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23 November 2021

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First version, October 2021
This version, November 2021

Abstract

This paper studies optimal monetary policy in a small open economy DSGE model with non-tradable goods and sticky prices. The introduction of non-traded goods is shown to have important implications for the transmission of shocks and monetary policy arrangements. First, the results show that positive technology shocks need not lead to deflation. In response to technology shocks, real exchange rates and the terms of trade depreciate. The relative price of tradable to non-tradable goods may increase or decrease, depending on the shocks. Second, based on welfare analysis, this paper evaluates the performance of different interest rate rules. The results show that if monetary policy is not very aggressive, the Taylor-type interest rate policy that targets CPI inflation performs the best. However, as monetary policy becomes relatively aggressive, the policy that targets domestic inflation is shown to yield the highest level of welfare. Third, this paper studies the Ramsey policy and optimal allocations. The results indicate that the Ramsey optimal policy stabilizes the inflation rates in both production sectors, while allowing for volatilities in CPI inflation, real exchange rates, the terms of trade, and the relative price of tradable goods. This suggests that the interest rate rules targeting CPI inflation or exchange rates are suboptimal. The results also show that in response to sector specific shocks, the Ramsey planner only cares about the inflation rate in the sector where the shock originates.

JEL Classification Numbers: E31 E32 E52 F31 F41.

Keywords: Optimal monetary policy, Small open economy, Non-tradable goods, Business cycles, Exchange rates.

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*School of Economics, Nanjing University, China. For useful comments and discussions, I am grateful to Christoph Himmels, Giovanni Lombardo, Wentao Ma, Haopeng Shen, Chan Wang and seminar participants at Nanjing University. Financial support from the National Natural Science Foundation of China (project 72104101) is gratefully acknowledged. The views expressed in this paper and any errors are my own. E-mail address: pengfei@nju.edu.cn

1 Introduction

The presence of non-tradable goods in consumption is a prominent feature of international trade data. Empirical studies have well-documented that non-traded goods constitute a substantial portion of aggregate consumption baskets (see Stockman and Tesar, 1995; Dotsey and Duarte, 2008; Rabanal, 2009; Lombardo and Ravenna, 2014). For example, in the United States, consumption of non-traded goods represents about 40 percent of GDP (Dotsey and Duarte, 2008). Lombardo and Ravenna (2014) provide estimates of the shares of tradable and non-tradable goods in consumption and investment, using input-output data for 25 countries. They find that, small open economies have consumption non-tradable shares of around 20%, although variations among countries can be large.

Accounting for non-traded goods is not only consistent with the real data. There is also empirical evidence supporting the role of non-tradable goods for understanding real exchange rate dynamics. For instance, Betts and Kehoe (2006) provide evidence of the important role of non-traded goods in explaining the movements of US real exchange rates. Similarly, Burstein et al. (2006) find that over the period 1971–2002, about 61% of the US trade-weighted real exchange rate volatility is explained by the movements in the relative price of tradable to non-tradable goods.

On the theoretical side, many studies have used open economy macroeconomic models with non-traded goods to analyze the transmission of shocks and explain international macroeconomics facts (e.g., Benigno and Thoenissen, 2003, 2008; Dotsey and Duarte, 2008; Duarte and Obstfeld, 2008; Rabanal, 2009; Lombardo and Ravenna, 2014). Dotsey and Duarte (2008) find that non-traded goods are an important aspect in driving international relative price dynamics, in the context of an otherwise standard open economy model. They show that the model with non-tradable goods generate implications that are more closely in line with data relative to the one that abstracts from non-tradable goods. Rabanal (2009) builds a two-country New Keynesian DSGE model to explain inflation differentials in the European Monetary Union (EMU). He finds that inflation dynamics in both countries are different in the non-tradable sector only.

Given the prominent role of non-tradable goods in international macroeconomics, however, there remain few studies in the literature that focus on how the introduction of non-tradable goods affects monetary policy arrangements. In particular, what is the optimal monetary policy in an environment that features non-traded goods? To this end, this paper studies optimal monetary policy in a small open economy DSGE model with non-tradable goods. The model belongs to the class of models in the New Open Economy Macroeconomics (NOEM) literature, see Obstfeld and Rogoff (1995) and Galí and Monacelli (2005).[1]

The model has two production sectors that produce tradable goods and non-tradable goods, and sticky prices *à la* Calvo (1983). Final traded goods are used for home consumption or exported to the foreign country, whereas final non-traded goods are consumed domestically. Aggregate consumption is a composite of non-tradable and tradable consumption baskets, where the tradable basket combines home produced traded goods and imported foreign goods. Note that, since the model accounts for non-tradable goods, the movements in real exchange rates can be decomposed into changes in the terms of trade and the relative price of tradable to non-tradable goods (see Benigno and Thoenissen, 2003, 2008). There are four exogenous shocks in the model: an economy-wide technology shock, sector-specific technology shocks (tradable and non-tradable sectors), and a demand shock.

The main objectives of the paper are three-fold: (i) to understand the transmission

[1] Early contributions also include Betts and Devereux (2000), Obstfeld and Rogoff (2000), Corsetti and Pesenti (2001), Kollman (2001), and Chari et al. (2002), among others.

mechanism of supply and demand shocks; (ii) to evaluate the performance of alternative interest rate policies, based on welfare analysis; (iii) to study the Ramsey policy and optimal allocations. The paper makes contributions to the literature by providing several novel findings.

First, the results show that, by allowing for rich measures of inflation, positive technology shocks need not lead to deflation.[2] It depends crucially on the nature of exogenous shocks (economy-wide or sector-specific) as well as the particular interest rate policy. For example, in response to a positive technology shock in the non-tradable goods sector, the inflation rate in this sector falls whereas CPI inflation, domestic inflation, and inflation in the tradable sector all increase. This is induced by the dynamic movements of the relative price of tradable goods. The relative price of tradables may decrease or increase, also depending on the shock. And this price falls in response to a positive demand shock. In addition, real exchange rate depreciates in response to all types of technology shocks, so do the terms of trade.

