is

$$(1+\mu_t) C_t(h)^{\sigma} N_t(h)^{\varphi} = \frac{W_t(h)}{P_{ft}}, \tag{5}$$

where $\mu_t \equiv \frac{1}{\eta_t - 1}$. Equation (5) implies that the real wage is a time-varying markup over the marginal rate of substitution between leisure and consumption. Following Clarida et al. (2002), and Engel (2011), the elasticity of substitution between differentiated labor services, η_t, follows a stochastic process. Thus the mark-up shock μ_t and its foreign counterpart are termed cost-push shocks, which give rise to a tradeoff between keeping price stability and achieving a zero output gap.

2.2. Firms

The production is integrated vertically, from the intermediate goods to the final goods. At the stage of final-goods production, a continuum of firms input domestic and imported intermediate inputs to produce differentiated final goods. The representative final-good producer $j_f \in [0,1]$ has the following production function

$$Y_{ft}(j_f) = \frac{A_{ft} Y_{Hit}^{\phi}(j_f) Y_{Fit}^{1-\phi}(j_f)}{\phi^{\phi}(1-\phi)^{1-\phi}}, \tag{6}$$

in which $Y_{Hit}(j_f) = \left[\int_0^1 Y_{Hit}(j_f, j_i)^{\frac{\xi_i - 1}{\xi_i}} dj_i\right]^{\frac{\xi_i}{\xi_i - 1}}$ and $Y_{Fit}(j_f) = \left[\int_0^1 Y_{Fit}(j_f, j_i^*)^{\frac{\xi_i - 1}{\xi_i}} dj_i^*\right]^{\frac{\xi_i}{\xi_i - 1}}$ are home and foreign aggregates of intermediate inputs, respectively, $\xi_i > 1$ is the elasticity of substitution between differentiated intermediate inputs, and A_{ft} is a common productivity shock to all home final-goods producers. Following Devereux and Engel (2007), and Gong et al. (2016), we allow the final-goods producers to have home bias in their production function, which happens when $\phi > \frac{1}{2}$. The foreign representative final-good producer has a symmetric production function with the weight ϕ on domestic intermediate inputs.

At the stage of intermediate-goods production, a continuum of firms input domestic labor to produce differentiated intermediate inputs. The representative intermediate-good producer $j_i \in [0,1]$ has the following production function

$$Y_{it}(j_i) = A_{it} N_t(j_i), \tag{7}$$

where A_{it} is a common productivity shock to all home intermediate-goods producers, $N_t(j_i)$ is a CES composite of differentiated domestic labor services, given by:

$$N_t(j_i) = \left[\int_0^1 N_t(j_i, h)^{\frac{\eta_t - 1}{\eta_t}} dh\right]^{\frac{\eta_t}{\eta_t - 1}} \tag{8}$$

where the elasticity of substitution between differentiated labor services, η_t, is common to all home intermediate-goods producers.

Solving the intermediate-good producer $j_i's$ cost minimization problem, we can obtain its demand for labor type h

$$N_t(j_i, h) = \left(\frac{W_t(h)}{W_t}\right)^{-\eta_t} N_t(j_i), \tag{9}$$

in which $W_t = \left(\int_0^1 W_t(h)^{1-\eta_t}\, dh\right)^{\frac{1}{1-\eta_t}}$ is the aggregate wage index. In line with Clarida et al. (2002), Gali (2008), and Engel (2011), the households are monopolistically competitive suppliers of labor services, but the wages are perfectly flexible. The total labor services supplied by the representative household h are given by: $N_t(h) = \int_0^1 N_t(j_i, h)\, dj_i$.

As in Calvo (1983), firms at both stages of production set prices in a staggered fashion. In each period, a final-good producer (an intermediate-good producer) has the chance to adjust its price with probability $1 - \theta_f(1-\theta_i)$. Under the PCP specification, when the firm resets its price to maximize the discounted flow of profits, it can adjust its prices for sales in both home and foreign markets simultaneously, thus the law of one price holds.

3. Equilibrium

Final-goods market clearing condition in the home country is given by

$$Y_{ft} \equiv \left(\int_0^1 Y_{ft}(j_f)^{\frac{\xi_f - 1}{\xi_f}}\, dj_f\right)^{\frac{\xi_f}{\xi_f - 1}} = \frac{\upsilon}{2}\frac{P_{ft}}{P_{Hft}}C_t + \left(1 - \frac{\upsilon}{2}\right)\frac{P_{ft}^*}{P_{Hft}^*}C_t^* = k^{-1}\left(\frac{\upsilon}{2}S_{ft}^{1-\frac{\upsilon}{2}}C_t + \left(1 - \frac{\upsilon}{2}\right)S_{ft}^{\frac{\upsilon}{2}}C_t^*\right) \tag{10}$$

in which $P_{Hft} = \left(\int_0^1 P_{Hft}(j_f)^{1-\xi_f}\, dj_f\right)^{\frac{1}{1-\xi_f}}$ is the home final-goods producer price index, $S_{ft} = \frac{P_{Fft}}{P_{Hft}}$ is the relative price of foreign final goods in terms of home final goods.

Intermediate-goods market clearing condition in the home country is given by

$$\begin{aligned} Y_{it} &\equiv \left(\int_0^1 Y_{it}(j_i)^{\frac{\xi_i - 1}{\xi_i}}\, dj_i\right)^{\frac{\xi_i}{\xi_i - 1}} \\ &= \phi\frac{MC_{ft}}{P_{Hit}}Y_{ft}D_{ft} + (1-\phi)\frac{MC_{ft}^*}{P_{Hit}^*}Y_{ft}^*D_{ft}^* = \frac{\phi}{A_{ft}}S_{it}^{1-\phi}Y_{ft}D_{ft} + \frac{1-\phi}{A_{ft}^*}S_{it}^{\phi}Y_{ft}^*D_{ft}^* \end{aligned} \tag{11}$$

where $MC_{ft} = \frac{P_{Hit}^{\phi}P_{Fit}^{1-\phi}}{A_{ft}}$ is the cost function for home final-goods producers, $P_{Hit} = \left[\int_0^1 P_{Hit}(j_i)^{1-\xi_i}\, dj_i\right]^{\frac{1}{1-\xi_i}}$ and $P_{Fit} = \left[\int_0^1 P_{Fit}(j_i^*)^{1-\xi_i}\, dj_i^*\right]^{\frac{1}{1-\xi_i}}$ are the home and imported intermediate-goods producer price indices, $D_{ft} \equiv \int_0^1 \left(\frac{P_{Hft}(j_f)}{P_{Hft}}\right)^{-\xi_f} dj_f$ is the home final-goods price dispersion, and $S_{it} = \frac{P_{Fit}}{P_{Hit}}$ is the relative price of foreign intermediate goods in terms of home intermediate goods.

Aggregate employment is determined by total outputs of intermediate-goods producers in the home country

$$N_t = \int_0^1 N_t(j_i)\, dj_i = \frac{Y_{it}}{A_{it}} D_{it} \tag{12}$$

in which $D_{it} = \int_0^1 \left(\frac{P_{Hit}(j_i)}{P_{Hit}}\right)^{-\xi_I} dj_i$ is the home intermediate-goods price dispersion.

Before the central banks announce the monetary policies, both home and foreign households can trade in a complete set of state-contingent claims denominated in the home currency to achieve risk sharing. The risk-sharing condition is given by

$$\left(\frac{C_t}{C_t^*}\right)^{\sigma} = \mathbb{Q}_t = S_{ft}^{v-1}, \tag{13}$$

where $\mathbb{Q}_t = \frac{E_t P_{ft}^*}{P_{ft}}$ is the real exchange rate. In the expression for the real exchange rate, E_t is the nominal exchange rate representing the home currency price of one unit of foreign currency.

3.1. The steady state and the flexible-price equilibrium

In general, the terms-of-trade manipulation in the noncooperative policy game induces the policymakers in both countries not to eliminate the distortions from the price and wage markups entirely (Corsetti and Pesenti, 2001; Clarida et al., 2002), thereby the steady states in the cooperative and noncooperative policy game do not coincide. To calculate the welfare gains from monetary policy cooperation, we need to compare the welfare losses incurred in two policy games. Following the literature, we take a second-order log approximation around the non-stochastic steady state to derive the welfare loss function in each policy game. The comparison of the welfare losses requires that the two policy games have the same steady state. In line with the literature (Benigno and Woodford, 2005, 2012; Benigno and Benigno, 2006; Fujiwara and Wang, 2017), we adopt the timeless perspective to ensure the identical steady state. Assuming that the governments can levy a lump-sum tax to subsidize the monopolistic suppliers of labor services, and the firms at both stages of production, respectively, we can obtain the efficient steady state, which is given with detailed derivation in Gong et al. (2016).

When deriving the welfare losses incurred in two policy games, we calculate the welfare loss as the difference between the welfare in the sticky price equilibrium and that in the flexible-price equilibrium. Thus, we need to solve the flexible-price equilibrium. As emphasized in Engel (2011), it requires a time-varying subsidy to the monopolistic suppliers of labor services, and the constant subsidies to firms at both stages of production to obtain the efficient flexible-price equilibrium. However, we assume that the governments implement the same subsidy policies as in the steady state to analyze the effects of the cost-push shocks on the monetary policy. Please refer to Gong et al. (2016) for the solution to the flexible-price equilibrium.

3.2. Equilibrium dynamics under sticky prices

We take log-linear approximations to the equilibrium equations under sticky prices, and present those that are used in solving the optimal policy problem. The readers can find the remaining equilibrium equations in Gong et al. (2016). In this section, we use a lower-case variable to denote the log deviation of the corresponding upper-case variable from the steady state value.

The New Keynesian Phillips curve describing the motion of the home final-goods PPI inflation is

$$\pi_{Hft} = \delta_f \left[\phi \widetilde{\upsilon}_t + (1-\phi)\, \widetilde{\upsilon}_t^{\,*} + \frac{(1-\phi)}{\Sigma} \left(\widetilde{y}_{ft} - \widetilde{y}_{ft}^{*} \right) \right] + \beta \mathbf{E}_t \pi_{Hft+1}, \tag{14}$$

where $\delta_f \equiv (1-\theta_f)(1-\beta\theta_f)/\theta_f$, $\Sigma \equiv (\upsilon-1)^2/\sigma + \upsilon(2-\upsilon)$, and $\upsilon_t = p_{Hit} - p_{Hft}$ is the relative price of home intermediate goods in terms of home final goods. Variables with a tilde denote log deviations from the corresponding value in the flexible-price equilibrium.

Similarly, the New Keynesian Phillips curve describing the motion of the foreign final-goods PPI inflation is

$$\pi_{Fft}^{*} = \delta_f \left[\phi \widetilde{\upsilon}_t^{*} + (1-\phi)\, \widetilde{\upsilon}_t - \frac{1-\phi}{\Sigma} \left(\widetilde{y}_{ft} - \widetilde{y}_{ft}^{*} \right) \right] + \beta \mathbf{E}_t \pi_{Fft+1}^{*}. \tag{15}$$

Different from Clarida et al. (2002), and Engel (2011), after introducing international trade in intermediate inputs, there are also two New Keynesian Phillips curves to describe the home and foreign intermediate-goods PPI inflation rates, they are given by, respectively

$$\pi_{Hit} = \delta_i \left\{ 2\varphi\phi(1-\phi)\left(\widetilde{\upsilon}^{*} - \widetilde{\upsilon}_t\right) - \widetilde{\upsilon}_t + \left[(\sigma + \varphi\phi) + \frac{\Pi}{\Sigma} \right] \widetilde{y}_{ft} + \left[\varphi(1-\phi) - \frac{\Pi}{\Sigma} \right] \widetilde{y}_{ft}^{*} \right\} + \beta \mathbf{E}_t \pi_{Hit+1} + u_t, \tag{16}$$

$$\pi_{Fit}^{*} = \delta_i \left\{ 2\varphi\phi(1-\phi)\left(\widetilde{\upsilon} - \widetilde{\upsilon}_t^{\,*}\right) - \widetilde{\upsilon}_t^{\,*} + \left[(\sigma + \varphi\phi) + \frac{\Pi}{\Sigma} \right] \widetilde{y}_{ft}^{*} + \left[\varphi(1-\phi) - \frac{\Pi}{\Sigma} \right] \widetilde{y}_{ft} \right\} + \beta \mathbf{E}_t \pi_{Fit+1}^{*} + u_t^{*}, \tag{17}$$

in which $\delta_i \equiv (1-\theta_i)(1-\beta\theta_i)/\theta_i$, $\Pi \equiv 2\varphi\phi(1-\phi) - (1-\upsilon/2)(\sigma-1)\upsilon$, and $u_t = \delta_i \mu_t, u_t^{*} = \delta_i \mu_t^{*}$ are the cost-push shocks. In a standard closed-economy new Keynesian model, the central bank faces no trade-off between stabilizing the inflation rate and closing the output gap, which is called the divine coincidence (Blanchard and Gali, 2007; Gali, 2008). However, when the business cycles are driven by the cost-push shock, the divine coincidence disappears, (Clarida et al., 1999; Blanchard and Gali, 2007; Gali, 2008). The same conclusion also holds in an open-economy new Keynesian model (Clarida et al., 2002). Thus, the cost-push shocks result in a change in the monetary policy prescription. In addition, as pointed out by Engel (2016), the cost-push shocks can lead to a supply-side recession and seem more like what happens in the real world.

In Clarida et al. (2002), the real marginal costs are determined by the world output gaps. When making the concluding remarks, Clarida et al. (2002) believe that the introduction of the international trade in intermediate inputs is particularly interesting, as it would provide an additional effect of openness on marginal cost. From equation (14) to equation (17), we know that the prediction in Clarida et al. (2002) is right. When there is the international trade in intermediate inputs, the real marginal costs are determined not only by the world output gaps but also by the world relative-price gaps.

According to the expression of the relative price of intermediate goods in terms of final goods, we can develop an equation associating the relative-price gap with the final-goods PPI inflation rate, the intermediate-goods PPI inflation rate, and the relative-price value in the flexible-price equilibrium, it is

$$\widetilde{\upsilon}_t = \widetilde{\upsilon}_{t-1} + \pi_{Hit} - \pi_{Hft} - \triangle\, \overline{\upsilon}_t, \tag{18}$$

in which $\triangle \overline{v_t} = \overline{v_t} - \overline{v}_{t-1}$, and

$$\overline{v}_t = a_{ft} + \Xi \left(a_{ft} - a_{ft}^*\right) - \digamma \left(a_{it} - a_{it}^*\right),$$

where $\Xi \equiv \frac{\varphi(1-\phi)(1-2\Lambda)}{(1-2\phi)(1+2\varphi\Lambda)}, \digamma \equiv \frac{(1+\varphi)(1-\phi)}{(1+2\varphi\Lambda)}$, and $\Lambda \equiv 2\phi\left(1-\phi\right) + \left(1-2\phi\right)^2 \left[\upsilon\left(1-\frac{\upsilon}{2}\right) + \frac{(\upsilon-1)^2}{2\sigma}\right]$. From equation (18), even though the central bank can stabilize the PPI inflation rates at both stages of production simultaneously, it still cannot stabilize the relative-price gap.