Second, there is still no consensus on which inflation should the monetary authority target in open economy models. This paper contributes to the debate by studying the dynamic response of the economy under three different interest rate rules: the one that targets CPI inflation (policy I), the one that targets domestic inflation (policy II), and the interest rate policy that allows for exchange rate stabilization (policy III).[3] The results show that interest rate rules have important implications for the dynamics of macroeconomic variables, including different types of inflation.

The paper also provides welfare based analysis to rank the three interest rate policies. The results are mixed. Policy I outperforms the other two if monetary policy is not very aggressive. However, if monetary policy becomes relatively aggressive, policy

[2] Note that in this model, there are four types of inflation: CPI inflation, domestic inflation, inflation in the tradable goods sector, and inflation in the non-tradable goods sector.

[3] See the text later for the motivations of the three interest rate policies.

II then turns out to yield the highest level of welfare. Policy III performs the worst in terms of welfare, which suggests that central banks should not allow for exchange rate smoothing. Note that since aggressive monetary policy features higher welfare, the previous result seems to suggest that policy II is more in line with the optimal monetary policy.

Third, this paper then studies the Ramsey policy and derives optimal allocations. Indeed, consistent with our conjecture, the Ramsey planner is shown to stabilize the inflation rates in both production sectors, while allowing for volatilities in CPI inflation, real exchange rates, the terms of trade, and the relative price of tradable goods. This suggests that the interest rate rules targeting CPI inflation or exchange rates are suboptimal, and outperformed by the one that targets domestic inflation. In addition, the results show that in response to sector specific shocks, the Ramsey planner only cares about the inflation rate in the sector where the shock originates.

Related Literature. This paper relates closely to two strands of literature in open economy DSGE models. One strand of literature studies optimal monetary policy using variants of Galí-Monacelli (2005) model. Monacelli (2005) finds that a model with imperfect exchange rate pass-through generates a policy trade-off between the stabilization of domestic inflation and output gap. Faia and Monacelli (2008) study optimal monetary policy in a small open economy model with home bias in consumption. They find that, home bias emerges as an independent factor that induces the monetary policymaker to depart from strict domestic inflation targeting. De Paoli (2009b) studies the same problem in an environment where the assumption of complete financial markets is relaxed. She finds that the degree of international risk sharing significantly affects optimal monetary policy and the performance of policy rules. Engel (2011) studies optimal monetary policy by assuming local currency pricing. He finds that this modification warrants a focus on CPI inflation, instead of domestic inflation. This paper contributes to this literature by studying optimal monetary policy with non-tradable goods. The results summarized before indicate that the introduction of non-tradable goods makes the nature of optimal monetary policy fundamentally different from the one of the standard Galí-Monacelli environment.

Another strand of literature studies the transmission of shocks in an open economy DSGE model that includes non-traded goods. Dotsey and Duarte (2008) argue that non-traded goods play an important role on driving real exchange rate dynamics. Their results also suggest that the model with tradable goods is useful in bringing the model closer to the real data. Benigno and Thoenissen (2008) use an open economy model with non-traded goods to study the consumption–real exchange rate anomaly. They show that such an anomaly can be successfully addressed by models that feature non-traded goods production sector and incomplete international financial markets. Lombardo and Ravenna (2014) study the implications of monetary policy using a simple, analytically tractable, small open economy model with predetermined prices and non-tradable goods. They show that through which channels the composition of imports can affect the policy trade-off across inefficiency gaps.[4] Rabanal (2009) develops an open economy model with non-traded goods to study inflation differentials between Spain and the EMU. He finds that inflation dynamics are different across countries in the non-traded sector only. Different from these studies, this paper focuses on the welfare implications of alternative interest rate policies, as well as characterizing the Ramsey optimal allocations.

The rest of the paper is organized as follows. In Section 2, I lay out a small open economy model with non-tradable goods. I also derive the equilibrium of the model. In Section 3, I calibrate the model using conventional values in the literature. Section 4 studies the dynamic responses of macroeconomic variables to supply and demand

[4] In their extended model, they develop a Calvo price, open economy model with non-tradable goods. Different from this paper, however, their focus is on the welfare cost of an exchange rate peg.

shocks. In Section 5, I study the dynamic performance of alternative monetary policy rules. I also provide welfare based analysis. Section 6 studies the Ramsey optimal policy and derives optimal allocations. Section 7 conducts sensitivity analysis. Section 8 offers concluding remarks.

2 The model

The model builds on the standard small open economy New Keynesian DSGE framework developed in Galí and Monacelli (2005, 2016). The economy features two sectors that produce tradable goods and non-tradable goods, respectively, similar to Dotsey and Duarte (2008), Rabanal (2009), and Lombardo and Ravenna (2014). Firms produce a continuum of tradable goods and a continuum of non-tradable goods, with each producer being a monopolistic supplier of a variety. Prices are sticky *à la* Calvo (1983) in both sectors of production. The final good (tradable and non-tradable) is a composite of differentiated varieties. Final traded goods are used for home consumption or exported to the foreign country, whereas final non-traded goods are consumed domestically. Aggregate consumption is a composite of non-tradable and tradable consumption baskets, where the tradable basket combines domestically produced traded goods and imported foreign goods.

Furthermore, I assume that labor is the only input in the production function. The law of one price holds and international financial markets are complete. The monetary authority is assumed to follow a standard Taylor-type interest rate rule that targets CPI inflation. In addition to that, two stylized Taylor-type rules are considered: one targets domestic inflation and one allows for some concern for exchange rate fluctuations. Finally, as in Galí and Monacelli (2005), I assume that the size of the home economy is negligible relative to that of the world economy, which allows us to take world aggregates as exogenous. The model also incorporates four exogenous shocks: an economy-wide technology shock, sector-specific technology shocks (tradable and non-tradable sectors), and a demand shock.

2.1 Households

The home economy is populated by a continuum of infinitely-lived households. A representative household has utility function of the form:

$$U_t = E_0 \sum_{t=0}^{\infty} \beta^t \left(\frac{C_t^{1-\sigma}}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi}\right) Z_t, \tag{1}$$

where $\sigma, \varphi > 0$, are the inverse elasticities of intertemporal substitution and labor disutility, C_t is an aggregate consumption index defined across tradable goods and non-tradable goods, E is the expectations operator, $\beta \in (0,1)$ is the intertemporal discount factor, and N_t is aggregate labor supply. Z_t is an exogenous demand shock (a preference shifter), which follows an exogenous process:

$$Z_t = \bar{Z}^{1-\rho_z} Z_{t-1}^{\rho_z} e^{\epsilon_t^z}, \tag{2}$$

where ρ_z is the first-order autocorrelation, $\bar{Z} = 1$ is the steady state value, and the standard deviation of ϵ_t^z is σ_z.

The consumption index C_t for home agents is defined as a constant elasticity of substitution (CES) aggregate of tradable (C_t^T) and non-tradable goods (C_t^N):

$$C_t \equiv [(1-\gamma)^{\frac{1}{\xi}} (C_t^N)^{\frac{\xi-1}{\xi}} + \gamma^{\frac{1}{\xi}} (C_t^T)^{\frac{\xi-1}{\xi}}]^{\frac{\xi}{\xi-1}}, \tag{3}$$

where γ is the share of tradable goods in the consumption basket and ξ is the elasticity of substitution between tradable and non-tradable goods. C_t^N is a composite index of consumption of non-traded goods, given by:

$$C_t^N \equiv (\int_0^1 C_t^N(n)^{\frac{\epsilon_N - 1}{\epsilon_N}} dn)^{\frac{\epsilon_N}{\epsilon_N - 1}},$$

with n denoting the good variety. $\epsilon_N > 1$ is the elasticity of substitution between types of differentiated varieties.

The subindex of consumption for tradable goods (C_t^T), in turn is defined as the following function of domestically produced tradable goods (C_t^H) and imported foreign goods (C_t^F):

$$C_t^T \equiv [(1-\upsilon)^{\frac{1}{\eta}}(C_t^H)^{\frac{\eta-1}{\eta}} + \upsilon^{\frac{1}{\eta}}(C_t^F)^{\frac{\eta-1}{\eta}}]^{\frac{\eta}{\eta-1}}, \tag{4}$$

where υ denotes the fraction of home-produced consumption goods, and hence can be interpreted as a measure of openness, η is the elasticity of substitution between home and foreign goods. Similarly, C_t^H and C_t^F are Dixit–Stiglitz aggregates of the available domestic and foreign produced goods given by:

$$C_t^H \equiv (\int_0^1 C_t^H(h)^{\frac{\epsilon_H - 1}{\epsilon_H}} dh)^{\frac{\epsilon_H}{\epsilon_H - 1}}, C_t^F \equiv (\int_0^1 C_t^F(f)^{\frac{\epsilon_F - 1}{\epsilon_F}} df)^{\frac{\epsilon_F}{\epsilon_F - 1}}.$$

Given household's preferences, optimal consumption demand for each category of consumption good is:

$$C_t^N(n) = (\frac{P_t^N(n)}{P_t^N})^{-\epsilon_N} C_t^N, C_t^H(h) = (\frac{P_t^H(h)}{P_t^H})^{-\epsilon_H} C_t^H, C_t^F(f) = (\frac{P_t^F(f)}{P_t^F})^{-\epsilon_F} C_t^F.$$

And demand functions for domestically produced tradable goods, foreign imported goods, non-tradable goods, and tradable goods are given by:

$$C_t^H = (1-\upsilon)(\frac{P_t^H}{P_t^T})^{-\eta} C_t^T, \tag{5}$$

$$C_t^F = \upsilon(\frac{P_t^F}{P_t^T})^{-\eta} C_t^T, \tag{6}$$

$$C_t^N = (1-\gamma)(\frac{P_t^N}{P_t})^{-\xi} C_t, \tag{7}$$

$$C_t^T = \gamma(\frac{P_t^T}{P_t})^{-\xi} C_t, \tag{8}$$

where $P_t^H \equiv (\int_0^1 P_t^H(h)^{1-\epsilon_H} dh)^{\frac{1}{1-\epsilon_H}}$ is the *domestic* price index in the traded goods sector (i.e., an index of prices of domestically produced tradable goods), $P_t^N \equiv (\int_0^1 P_t^N(n)^{1-\epsilon_N} dn)^{\frac{1}{1-\epsilon_N}}$ is the price index in the non-traded goods sector.

Finally, the price index for tradable goods has the following form:

$$P_t^T \equiv [(1-\upsilon)(P_t^H)^{1-\eta} + \upsilon(P_t^F)^{1-\eta}]^{\frac{1}{1-\eta}}, \tag{9}$$

and the aggregate *Consumer Price Index* (CPI) is given by:

$$P_t \equiv [(1-\gamma)(P_t^N)^{1-\xi} + \gamma(P_t^T)^{1-\xi}]^{\frac{1}{1-\xi}}. \tag{10}$$

In this model, households are assumed to have access to a complete set of state-contingent Arrow securities, traded internationally. The period budget constraint is given by:[5]

$$P_t C_t + E_t\{Q_{t,t+1} D_{t+1}\} = D_t + W_t N_t + T_t, \tag{11}$$

[5]Note that, following the above preferences, we have: $P_t^N C_t^N + P_t^T C_t^T = P_t C_t$, $P_t^H C_t^H + P_t^F C_t^F = P_t^T C_t^T$, where $\int_0^1 P_t^N(n) C_t^N(n) dn = P_t^N C_t^N$, $\int_0^1 P_t^H(h) C_t^H(h) dh + P_t^F(f) C_t^F(f) = P_t^T C_t^T$.

where $W_t N_t$ is wage income, with W_t being the nominal wage, T_t denotes lump-sum transfers/taxes, D_{t+1} is the stochastic nominal payoff in period $t+1$ of the portfolio held at the end of period t (including shares in traded and non-traded goods firms), and $Q_{t,t+1} \equiv \beta(C_t/C_{t+1})^{\sigma}(P_t/P_{t+1})(Z_{t+1}/Z_t)$ is the stochastic discount factor for one-period-ahead nominal payoffs. Note that $Q_t \equiv E_t\{Q_{t,t+1}\} = 1/R_t$ is considered as the price of a one-period discount bond paying off one unit of domestic currency in all possible states at $t+1$, where R_t is the gross interest rate.