Equation (18)'s foreign counterpart is

$$\widetilde{v_t}^* = \widetilde{v}_{t-1}^* + \pi_{Fit}^* - \pi_{Fft}^* - \triangle\, \overline{v}_t^*, \tag{19}$$

where $\triangle \overline{v_t}^* = \overline{v_t}^* - \overline{v}_{t-1}^*$, and

$$\overline{v}_t^* = a_{ft}^* - \Xi \left(a_{ft} - a_{ft}^*\right) + \digamma \left(a_{it} - a_{it}^*\right).$$

4. Optimal monetary policy in open economies

To evaluate the welfare gains from the monetary policy cooperation, we need to make a comparison between the welfare loss incurred in the cooperative case with that incurred in the noncooperative case. Following the literature (Woodford, 2003; Gali, 2008), we take a second-order approximation to the households' utility functions. [7]In the cooperative case, the cooperative policymaker aims to minimize a weighted average of the welfare losses incurred by the households in both countries. By contrast, in the noncooperative case, the central bank in either country seeks to minimize the welfare loss incurred by the domestic household, while taking the entire path of the policy instrument chosen by its counterpart as given. In both cases, the monetary policies are conducted from the timeless perspective (Benigno and Woodford, 2005, 2012; Benigno and Benigno, 2006; Fujiwara and Wang, 2017; Bodenstein et al., 2019). Since the welfare loss functions are quite cumbersome for the general CRRA case, we present them for a special case in which the utility function of consumption is logarithmic ($\sigma = 1$) and will examine the general CRRA case in the Appendix.

In the cooperative case, the cooperative policymaker aims to minimize the following welfare loss function

$$\mathbf{W} = \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbf{X}_t + t.i.p. + O\left(\| \, a \, \|^3\right), \tag{20}$$

in which

[7] By contrast, Bodenstein et al. (2019) develop a toolbox to characterize the optimal policy responses in cooperative and noncooperative cases, respectively. According to Bodenstein et al. (2019), the standard linear-quadratic approach used in our paper produces the same solutions as the numerical procedure proposed by them. However, compared with their numerical procedure, the standard linear-quadratic approach has the advantage of decomposing the welfare loss clearly.

$$\mathbf{X}_t = \phi(1-\phi)\left[2(1-\phi)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)-(1-2\phi)\left(\tilde{v}_t-\tilde{v}^*_t\right)\right]^2+\frac{\xi_f}{2\delta_f}\left(\pi^2_{Hft}+\pi^{*2}_{Fft}\right)+\frac{\xi_i}{2\delta_i}\left(\pi^2_{Hit}+\pi^{*2}_{Fit}\right)$$
$$+\frac{1+\varphi}{2}\left[\left((\phi+\iota)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)+\tilde{y}^*_{ft}+\iota\left(\tilde{v}^*_t-\tilde{v}_t\right)\right)^2+\left((\phi+\iota)\left(\tilde{y}^*_{ft}-\tilde{y}_{ft}\right)+\tilde{y}_{ft}+\iota\left(\tilde{v}_t-\tilde{v}^*_t\right)\right)^2\right] \tag{21}$$

in which $\iota = 2\phi(1-\phi)$, *t.i.p.* stands for the terms independent of the monetary policy, and $O\left(\| a \|^3\right)$ collects all terms of third order or higher.[8]

The cooperative policymaker chooses $\tilde{y}_{ft}, \tilde{y}^*_{ft}, \tilde{v}_t, \tilde{v}^*_t, \pi_{Hft}, \pi^*_{Fft}, \pi_{Hit}$,and π^*_{Fit} to minimize equation (20) subject to the sequence of equilibrium dynamics given by equations (14)-(19). When solving the optimization problem, the cooperative policymaker can commit with full credibility to the sequence of the output gaps, the inflation rates, and the relative-price gaps.

In the noncooperative case, the central bank in the home country aims to minimize the following welfare loss function

$$\mathbf{W}_H = \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbf{X}_{Ht} + t.i.p. + O\left(\| a \|^3\right), \tag{22}$$

in which

$$\mathbf{X}_{Ht} = -\frac{\zeta_1}{2}\widetilde{mc}^*_{it}\left(\rho_3\tilde{y}_{ft}+\rho_4\tilde{y}^*_{ft}+(2+\varphi)\iota\left(\tilde{v}_t-\tilde{v}^*_t\right)+\tilde{v}^*_t+\mu^*_t\right)-\frac{\zeta_2}{2}\widetilde{mc}^{*2}_{ft}$$
$$+\frac{\zeta_1}{2}\widetilde{mc}_{it}\left(\rho_4\tilde{y}_{ft}+\rho_3\tilde{y}^*_{ft}+(2+\varphi)\iota\left(\tilde{v}^*_t-\tilde{v}_t\right)+\tilde{v}_t+\mu_t\right)+\frac{\zeta_2}{2}\widetilde{mc}^2_{ft}$$
$$+\frac{\phi(1-\phi)}{2}\left[2(1-\phi)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)-(1-2\phi)\left(\tilde{v}_t-\tilde{v}^*_t\right)\right]^2$$
$$+\frac{(1+\varphi)}{2}\left((\phi+\iota)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)+\tilde{y}^*_{ft}+\iota\left(\tilde{v}^*_t-\tilde{v}_t\right)\right)^2$$
$$+\frac{\xi_i}{2\delta_i}\left[\left(\frac{\nu}{2}+\phi(1-\nu)\right)\left(\pi^{*2}_{Fit}-\pi^2_{Hit}\right)+\pi^2_{Hit}\right]+\frac{\xi_f}{2\delta_f}\left[\frac{\nu}{2}\left(\pi^2_{Hft}-\pi^{*2}_{Fft}\right)+\pi^{*2}_{Fft}\right]. \tag{23}$$

In the foreign country, the welfare loss function that the central bank aims to minimize is given by

$$\mathbf{W}_F = \mathbf{E}_0 \sum_{t=0}^{\infty} \beta^t \mathbf{X}_{Ft} + t.i.p. + O\left(\| a \|^3\right), \tag{24}$$

in which

[8] When deriving equation (20), we take a second-order approximation to the sum of the linear terms.

$$\begin{aligned}
\mathbf{X}_{Ft} &= \frac{\zeta_1}{2}\widetilde{mc}^*_{it}\left((\rho_3\tilde{y}_{ft}+\rho_4\tilde{y}^*_{ft}+(2+\varphi)\iota\left(\tilde{v}_t-\tilde{v}^*_t\right)+\tilde{v}^*_t+\mu^*_t)\right)+\frac{\zeta_2}{2}\widetilde{mc}^{*2}_{ft} \\
&-\frac{\zeta_1}{2}\widetilde{mc}_{it}\left(\rho_4\tilde{y}_{ft}+\rho_3\tilde{y}^*_{ft}+(2+\varphi)\iota\left(\tilde{v}^*_t-\tilde{v}_t\right)+\tilde{v}_t+\mu_t\right)-\frac{\zeta_2}{2}\widetilde{mc}^2_{ft} \\
&+\frac{\phi\left(1-\phi\right)}{2}\left[2\left(1-\phi\right)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)-\left(1-2\phi\right)\left(\tilde{v}_t-\tilde{v}^*_t\right)\right]^2 \\
&+\frac{(1+\varphi)}{2}\left(\left(\phi+\iota\right)\left(\tilde{y}^*_{ft}-\tilde{y}_{ft}\right)+\tilde{y}_{ft}+\iota\left(\tilde{v}_t-\tilde{v}^*_t\right)\right)^2 \\
&+\frac{\xi_i}{2\delta_i}\left[\left(\frac{\nu}{2}+\phi\left(1-\nu\right)\right)\left(\pi^2_{Hit}-\pi^{*2}_{Fit}\right)+\pi^{*2}_{Fit}\right]+\frac{\xi_f}{2\delta_f}\left[\frac{\nu}{2}\left(\pi^{*2}_{Fft}-\pi^2_{Hft}\right)+\pi^2_{Hft}\right] \qquad (25)
\end{aligned}$$