Each household chooses optimal portfolio of assets, consumptions and labor supplies that maximize the life-time utility (1) subject to the budget constraint (11) for $t \geq 0$. The first-order conditions of the representative household are:

$$\beta R_t E_t\{(\frac{C_t}{C_{t+1}})^{\sigma}(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})\} = 1, \tag{12}$$

$$w_t = C_t^{\sigma} N_t^{\varphi}, \tag{13}$$

where $\Pi_{t+1} \equiv \frac{P_{t+1}}{P_t}$ denotes the gross CPI inflation rate from period t to $t+1$, $w_t \equiv \frac{W_t}{P_t}$ denotes the real wage. Eq (12) is the conventional Euler equation, Eq (13) represents the optimal labor supply decision.

2.1.1 Terms of trade, the real exchange rate, and inflation

Next, several assumptions and definitions are introduced, and a number of identities are derived that are extensively used throughout the paper. The *terms of trade*, denoted by S_t, are defined as the relative price of the imported good:

$$S_t \equiv \frac{P_t^F}{P_t^H}. \tag{14}$$

The *real exchange rate* is defined as the ratio of world and domestic CPI's, both expressed in domestic currency:

$$Q_t \equiv \frac{P_t^F}{P_t}. \tag{15}$$

It is assumed that the law of one price holds for individual goods at all times (both for import and export goods). In particular, $P_t^F = \mathcal{E}_t P_t^*$, where $\mathcal{E}_t$ denotes the nominal exchange rate, that is, the price of foreign currency in terms of home currency, and $P_t^* = 1$ is the price of foreign goods expressed in foreign currency and can be interpreted as a world price index.[6] In addition, we define:

$$q_t^S \equiv \frac{P_t^T}{P_t^H} = [(1-\upsilon) + \upsilon {S_t}^{1-\eta}]^{\frac{1}{1-\eta}}. \tag{16}$$

The *relative price of tradable to non-tradable goods* is defined as:

$$T_t \equiv \frac{P_t^T}{P_t^N}. \tag{17}$$

And, we define:

$$h_t^T \equiv \frac{P_t}{P_t^N} = [(1-\gamma) + \gamma {T_t}^{1-\xi}]^{\frac{1}{1-\xi}}. \tag{18}$$

Note that, under our assumptions, we have $\partial q_t^S(S_t)/\partial S_t > 0$ and $\partial h_t^T(T_t)/\partial T_t > 0$.

Given the above relative prices, the real exchange rate can be rewritten as:

$$Q_t = \frac{S_t}{P_t/P_t^H} = \underbrace{(S_t/q_t^S)}_{\text{from terms of trade}} \times \underbrace{(T_t/h_t^T)}_{\text{from internal relative price}}. \tag{19}$$

That is, in this model, the movements in the real exchange rate can be decomposed

[6] Note that variables with asterisks denote foreign variables.

into two parts: the movements of the terms of trade and the movements in the relative price of tradable goods, see Benigno and Thoenissen (2003, 2008).

Finally, note that there are four types of inflation in this model: CPI inflation $\Pi_t \equiv \frac{P_t}{P_{t-1}}$, inflation in the domestic tradable sector (i.e., domestic inflation) $\Pi_t^H \equiv \frac{P_t^H}{P_{t-1}^H}$, inflation in the non-tradable sector $\Pi_t^N \equiv \frac{P_t^N}{P_{t-1}^N}$, and inflation in the tradable goods $\Pi_t^T \equiv \frac{P_t^T}{P_{t-1}^T}$. Given our assumptions, they are also linked as follows:

$$\Pi_t = \Pi_t^N \frac{h_t^T}{h_{t-1}^T}, \tag{20}$$

$$\Pi_t^T = \Pi_t^H \frac{q_t^S}{q_{t-1}^S}, \tag{21}$$

$$\frac{T_t}{T_{t-1}} = \frac{\Pi_t^T}{\Pi_t^N}. \tag{22}$$

2.1.2 International risk sharing

Under the assumption of a complete set of state-contingent bonds traded internationally, the portfolio choice by households in the foreign country implies the following Euler condition, analogous to (12):[7]

$$\beta R_t^* E_t\{(\frac{C_t^*}{C_{t+1}^*})^\sigma(\frac{1}{\Pi_{t+1}^*})(\frac{\mathcal{E}_t}{\mathcal{E}_{t+1}})\} = 1. \tag{23}$$

Combing optimality conditions between home households (12) and foreign households (23), and noting that the law of one price holds, we obtain the risk-sharing condition under complete markets, which determines the real exchange rate in this model:

[7] For simplicity, I assume that foreign households are not subject to demand shocks.

$$Q_t = \frac{U^*_{c,t}}{U_{c,t} Z_t} = \frac{(C^*_t)^{-\sigma}}{C_t^{-\sigma} Z_t}. \tag{24}$$

The above condition explicitly shows that risk-sharing in international financial markets equates the ratio of marginal utilities of consumption in both countries with the real exchange rate.[8] In this model, since the home economy is infinitesimally small and foreign variables are taken to be exogenous, marginal utility of consumption in the foreign country does not change in response to domestic shocks. Thus, there exists a mechanic link between domestic consumption and the real exchange rate.[9]

For example, if aggregate consumption increases (e.g., caused by a positive technology shock), marginal utility of consumption would fall, this then implies a depreciation of the real exchange rate. Intuitively, an increase in home consumption implies a smaller marginal utility of consumption, conditional on that a specific state of nature is realized, everything else equal, this means a higher growth rate of marginal utility and hence a higher price of the Arrow security. Note that the same security is traded internationally, under the assumption of no-arbitrage, for foreign households to hold the security and take the higher price, the real exchange rate has to depreciate.