In equations (23) and (25),

$$\zeta_1=\frac{(1-2\phi)(1-\nu)-1}{2\left(1+\varphi\right)},\zeta_2=\frac{\left(1+2\varphi\iota\right)\left(\nu-1\right)+\left(1-2\phi\right)}{2\left(1+\varphi\right)}$$

$$\widetilde{mc}_{ft}=\left(1-\phi\right)\left(\tilde{y}_{ft}-\tilde{y}^*_{ft}\right)+\phi\left(\tilde{v}_t-\tilde{v}^*_t\right)+\tilde{v}^*_t,\widetilde{mc}^*_{ft}=\left(1-\phi\right)\left(\tilde{y}^*_{ft}-\tilde{y}_{ft}\right)+\phi\left(\tilde{v}^*_t-\tilde{v}_t\right)+\tilde{v}_t$$

$$\widetilde{mc}_{it}=\left(\rho_2\tilde{y}_{ft}+\rho_1\tilde{y}^*_{ft}+\varphi\iota\left(\tilde{v}^*_t-\tilde{v}_t\right)-\tilde{v}_t+\mu_t\right),\widetilde{mc}^*_{it}=\left(\rho_1\tilde{y}_{ft}+\rho_2\tilde{y}^*_{ft}+\varphi\iota\left(\tilde{v}_t-\tilde{v}^*_t\right)-\tilde{v}^*_t+\mu^*_t\right)$$

$$\rho_1=\varphi(1-\phi)\left(1-2\phi\right),\rho_2=1+\varphi\left(\phi+\iota\right),\rho_3=\left(2+\varphi\right)\left(1-\phi\right)\left(1-2\phi\right),\rho_4=\left(2+\varphi\right)\left(\phi+\iota\right)-1$$

When the central banks in both countries choose the monetary policies in a noncooperative way, the resultant open-loop Nash equilibrium depends on the choice of the policy instruments (Lombardo and Sutherland, 2006; Wang, 2016). Following Benigno and Benigno (2006), Fujiwara and Wang (2017), and Bodenstein et al. (2019), we choose the final-goods inflation rates as the policy instrument variables. [9]The central bank in the home country chooses $\tilde{y}_{ft},\tilde{y}^*_{ft},\tilde{v}_t,\tilde{v}^*_t,\pi_{Hft},\pi_{Hit}$,and π^*_{Fit} to minimize equation (21) subject to the sequence of equilibrium dynamics given by equations (14)-(19), taken $\left\{\pi^*_{Fft}\right\}^{\infty}_{t=0}$ as given, while its foreign counterpart chooses $\tilde{y}_{ft},\tilde{y}^*_{ft},\tilde{v}_t,\tilde{v}^*_t,\pi^*_{Fft},\pi_{Hit}$,and π^*_{Fit} to minimize equation (23) subject to the sequence of equilibrium dynamics given by equations (14)-(19), taken $\{\pi_{Hft}\}^{\infty}_{t=0}$ as given.

As in the literature (Clarida, et al., 2002; Gali and Monacelli, 2005; Corsetti et al., 2011), the deviation of the output from the efficient level in either country can lead to the welfare loss, and the inflation rates can also result in the welfare loss due to the price dispersions caused by the price stickiness. Though the fluctuations in the terms of trade can adjust the substitution between the

[9]By comparison, other researchers choose a variety of variables as policy instruments, including the interest rate (Rabitsch, 2012), the nominal money balance (Obstfeld and Rogoff, 2000, 2002; Devereux and Engel, 2003; Devereux et al., 2007; Wang and Zou, 2015), and the growth rate of nominal money balance (Coenen et al., 2010; Xia, 2020).

home and foreign goods efficiently at both stages of production, the price rigidities at both stages of production prevent the final-goods firms' efficient inputs of domestic intermediate goods. Thus the cooperative policymaker should stabilize the relative-price gaps, in addition to the output gaps and the inflation rates (Gong et al., 2016).

In the noncooperative case, Clarida et al. (2002) point out that the spillover effect of foreign output on the home marginal cost is the source of the gains from monetary policy cooperation. In addition, they predict that the introduction of international trade in intermediate inputs can provide an additional effect of openness on the marginal cost, thereby increasing the gains from monetary policy cooperation. Equations (23) and (25) show that both the output and the relative price of intermediate goods in terms of final goods in one country can produce the spillover effects by influencing the marginal costs at both stages of production in the other country, thus verifying Clarida et al. (2002)'s prediction.

In Clarida et al. (2002), there are two effects of foreign output change on the home marginal cost that work in opposite directions. On the one hand, an increase in foreign output reduces the home marginal cost via the terms of trade effect, but on the other a rise in foreign output increases the home marginal cost due to the risk sharing effect. However, in the knife-edge case of logarithmic utility from consumption $(\sigma = 1)$, the terms of trade and risk sharing effects cancel out and the spillover effect of foreign output on the home marginal cost disappears. However, when we introduce the international trade in intermediate inputs, the spillover effect can occur at both stages of production, which stands in stark contrast to Clarida et al. (2002).

To illustrate the difference, we compare the expressions for the real marginal cost in Clarida et al. (2002) and our paper. In Clarida et al. (2002), the real marginal cost is transcribed as follows [10]

$$MC_t = (1-\tau)\, k^{\sigma-1} \left(1+\mu_t^w\right) A_t^{-(1+\phi)} Y_t^{\kappa} \left(Y_t^*\right)^{\kappa_0} V_t^{\phi}, \tag{26}$$

in which V_t is the price dispersion, and $\kappa_0 = \gamma(\sigma - 1)$. Thus, it is evident that, when the utility function of consumption is logarithmic $(\sigma = 1)$, the spillover effect of foreign output on the home marginal cost disappears. By contrast, in our paper, equation (26)'s counterpart when $\sigma = 1$ is

$$RMC_{ft} = \frac{1}{A_{ft}} V_t^{\phi} \left(V_t^*\right)^{1-\phi} Y_{ft}^{1-\phi} \left(Y_{ft}^*\right)^{-(1-\phi)}, \tag{27}$$

in which $V_t = \frac{P_{Hit}}{P_{Hft}}$ is the relative price of intermediate goods in terms of final goods. Thus, the international trade in intermediate inputs opens a new channel though which foreign output and the relative price of intermediate goods in terms of final goods produce the spillover effect on home final-goods real marginal cost, with the magnitude of the spillover effect being governed by the input share of foreign intermediate goods $(1 - \phi)$.

Furthermore, we can show that the spillover effect of foreign economic activity on home final-goods real marginal cost mainly originates from the terms of trade at the stage of intermediate-goods production. Solving home final-good firm's cost minimization problem, we can obtain $RMC_{ft} = \frac{P_{Hit}^{\phi} P_{Fit}^{1-\phi}}{A_{ft} P_{Hft}} = \frac{V_t S_{it}^{1-\phi}}{A_{ft}}$, which is equation (27) after some algebra. In addition, from $S_{it} = \frac{V_t^*}{V_t} S_{ft} = \frac{V_t^*}{V_t} \frac{Y_{ft}}{Y_{ft}^*}$, we know that an increase in foreign output first deteriorates foreign terms of trade at

[10] It is better for the readers to revisit Clarida et al. (2002) to make the distinction between the expressions for the real marginal cost in both papers.

the stage of final-goods production, then further deteriorates foreign terms of trade at the stage of intermediate-goods production, and finally reduces home real marginal cost. By contrast, an increase in foreign relative price of intermediate goods in terms of final goods directly improves foreign terms of trade at the stage of intermediate-goods production, thus increasing home real marginal cost.

After we introduce the international trade in intermediate inputs, foreign activity can also produce the spillover effect on home intermediate-goods real marginal cost, which is given by

$$RMC_{it} = \frac{Y_{ft}}{A_{it}V_t} \left\{ \frac{\phi}{A_{ft}A_{it}} \left(\frac{Y_{ft}V_t^*}{Y_{ft}^*V_t} \right)^{1-\phi} Y_{ft}D_{ft}D_{it} + \frac{(1-\phi)}{A_{ft}^*A_{it}} \left(\frac{Y_{ft}V_t^*}{Y_{ft}^*V_t} \right)^{\phi} Y_{ft}^*D_{ft}D_{it} \right\}^{\varphi}. \quad (28)$$

Thus foreign output and the relative price of intermediate goods in terms of final goods can also produce the spillover effect on the home intermediate-goods real marginal cost, which is absent in Clarida et al. (2002). Solving home intermediate-good firm's cost minimization problem, we can obtain $RMC_{it} = \frac{k^{-1}C_tN_t^{\varphi}S_{ft}^{1-\frac{\upsilon}{2}}}{A_{it}V_t} = \frac{k^{-1}kS_{ft}^{\frac{\upsilon}{2}-1}Y_{ft}N_t^{\varphi}S_{ft}^{1-\frac{\upsilon}{2}}}{A_{it}V_t} = \frac{Y_{ft}N_t^{\varphi}}{A_{it}V_t}$, from which we know that, as what is found in Clarida et al. (2002), the risk sharing effect counteracts the terms of trade effect from the stage of final-goods production entirely. But due to the existence of international trade in intermediate inputs, foreign economic activity can produce the spillover effect on the home real intermediate-goods real marginal cost via the channel created by international trade in intermediate inputs. To make the exposition clear, we express the home intermediate-goods real marginal cost further as

$$\begin{aligned} RMC_{it} &= \frac{Y_{ft}N_t^{\varphi}}{A_{it}V_t} = \frac{Y_{ft}\left(Y_{it}D_{it}\right)^{\varphi}}{A_{it}^{1+\varphi}V_t} \\ &= \frac{Y_{ft}D_{it}^{\varphi}}{A_{it}^{1+\varphi}V_t} \left(\frac{\phi}{A_{ft}} S_{it}^{1-\phi} Y_{ft}D_{ft} + \frac{(1-\phi)}{A_{ft}^*} S_{it}^{\phi} Y_{ft}^* D_{ft}^* \right)^{\varphi}. \end{aligned} \quad (29)$$

A casual inspection of equation (29) reveals that a rise in foreign output can directly produce a spillover effect on the home intermediate-goods real marginal cost. The reason is that a rise in foreign output increases the demand for the intermediate inputs produced by home firms, which then employ more domestic labors thus driving up the nominal wage. After replacing S_{it} with $\frac{Y_{ft}V_t^*}{Y_{ft}^*V_t}$, we can obtain equation (28). Thus, as analyzed previously, foreign output and the relative price of intermediate goods in terms of final goods can further produce the spillover effect on the home intermediate-goods real marginal cost via the terms of trade at the stage of intermediate-goods production.

Since the terms of trade and risk sharing effects cancel out and the spillover effect of foreign output on the home marginal cost disappears in the case of logarithmic utility from consumption $(\sigma = 1)$, Clarida et al. (2002) conclude that there are no gains from the monetary policy cooperation when $\sigma = 1$. However, our previous analysis implies that

Proposition 1. *In a model with international trade in intermediate inputs, there are gains from the monetary policy cooperation. The gains exist even if* $\sigma = 1$.

5. Quantitative analysis of the welfare gains from monetary policy cooperation

5.1. Parameterization

The baseline parameter values used in the simulation are listed in Table 1. The parameter value of the discount factor is chosen to generate an annual interest rate of about 4% in the steady state, with a period in our model being a quarter. Though it is in line with the literature that the coefficient of relative risk aversion σ takes a value in the range from 1 to 5, we set it to 1 to calculate the welfare gains from monetary policy cooperation in the case of logarithmic utility from consumption. There is a wide discrepancy between micro and macro estimates of the Frisch elasticity of labor supply (Chetty, et al., 2011), we follow the accepted standard (Nakamura and Steinsson, 2014; Christiano et al., 2014; and Gong et al., 2016), and set φ^{-1} to 1. We set the home-bias parameter in consumption, ν, to 1.5, which means that the consumption expenditure share on domestic final goods is 0.75 (Engel, 2011; Gong et al., 2016; Fujiwara and Wang, 2017). The home-bias parameter in production, ϕ, plays a pivotal role in our model, we set it to 0.6 in our baseline simulation, implying that the input share of the final-goods firms on imported intermediate goods is 0.4. After completing the baseline simulation, we will evaluate the effect of international trade in intermediate inputs on the welfare gains from monetary policy cooperation by choosing the home-bias parameter in production from a range from 0.55 to 0.85. We set the elasticity of substitution between differentiated final goods, ξ_f, and its counterpart at the stage of intermediate-goods production, ξ_i, to 6, which implies that the steady state markup is 20%. Following the literature (Gali, 2008; Corsetti et al., 2011; Engel, 2011; Fujiwara and Wang, 2017), we choose the probabilities of the firms at both stages not being able to reset its price at each period to ensure that the average duration of the nominal contracts is four quarters, thus $\theta_f = \theta_i = 0.75$

There are 6 shocks in our model, 4 productivity shocks and 2 cost-push shocks, which are uncorrelated with each other. All four productivity shocks, $a_{ft}, a_{it}, a^*_{ft}, a^*_{it}$,follow the same $AR(1)$ process, with the persistence parameter and the standard deviation being 0.95 and 0.01, respectively. According to Gali (2008) and Woodford (2010), the cost-push shocks u_t and u^*_t follow the same $AR(1)$ process, with the persistence parameter and the standard deviation being 0 and 0.01, respectively. In other words, the cost-push shocks are transitory in our model. [11]

5.2. The welfare gains from monetary policy cooperation

The question of whether there are welfare gains from monetary policy cooperation has long be at the heart of international macroeconomics (Hamada,1976; Oudiz and Sachs, 1984; Canzoneri and Gray, 1985; Canzoneri and Henderson, 1991; Persson and Tabellini, 1995). With the rise of the New Keynesian monetary economics, the researchers revist the classical question in the two-country New Keynesian model and usually they conclude that the welfare gains from monetary policy cooperation are quantitatively small (Obstfeld and Rogoff, 2002; Benigno and Benigno, 2003; Pappa, 2004; Corsetti and Pesenti, 2005; Fujiwara and Wang, 2017). In their concluding remarks, Clarida et al. (2002) advise to introduce the international trade in intermediate inputs, as it would provide an additional effect of openness on marginal cost, through which there are welfare gains from monetary cooperation in their model. In a survey article, Engel (2016) concludes that the sources of shocks are important to determine the welfare gains from monetary cooperation and

[11] The way we model the cost-push shocks is in line with most of the literature (Clarida et al., 2002; Gali, 2008; Woodford, 2010; Engel, 2011), but there are some other authors who model the cost-push shock as stochastic subsidy to firms (Coenen et al., 2010; Xia, 2010).

Table 1: Parameter values in the benchmark case

	Parameter	Value
Discount factor	β	0.99
Coefficient of relative risk aversion	σ	1
Frisch elasticity of labor supply	φ^{-1}	1
Home bias in consumption	ν	1.5
Home bias in production	ϕ	0.75
Elasticity of substitution between final goods	ξ_f	6
Elasticity of substitution between intermediate goods	ξ_i	6
Nominal contract duration at the stage of final-goods production	θ_f	0.75
Nominal contract duration at the stage of intermediate-goods production	θ_i	0.75

believes that the cost-push shock seems more like a real world shock, as it can lead to a supply-side recession, and a trade-off between stabilizing the inflation rate and closing the output gap facing a central bank. Following Clarida et al. (2002)'s advice, we reexamine the question of whether the welfare gains from monetary policy cooperation are sizable when the cost-push shocks are the driving forces of the business cycles, and find that the answer is yes.