Under the assumption that the size of the home country is negligible, relative to the rest of the world, $C^*_t = Y^*_t$ for all t. Thus, (24) is rewritten as:

$$C_t = Y^*_t Z_t^{\frac{1}{\sigma}} Q_t^{\frac{1}{\sigma}}. \tag{25}$$

[8] Technically, this condition also depends on initial conditions regarding relative net asset positions, see Chari et al. (2002) and De Paoli (2009b). Here, for simplicity, symmetric initial conditions are assumed, implying the above equation (24).

[9] The same argument also holds true if one considers a demand shock. According to (24), a positive preference shifter implies a real exchange rate appreciation, although this effect can be mitigated by the increase in consumption.

2.2 Firms

There are two sectors of production in the model: the non-traded goods sector and the traded goods sector. The two sectors are constructed symmetrically in assuming that firms in each sector produces a continuum of differentiated varieties and set prices in a standard Calvo (1983) fashion. In addition, firms in each sector feature two supply-side shocks: an economy-wide technology shock and a sector-specific technology shock.

Non-tradable goods sector. Assume a continuum of monopolistically competitive firms indexed by $n \in [0,1]$. Each firm produces a differentiated non-tradable good, using labor as the only input. The production function is:

$$Y_t^N(n) = A_t A_t^N N_t^N(n), \tag{26}$$

where A_t is the economy-wide technology, assumed to be common to all firms (tradable and non-tradable) and to evolve exogenously over time according to:

$$A_t = \bar{A}^{1-\rho_a} A_{t-1}^{\rho_a} e^{\epsilon_t^a}, \tag{27}$$

ρ_a is the first-order autocorrelation, $\bar{A} = 1$ is the steady state value of technology, and the standard deviation of ϵ_t^a is σ_a. A_t^N represents the technology in the non-traded goods sector, and it follows according to:

$$A_t^N = (\bar{A}^N)^{1-\rho_{a,N}} (A_{t-1}^N)^{\rho_{a,N}} e^{\epsilon_t^{a,N}}, \tag{28}$$

where $\rho_{a,N}$ is the first-order autocorrelation, $\bar{A}^N = 1$ is the steady state value of technology, and the standard deviation of $\epsilon_t^{a,N}$ is $\sigma_{a,N}$.

Firms set their prices subject to a Calvo (1983) price rigidity. Each firm may reset its price only with probability $1 - \theta_N$ in any given period, independent of the time elapsed since it last adjusted its price. Since the problem is symmetric, every firm faces the same decision problem and will choose the same optimal price $\bar{P}_t^N$. This pricing behavior implies the law of motion for the aggregate price index in the non-traded goods sector:

$$P_t^N = [(1-\theta_N)(\bar{P}_t^N)^{1-\epsilon_N} + \theta_N(P_{t-1}^N)^{1-\epsilon_N}]^{\frac{1}{1-\epsilon_N}}. \tag{29}$$

Alternatively, if we define $\tilde{p}_t^N \equiv \frac{\bar{P}_t^N}{P_t^N}$, the above condition can be written as:

$$1 = (1-\theta_N)(\tilde{p}_t^N)^{1-\epsilon_N} + \theta_N(\Pi_t^N)^{\epsilon_N - 1}. \tag{30}$$

A firm reoptimizing in period t will choose the price $\bar{P}_t^N$ that maximizes the current market value of the profits generated while that price remains effective. This corresponds to solving the problem:

$$\max_{\bar{P}_t^N} E_t \sum_{k=0}^{\infty} \theta_N^k Q_{t,t+1}[\bar{P}_t^N Y_{t+k|t}^N - (1/\mu_N^s)\Psi_{t+k}^N(Y_{t+k|t}^N)], \tag{31}$$

subject to the sequence of demand constraints:

$$Y_{t+k|t}^N = (\frac{\bar{P}_t^N}{P_{t+k}^N})^{-\epsilon_N} Y_{t+k}^N, \tag{32}$$

where $Q_{t,t+1}$ is the stochastic discount factor for nominal payoffs, $Y_{t+k|t}^N$ denotes output in period $t+k$ for a firm that last adjusts its price in period t, Ψ_t^N is the nominal cost function, and $\mu_N^s = \frac{\epsilon_N}{\epsilon_N - 1}$ is time-invariant employment subsidy which can be used to eliminate the steady-state distortion associated with monopolistic competition. In addition, minimizing labor costs yields the expression for the real marginal cost: $mc_t^N = \frac{W_t}{A_t A_t^N P_t^N}$. Note that $w_t \equiv \frac{W_t}{P_t}$ denotes the CPI real wage, thus:

$$mc_t^N = \frac{w_t h_t^T}{A_t A_t^N}. \tag{33}$$

The optimality condition associated with the problem above satisfies:

$$\tilde{p}_t^N = \frac{E_t \sum_{j=0}^{\infty} \theta_N^j Q_{t,t+k} (\frac{P_{t+j}^N}{P_t^N})^{\epsilon_N+1} mc_{t+j}^N Y_{t+j}^N}{E_t \sum_{j=0}^{\infty} \theta_N^j Q_{t,t+k} (\frac{P_{t+j}^N}{P_t^N})^{\epsilon_N} Y_{t+j}^N} = \frac{F_t^N}{K_t^N}, \tag{34}$$

where K_t^N and F_t^N are aggregate variables that satisfy the recursive relations:

$$K_t^N = Y_t^N + \beta\theta_N E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})K_{t+1}^N(\Pi_{t+1}^N)^{\epsilon_N}\}, \tag{35}$$

$$F_t^N = Y_t^N mc_t^N + \beta\theta_N E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})F_{t+1}^N(\Pi_{t+1}^N)^{\epsilon_N+1}\}. \tag{36}$$

Tradable goods sector. Most expressions in the tradable sector are analogous to those of the non-tradable sector. To save space, I only characterize the equilibrium conditions:

$$1 = (1-\theta_H)(\tilde{p}_t^H)^{1-\epsilon_H} + \theta_H(\Pi_t^H)^{\epsilon_H-1}, \tag{37}$$

$$\tilde{p}_t^H = \frac{F_t^H}{K_t^H}, \tag{38}$$

$$K_t^H = Y_t^H + \beta\theta_H E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})K_{t+1}^H(\Pi_{t+1}^H)^{\epsilon_H}\}, \tag{39}$$

$$F_t^H = Y_t^H mc_t^H + \beta\theta_H E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})F_{t+1}^H(\Pi_{t+1}^H)^{\epsilon_H+1}\}, \tag{40}$$

$$mc_t^H = \frac{w_t h_t^T q_t^S}{A_t A_t^H T_t}. \tag{41}$$

2.3 Export demand

Following Galí and Monacelli (2005), foreign demand for the home country's exported goods is assumed to be given by:

$$\begin{aligned} X_t &= \upsilon(\frac{P_t^H}{\mathcal{E}_t})^{-\eta} Y_t^* \\ &= \upsilon S_t^{\eta} Y_t^*. \end{aligned} \tag{42}$$

2.4 Monetary policy

Monetary policy is conducted as an interest rate schedule following a Taylor-type rule. In the benchmark case, I consider a simple interest rate rule as follows:

$$\frac{R_t}{\bar{R}} = (\frac{\Pi_t}{\bar{\Pi}})^{\phi_\pi}, \tag{43}$$

where $\bar{R}$ and $\bar{\Pi}$ are steady-state values of nominal interest rates and the central bank's headline inflation target (assumed to be one), $\phi_\pi > 1$ is the weight measuring the response of interest rate to inflation deviations.

In addition, I consider two alternative Taylor-type interest rate rules: one that targets domestic inflation and one allows for exchange rate smoothing (see Lombardo and Ravenna, 2014). The two rules are given by:

$$\frac{R_t}{\bar{R}} = (\frac{\Pi_t}{\bar{\Pi}^H})^{\phi_\pi}, \tag{44}$$

$$\frac{R_t}{\bar{R}} = (\frac{\Pi_t}{\bar{\Pi}})^{\phi_\pi}(\frac{\mathcal{E}_t}{\bar{\mathcal{E}}})^{\phi_e}. \tag{45}$$

2.5 Market clearing

Equilibrium in the market for each differentiated variety n in the non-traded goods sector requires:

$$N_t^N(n) = (\frac{P_t^N(n)}{P_t^N})^{-\epsilon_N} Y_t^N.$$

Integrating it yields:

$$\int_0^1 N_t^N(n) \equiv N_t^N = \Delta_t^N \frac{Y_t^N}{A_t A_t^N}, \tag{46}$$

where price dispersion $\Delta_t^N \equiv \int_0^1 (\frac{P_t^N(n)}{P_t^N})^{-\epsilon_N} dn$ evolves according to:

$$\Delta_t^N = (1-\theta_N)(\tilde{p}_t^N)^{-\epsilon_N} + \theta_N(\Pi_t^N)^{\epsilon_N}\Delta_{t-1}^N. \tag{47}$$

Analogously, for traded goods sector, we have:

$$N_t^H = \Delta_t^H \frac{Y_t^H}{A_t A_t^H}, \tag{48}$$

$$\Delta_t^H = (1-\theta_H)(\tilde{p}_t^H)^{-\epsilon_H} + \theta_N(\Pi_t^N)^{\epsilon_N}\Delta_{t-1}^N. \tag{49}$$

In addition, goods market clearing conditions imply:

$$
\begin{aligned}
Y_t^H &= C_t^H + X_t \\
&= (1-\upsilon)(q_t^S)^\eta \gamma (\frac{h_t^T}{T_t})^\xi C_t + \upsilon S_t^\eta Y_t^*,
\end{aligned} \tag{50}
$$

$$
Y_t^N = (1-\gamma)(h_t^T)^\xi C_t. \tag{51}
$$

The market clearing condition in the labor market is:

$$
N_t = N_t^H + N_t^N. \tag{52}
$$

Equilibrium equations and exogenous stochastic processes are given in Appendix A.

3 Parameterization

In this section I report the benchmark parameter values used in solving the model, summarized in Table 1. The model is parameterized at a quarterly frequency. Many parameter values are standard in the business cycle literature. The discount factor β is set at 0.99, which gives a steady state annualized interest rate of 4%. The intertemporal elasticity of substitution between bundles is set to one ($\sigma = 1$). I choose $\varphi = 5$, which implies a Frisch elasticity of labour supply of 0.2 (see Galí, 2015). The elasticity of substitution between intermediate goods among domestically produced traded goods, ϵ_H, is set equal to 9, which is a common value in the literature. It implies a value for the steady state mark-up rate, $\epsilon_H/(\epsilon_H - 1)$, of approximately 12.5%. The price stickiness parameter, θ_H, is set at 0.75, which corresponds to the average duration of price contracts of about four quarters (see Monacelli, 2004; Faia and Monacelli, 2008). Since both production sectors are constructed as symmetric, I set the same parameter values for the non-traded goods sector: $\epsilon_N = 9$ and $\theta_N = 0.75$. Regarding the parameters characterizing interest rate rules, I set $\phi_\pi = 1.5$, and $\phi_e = 0.1$ (see Monacelli, 2004; Lombardo and Ravenna, 2014).