We report our findings in Table 2. There is no doubt that the parameter $1-\phi$, which measures the degree of intermediate-goods trade openness, plays a pivotal role in arriving at our conclusion. Thus we consider a wide range of values of $1-\phi$ to examine the effect of the degree of intermediate-goods trade openness on the welfare gains from monetary policy cooperation. In the baseline model ($1-\phi=0.4$), the welfare gain from monetary policy cooperation is 3.7230% of the steady state consumption. By comparison, when the utility function of consumption is logarithmic ($\sigma=1$), some authors find that there are no welfare gains from the monetary policy cooperation (Obstfeld and Rogoff, 2002; Clarida et al., 2002; Pappa, 2004; Rabitsch, 2012; Xia, 2020); even if some others find that there exist the welfare gains, they are usually quantitatively small, such as 0.037% in Fujiwara and Wang (2017), 0.62% in Liu and Pappa (2008).[12] The welfare gain from monetary policy cooperation in our model also dwarfs the results found in Liu and Pappa (2008), Rabitsch (2012), and Xia (2020), in which the welfare gains are 0.62%, 0.14% and 1.03% of the steady state consumption, respectively. Considering that the welfare gains from monetary policy cooperation found in the aforementioned literature are believed to be relatively sizable (Liu and Pappa, 2008; Rabitsch, 2012; and Xia, 2020), the welfare gain in our baseline model is more striking thus should not be ignored by the monetary policymakers.

To illustrate the role of the international trade in intermediate inputs in increasing the welfare gains from monetary policy cooperation, we consider the case of no intermediate-goods trade between the home and foreign countries ($1-\phi=0$). It is not surprising that the welfare gain is only 0.0049% of the steady state consumption and can be ignored by the monetary policymakers as found in the literature. In addition, from Table 2, it seems that the welfare gain from monetary policy cooperation increases with the degree of intermediate-goods trade openness. Though the

[12] Though Rabitsch (2012) find that the changes in financial market structure and the trade elasticity can produce a welfare gain larger than those found in the literature, it disappears when the intratemporal elasticity of substitution between domestic and foreign goods is set to one as in our model. Xia (2020) also draws the same conclusion.

Table 2: The welfare gains

Degree of intermediate-goods trade openness	Losses-Nash	Losses-Cooperation	Welfare gains
$1-\phi=0$	0.2943	0.2453	0.0049
$1-\phi=0.15$	0.5016	0.2568	0.2448
$1-\phi=0.2$	0.6564	0.2593	0.3971
$1-\phi=0.25$	0.9108	0.2615	0.6493
$1-\phi=0.3$	1.3555	0.2635	1.0920
$1-\phi=0.35$	2.1985	0.2654	1.9331
$1-\phi=0.4$	3.9904	0.2674	3.7230
$1-\phi=0.45$	8.5484	0.2694	8.2790

conclusion is quite intuitive, we cannot draw the conclusion only from the observation of several welfare gain values. To prove the conclusion, we need to present the relationship between the welfare gain from monetary policy cooperation and the degree of intermediate-goods trade openness graphically. The left panel in Figure 1 reports the welfare losses in cooperative and noncooperative cases, and the welfare gain from monetary policy cooperation for the baseline model, respectively. The observation of it reveals that

Proposition 2. *In a model with international trade in intermediate inputs, the welfare gain from monetary policy cooperation increases with the degree of intermediate-goods trade openness. Furthermore, the marginal gain is also an increasing function of the degree of intermediate-goods trade openness.*

Our result given in Propositions 2 confirms Clarida et al. (2002)'s prediction that the introduction of international trade in intermediate inputs increases the welfare gains from monetary policy cooperation. By contrast, Xia (2020) finds that the welfare gain from monetary policy cooperation decreases with the degree of intermediate-goods trade openness thus contradicting Clarida et al. (2002)'s prediction. Despite the fact that Xia (2020)'s finding is quite surprising, the author does not explain it intuitively.[13] Following Clarida et al. (2002)'s modeling techniques, we can explain our result intuitively by taking the hint given in their concluding remarks.

In Clarida et al. (2002), the terms of trade and risk sharing effects cancel out and the spillover effect of foreign output on the home real marginal cost vanishes in the case of logarithmic utility from consumption $(\sigma=1)$, thus there are no gains from the monetary policy cooperation. In our model, the introduction of international trade in intermediate inputs implies that a new terms of trade channel created at the stage of intermediate-goods production can produce the spillover effect of the economic activity in one country on the real marginal costs in the other country, even if the risk sharing effect nullifies the terms of trade effect entirely at the stage of final-goods production. Since the real marginal cost gaps affect both countries oppositely, there is a tug-of-war between the two countries. Thus when conducting the monetary policy in the noncooperative case, the central bank in one country always chooses the policy in favor of themselves at the expense the other. By

[13] Another difference between our conclusion and that in Xia (2020) is that, in our paper, there are welfare gains from monetary policy cooperation when $\sigma \geq 1$, by contrast, the welfare gains only exist when $\sigma > 1$ while they disappear when $\sigma = 1$ in Xia (2020).

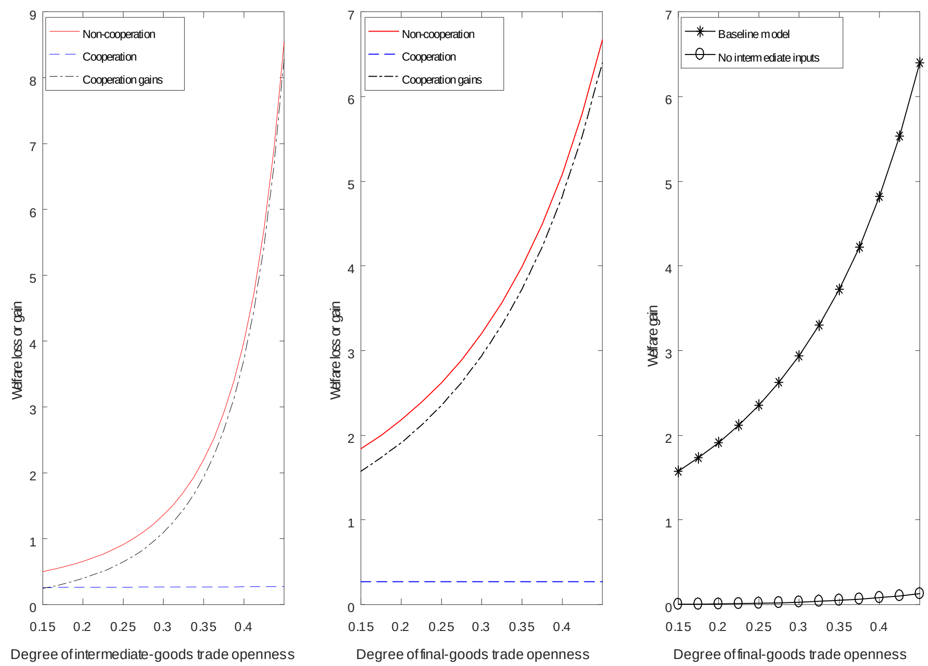

Figure 1: Welfare gains from monetary policy cooperation for varying degrees of openness in trade. Figure 1 reports welfare gains for three different settings: (i) how the welfare gains change with the degree of openness in intermediate-goods trade $(1-\phi)$ (the left panel); (ii) how the welfare gains change with the degree of openness in final-goods trade $\left(1-\frac{v}{2}\right)$ (the middle panel); (iii) how the welfare gains change with the degree of openness in final-goods trade $\left(1-\frac{v}{2}\right)$ when there is no intermediate-goods trade and $1-\phi$ equals 0.4, respectively.

contrast, the monetary policymaker in the cooperative case internalizes the spillover effects, thereby generating the welfare gains from monetary policy cooperation.