The share of traded goods in the consumption index is set to 0.87, which is the value estimated by Lombardo and Ravenna (2014) for the Czech Republic using a small open economy model. The elasticity of substitution between tradable and non-tradable goods, ξ, is set to 0.7. This is in line with the estimates used in the literature, see, for example, Mendoza (1995), Dotsey and Duarte (2008), and Lombardo and Ravenna (2014). Since the two parameters are important for this model, I perform sensitivity analysis with respect to them. In addition, there exists home bias towards domestically produced tradable goods, and the weight on foreign goods, υ, is assumed to be 0.26 (Galí and Monacelli, 2005; Lombardo and Ravenna, 2014). I assume an elasticity of substitution between home and foreign-produced traded goods, η, of 2 (see Benigno and Thoenissen, 2008; Faia and Monacelli, 2008).

Finally, to calibrate the sources of stochastic volatility, I choose the autoregressive coefficients of economy-wide technology shock ρ_a and demand shock ρ_z, to 0.9 and 0.8, respectively (see Monacelli, 2004, 2005). Standard deviations of innovation to technology shocks and demand shocks are assumed to be one percent, i.e., $\sigma_a = 0.01$ and $\sigma_z = 0.01$, see Monacelli (2005), Dotsey and Duarte (2008), and Lombardo and Ravenna (2014). Exogenous processes of sector-specific technology are assumed to be the same as those in the economy-wide technology, implying $\rho_{a,N} = 0.9, \sigma_{a,N} = 0.01$ and $\rho_{a,H} = 0.9, \sigma_{a,H} = 0.01$. These values are well in the range of the estimates of Rabanal and Tuesta (2013) who employ Bayesian estimation of an open economy DSGE model with tradable goods.

4 Transmission of exogenous shocks

In this paper, I study the macroeconomic impact of three supply-side shocks and one demand shock. I start by describing the dynamic effects of an expansionary economy-wide technology shock on a number of macroeconomic variables, as shown in Figure 1. In the benchmark case, monetary policy is assumed to follow a Taylor rule that targets CPI inflation (black solid lines). The level of technology for both production sectors (tradable and non-tradable) is assumed to increase by one percent. The increase in technology leads to an immediate increase in output (Y_t^H and Y_t^N) and a fall in sector-wide inflation (Π_t^H and Π_t^N). This, in turn, puts downward pressures on the inflation rate in the tradable goods Π_t^T and CPI inflation Π_t. As a result, we see the falls in Π_t^T and Π_t.[10] Following the Taylor rule, the monetary authority cuts the nominal interest rate R_t. This leads to a decrease in the real interest rate, triggering an increase in aggregate demand.

From the international risk-sharing condition (25), the increase in consumption causes the real exchange rate to depreciate. According to (19), the depreciation of real exchange rates can be decomposed into the deterioration of terms of trade and the increase the relative price of tradable goods, caused by the fall in the price of home produced goods (tradable and non-tradable). In addition, through the intratemporal condition, households supply less labor. This is met by the falls in working hours in both production sectors. In this experiment, the fall in labor supply also implies a decline in the real wage rate.

Next, we discuss the transmission mechanism of sector-specific shocks. Figure 2 and Figure 3 depict dynamic responses to the productivity shocks in the tradable and non-tradable goods sectors. Comparing with the result in Figure 1, there are interesting differences for inflation dynamics and real exchange rates. In Figure 2, in response to

[10] Note that this happens despite the increases in q_t^S and h_t^T.

the positive shock in the tradable goods sector, the price of home produced tradable goods falls, which tends to lower the inflation rate in the tradable goods, Π_t^H. It also leads to a depreciation of terms of trade. From (21), these two opposing effects imply deflation in the tradable goods (Π_t^T) in our benchmark exercise. This causes the relative price of tradable goods to *fall*, although this price hardly moves initially. According to (22), we now have an *increase* in the inflation rate in the non-traded goods sector, Π_t^N, different from the result in Figure 1.

The reverse picture holds true for a positive technology shock in the non-tradable goods sector, shown in Figure 3. That is, in response to the shock, we have deflation in the non-traded goods sector Π_t^N whereas inflation in the home produced tradable goods sector Π_t^H. The latter leads to an *increase* in the inflation rate of tradable goods Π_t^T. Combing with the fall in the price of non-traded goods, we see a big increase in the relative price of tradable goods, contributing to the depreciation of real exchange rates. However, the terms of trade depreciates only modestly, owing to the increase of the price in the home produced tradable goods.

Finally, Figure 4 depicts the dynamic response to a positive demand shock. I report impulse responses to a one percent increase in preference. From the Euler equation, as agents give more weight to current utility, relative to future utility, the shift in preference induces an increase in consumption and hence in aggregate demand. To match the high level of demand, the increase in Z_t leads to an increase in output (tradable and non-tradable), employment (tradable and non-tradable), and real wages. Higher output in turn pushes up inflation in both sectors Π_t^N and Π_t^H. One the one hand, it contributes to the increases in Π_t and Π_t^T. On the other hand, this causes the terms of trade to deteriorate and the relative price of tradable goods to fall. Both effects imply a depreciation of the real exchange rate.

Note that the above findings indicate that, unlike the result of the standard Galí-

Monacelli (2005) setup, positive technology shocks need not cause deflation. Owing to the presence of non-tradable goods, it depends crucially on the source of exogenous shocks (economy-wide or sector-specific) and the particular type of inflation that one refers to. In addition, the model with a non-traded goods sector can generate interesting dynamics for the relative price of tradable to non-tradable goods, which in turn has important implications for exchange rate dynamics.

5 Monetary policy rules and welfare

No doubt that one of the key objectives of monetary policy is to stabilize inflation. In a closed economy, the measure of inflation is well defined. However, in an open economy, there typically exist many types of inflation, including CPI inflation and domestic inflation, which are most commonly discussed in the literature. Which inflation should be the target variable for the central bank? This is a relevant question given that the two variables often display quite different dynamics (see Campolmi, 2014). It gets even more important because in practice central banks often adopt CPI inflation as the target variable (see Bernanke and Mishkin, 1997), whereas many studies in the new open economy macroeconomics literature suggest the central bank should instead use domestic inflation as the target (see Clarida et al., 2001; Galí and Monacelli, 2005; Kirsanova et al., 2006). Another important debate surrounding optimal monetary policy in open economies lays the question of whether central banks should allow for some exchange rate stabilization (see De Paoli, 2009a, 2009b; Lombardo and Ravenna, 2014).