Along this line of reasoning, it is doubtless that the welfare gains increase with the degree of openness in intermediate-goods trade $(1-\phi)$, as shown in Figure 1 (the left panel). For the general CRRA case ($\sigma > 1$), the new channel through which the terms of trade at the stage of intermediate-goods production produce the spillover effects still works, but as pointed out in Clarida et al. (2002), the positive risk sharing effect dominates the negative spillover effect produced by the terms of trade at the stage of final-goods production, thus the welfare gains become smaller but still striking compared with the findings in the literature for a wide range of σ. We will discuss how the welfare gain changes with the coefficient of relative risk aversion in the following section.

The middle panel in Figure 1 reports how the welfare gain from monetary policy cooperation changes with the degree of openness in final-goods trade in our baseline model. In line with the findings in the literature (Pappa, 2004; Xia, 2020), we find that the welfare gain from monetary policy cooperation increases with the degree of final-goods trade openness. However, most of the literature draws the conclusion in the CRRA case ($\sigma > 1$), while the welfare gain disappears when the utility from consumption is logarithmic. By contrast, we arrive at the same conclusion in the case of logarithmic utility from consumption. In addition, the welfare gain from the increased openness in final-goods trade is far greater than what is found in the literature.

The international trade in intermediate inputs amplifies the influence of the final-goods trade on the welfare gain. The right panel in Figure 1 reports how the welfare gains from monetary policy cooperation change with the degree of openness in final-goods trade for the case of no intermediate-inputs trade and that of the baseline model, respectively. It is evident that, though the welfare gain increases with the degree of openness in final-goods trade for the case of no intermediate-inputs trade, it decreases substantially to the degree of no monetary policy relevance compared with that with international trade in both final goods and intermediate inputs.

5.3. Impulse responses

To facilitate the understanding of the welfare analysis, we draw impulse responses of the main variables of the two countries to a positive cost-push shock hitting the home country. Figure 2 depicts the impulse responses in both cooperative and noncooperative cases to a one-standard-deviation positive cost-push shock. It is evident that the monetary policy in cooperative case can better stabilize the fluctuations in the main variables than that in noncooperative case, thereby producing the welfare gains from monetary policy cooperation.

It is noteworthy to emphasize that the monetary policymaker faces the different trade-offs when making decisions about monetary policy in both cooperative and noncooperative cases. An inspection of Table 3 reveals that the monetary policymaker gives top priority to stabilizing the inflation in the cooperative case, while other concerns distract the monetary policymaker in noncooperative case and the stabilization of the inflation is no longer as important as it is in the cooperative case.

We first analyze the cooperative case. In response to the positive cost-push shock, home central bank implements a contractionary monetary policy to combat the rising intermediate-goods inflation. Facing a rising cost of imported inputs, foreign final-goods firms sluggishly adjust the prices to higher levels. As a result, foreign central bank also contracts the money supply to curb the final-goods inflation. Calvo mechanism implies that the degree of the increase in home intermediate-goods prices is higher than that in foreign final-goods prices. Thus home monetary policy is more contractionary than that in the foreign country, which results in the appreciation of home relative to foreign currency.

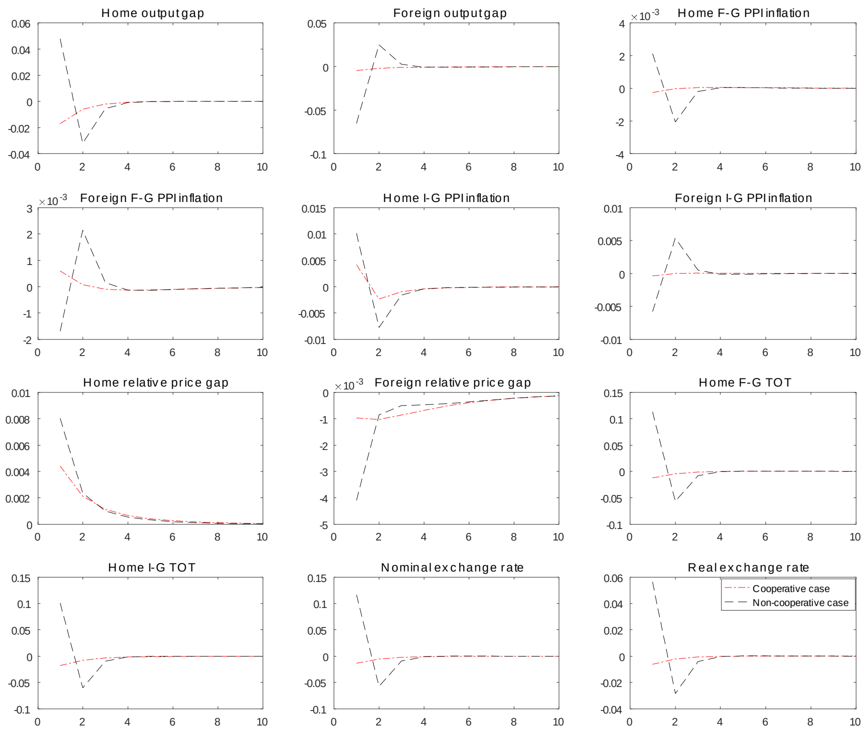

Figure 2: Impulse responses to a positive home cost-push shock. In the figure, final-goods and intermediate-goods are abbreviated as F-G and I-G, respectively.

Table 3: The ratio of welfare loss caused by inflation and aggregate welfare loss

	Welfare losses-cooperation	Welfare losses-Nash
Welfare loss caused by inflation	0.1681	1.6390
Aggregate welfare loss	0.2674	3.9904
The ratio	63%	41%

Under the PCP pricing regime, the expenditure-switching mechanism of the exchange rate directs the world consumption towards final goods produced in the foreign country. In the home country, the expenditure-level effect (affecting total aggregate demand) and the expenditure-switching effect (affecting the relative demand for one country's goods) move in the same direction and drive the final-goods output in the home country down, thus generating a negative final-goods output gap in the home country. By contrast, in the foreign country, the expenditure-level effect and the expenditure-switching effect move in the opposite direction with the former driving down the final-goods output while the latter driving it up, but the expenditure-level effect dominates the expenditure-switching effect and the final-goods output falls in our baseline model, thereby also producing a negative final-goods output gap. Evidently, our analysis implies that the degree of decrease in home final-goods output is higher than that in foreign final-goods output, thus the negative final-goods output gap in the home country is larger than that in the foreign country.

Though the higher prices of domestic intermediate-goods inputs tend to inflate the final-goods prices in the home country, the effects of asymmetrically contractionary monetary policies in both countries and ensuing appreciation of home relative to foreign currency gain the upper hand and depress the home final-goods prices finally. The situation is different in the foreign country, the expenditure-level effect of the contractionary monetary policy tends to decrease the final-goods prices, while the expenditure-expenditure effect plays a part in the opposite direction and increases the final-goods prices. In addition, the depreciation in the exchange rate and the rising prices of imported intermediate inputs contribute to the increase in the foreign final-goods prices. The net effect of these forces is to increase the foreign final-goods prices. The fall in final-goods outputs in both countries implies the lower demands for world intermediate inputs, which tend to drive down the intermediate-goods prices. It is true for the foreign country, but the positive cost-push shock dominates the depressing effect of lower demands thus home intermediate-goods prices increase on impact.

The direction of change in the relative price of intermediate goods in terms of final goods depends on the price movements. Our analysis implies that the relative price of home intermediate goods in terms of domestic final goods increases, while its foreign counterpart falls. By contrast, the movement in the nominal exchange rate determines the terms of trade at both stages of production and the real exchange rate. To be specific, the appreciation of the nominal exchange rate results in the improvement of home terms of trade at both stages of production and the appreciation of the real exchange rate.

In the noncooperative case, facing a positive cost-push shock, the home central bank implements the expansionary monetary policy to export some of the volatility in the labor costs to the foreign country initially at the expense of the further increase in prices at both stages of production. Consequently, the foreign central bank has no choice but to implement the contractionary monetary policy to avoid the welfare losses incurred due to the higher inflation rates, yielding the depreciation of the nominal exchange rate. The expenditure-level and the expenditure-switching effects work in the same direction and cause expansion in the home country, thus driving the inflation rates at both stages of production further up and producing a positive output gap. While the expenditure-level and the expenditure-switching effects also work in the same directions but cause contraction in the foreign country, thereby driving the inflation rates at both stages of production down and at the same time generating a negative output gap.

Though the inflation rates at both stages of production rise on impact, the increases are disproportionate with the intermediate-goods inflation rate being higher than the final-goods inflation rate, thus yielding a rising relative price of intermediate goods in terms of final goods in the home country. By contrast, due to the fact that the rising cost of imported inputs counteracts the depressing effects of the monetary policies on the final-goods inflation rate to some degree in the foreign country, the degree of decrease in the final-goods inflation rate is smaller than that in the intermediate-goods inflation rate, thereby causing a falling relative price of intermediate goods in terms of final goods. In addition, the depreciation of the nominal exchange rate deteriorates the home terms of trade at both stages of production and depreciates the real exchange rate.

Since the home cost-push shock is transitory, the trade-offs facing the central banks in both countries are reversed after the disappearance of the shock. Therefore, the central bank in the home country gives top priority to stabilizing the inflation again and reverses the monetary policy, while its foreign counterpart focuses on the welfare losses associated with the output gap and also reverses the monetary policy. Consequently, as shown in Figure 2, the impulse responses of the main variables are reversed.

5.4. Sensitivity analysis

Our previous analysis implies that the welfare gain from monetary policy cooperation is substantially higher than that found in the literature after we introduce the international trade in intermediate inputs into the standard two-country New Keynesian model, as suggested by Clarida et al. (2002). In addition, we find that the welfare gain from monetary policy cooperation increases with the degree of intermediate-goods trade openness. Readers may wonder whether our conclusions depend on the calibrated values of the key parameters. In this section, we perform sensitivity analysis and examine how the welfare gain from monetary policy cooperation changes when two key parameters vary within a reasonable range. The two parameters are the standard deviation of the cost-push shocks and the coefficient of relative risk aversion, respectively.

In the baseline model, we follow Gali (2008) and Woodford (2010) to set the standard deviation of the cost-push shocks to 0.01. By contrast, both Coenen et al. (2010) and Xia model the cost-push shock by introducing a stochastic subsidy to firms, and calibrate the standard deviations of the cost-push shocks to 0.06 and 0.1, respectively. To dispel doubts on whether the welfare gain from monetary policy cooperation will become quantitatively small when the standard deviation of the cost-push shocks is set to be smaller than 0.01, we plot the welfare gain from cooperation when the standard deviation of the cost-push shocks is greater than or equal to 0.005 but smaller than or equal to 0.01 in Figure 3 (the left panel). It is evident that with a smaller value of the standard deviation of the cost-push shocks, the welfare gain from cooperation also becomes smaller but is still quantitatively striking. To be specific, it decreases to 0.9308% of the steady state consumption, when the standard deviation of the cost-push shocks is 0.005. Thus, our conclusion that the welfare gain from cooperation is quantitatively striking when there is international trade in intermediate inputs holds only if small cost-push shocks hit the world economy.

The coefficient of relative risk aversion governs the magnitude of the risk sharing effect thus plays an important role in our model. We examine the welfare gains from monetary policy cooperation for the case in which the utility function of consumption is logarithmic ($\sigma = 1$) in the baseline model to

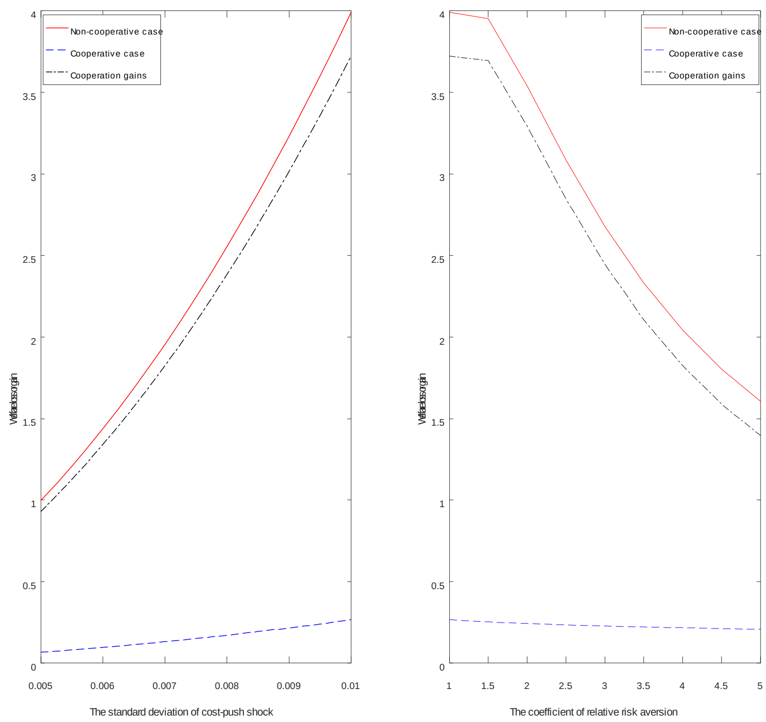

Figure 3: Sensitivity analysis

avoid presenting cumbersome welfare loss functions for the general CRRA case, which are provided in the Appendix. To see how the coefficient of relative risk aversion affects the welfare gains from monetary policy cooperation, we plot the welfare gain from cooperation when the coefficient of relative risk aversion is in the interval $[1, 5]$ in Figure 3 (the right panel), from which we can see that the welfare gain from monetary policy cooperation decreases with the coefficient of relative risk aversion. The welfare gain from monetary policy cooperation decreases to 1.3957% of the steady state consumption, when the coefficient of relative risk aversion is set to 5.

Intuitively, the welfare gains from monetary policy cooperation originate from the negative spillover effects of the economic activity in one country on the real marginal costs in the other country through the terms of trade channels at both stages of production. It is evident that the welfare gains increase with the spillover effects. According to Clarida et al. (2002), an increase in the coefficient of relative risk aversion produces a greater risk sharing effect, which outweighs the negative spillover effect produced by the terms of trade at the stage of final-goods production. Thus, the welfare gains from monetary policy cooperation decrease with the coefficient of relative risk aversion.

6. Conclusion

This paper examines the welfare gains from monetary policy cooperation in a two-country New Keynesian model with international trade in intermediate inputs. We find that the introduction of the international trade in intermediate inputs creates a new terms of trade channel at the stage of intermediate-goods production, through which the economic activity in one country can cause the spillover effect on the real marginal costs in the other country. Thus, even if the risk sharing effect nullifies the spillover effect entirely produced through the terms of trade channel at the stage of final-goods production in the case of logarithmic utility from consumption, the monetary policymaker in the cooperative case internalizes the spillover effects produced through the new channel, thus generating the welfare gains.

In addition, we find that the welfare gain from monetary policy cooperation increases with the degree of intermediate-goods trade openness, and the marginal gain is also an increasing function of the degree of intermediate-goods trade openness. In the general CRRA case, the risk sharing effect outweighs the negative spillover effect produced by the terms of trade at the stage of final-goods production, thus reducing the welfare gains from the monetary policy cooperation. However, our quantitative analyses show that the welfare gains from the monetary policy cooperation are striking in both cases compared to the findings in the literature.

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