To this end, this section studies the dynamic responses of exogenous shocks under two alternative Taylor-type interest rules: one that targets domestic inflation and one that allows for exchange rate smoothing, see (44) and (45). In addition, since the model dynamics under alternative rules are often different, a concrete welfare-based analysis is needed to rank monetary policy rules. I follow the standard approach in Lester et al. (2014) and Jia (2020) to conduct welfare evaluation.

5.1 Alternative monetary policy rules

The dashed blue lines in Figure 1 to Figure 4 display the dynamic responses of macroeconomic variables to supply and demand shocks, in which the monetary authority uses domestic inflation as the target. In Figure 1, since the central bank targets domestic inflation, Π_t^H falls by less, compared to our benchmark case. This implies a smaller fall in the inflation rate of tradable goods. In fact, Π_t^T now *increases*. This in turn *raises* CPI inflation. Again, it is interesting to note that in response to positive technology shocks, the economy need not feature deflation. It depends on the particular interest rate policy that is in play.

Following the Taylor rule targeting Π_t^H, nominal interest rates also fall by more, compared with the benchmark experiment. It then means a lower real interest rate, causing aggregate consumption to increase. The increase in aggregate demand is met by the increases in output and employment in both sectors. Through the New Keynesian Phillips curve, the increase in the real wage also tends to increase inflation in the non-traded goods sector. Furthermore, as for the dynamic movements of real exchange rates, the increase in consumption implies that the real exchange rate has to depreciate by more. This is also met by the depreciation of terms of trade (caused by nominal exchange rate depreciation) and the increase in the relative price of tradable goods (caused by the increase in the price of home produced tradable goods).

Overall, the model where the central bank targeting the domestic inflation does seem to generate more volatilities. It may suggest that the interest rate rule with CPI inflation could outperform the one with domestic inflation target. This argument, however, can only be confronted by a rigorous welfare evaluation.[11]

The same story holds true for other exogenous shocks, shown in Figure 2 to Figure 4. There are some additional points that are worth noting. First, in Figure 2, the inflation rate in the non-traded goods sector actually *increases*, caused by the big increase in real marginal costs. Note that in response to a positive technology shock in the traded goods sector, the economy features three types of *inflation*. Second, responding to the technology shock in the non-traded goods sector, the model generates falls in all the measures of inflation. Therefore, according to our results, inflation dynamics very much depend on the source of the shocks as well as the monetary policy rule.

Next, I study the scenario where the monetary authority allows for exchange rate stabilization and compare the results with those in the benchmark case, shown by the dashed red lines in Figure 1 to Figure 4. In Figure 1, as the central bank makes some room for exchange rate stabilization, real exchange rates display less volatilities. The smaller movement in the real exchange rate is also met by smaller volatilities in the terms of trade and the relative price of tradable goods. Deviating from strict CPI inflation targeting, CPI inflation now decreases by more. It also implies more volatilities in the inflation rates of non-traded goods sector and tradable goods. In addition, smaller movement in the CPI inflation rate causes the nominal interest rate to fall. The real interest rate, however, increases compared to the benchmark experiment, leading to a decline in aggregate demand. The fall in consumption is also met by the supply side of the economy. By and large, the model seems to generate more volatilities compared to the benchmark case but less volatilities compared to the model with domestic inflation targeting. Again, welfare evaluation is needed to rank alternative monetary policy rules. The same story carries over for the other three exogenous shocks, shown in Figure 2 to Figure 4.

[11]Indeed, the model with interest rate targeting domestic inflation does yield a lower Π_t^H but a higher Π_t. Thus, there exists a trade-off with different types of inflation.

5.2 Welfare analysis

Following Faia and Monacelli (2007) and Gertler and Karadi (2011), we assume the objective of the central bank is to maximize the average welfare of households. We begin by writing the household utility function in a recursive form:

$$V_t = U(C_t, N_t; Z_t) + \beta E_t V_t, \tag{53}$$

where V_t is the value function evaluated at a particular point in the state space. We then take a second order approximation of this function around the deterministic steady state. We next take a second order approximation of all model equations around the steady state and then use this approximation to express the objective as a second order function of the predetermined variables and shocks to the system.[12]

We then evaluate each policy specification by calculating the compensating variations in consumption, expressed in terms of the proportion of each period's consumption that a typical household would need to be compensated in the stochastic world in order to be indifferent from living in a deterministic risk-free world (see, e.g., Lester et al., 2014; Jia, 2020). More precisely, we calculate λ that satisfies the following equation:

$$E_0 \sum_{t=0}^{\infty} \beta^t [\ln(1+\lambda)C_t - \frac{N_t^{1+\varphi}}{1+\varphi}] = \tilde{V}, \tag{54}$$

where $\tilde{V} = (\ln \tilde{C} - \frac{\tilde{N}^{1+\varphi}}{1+\varphi})/(1-\beta)$ is the value of Ω_t in the deterministic risk-free steady state, $\tilde{C}$ and $\tilde{N}$ are the steady state values of consumption and aggregate employment.

In addition, define two auxiliary value functions V_t^C, V_t^N:

[12] Note that as it is well-documented in the literature, policy arrangements can be correctly evaluated only by resorting to a higher order approximation of the policy functions, see Schmitt-Grohé and Uribe (2004).

$$V_t^C = E_0 \sum_{t=0}^{\infty} \beta^t \ln C_t, \tag{55}$$

$$V_t^N = E_0 \sum_{t=0}^{\infty} \beta^t \left(-\frac{N_t^{1+\varphi}}{1+\varphi}\right), \tag{56}$$

$$V_t = V_t^C + V_t^N. \tag{57}$$

Under our specification of utility function one can solve for λ and obtain:

$$\lambda = \exp[(1-\beta)(\tilde{V} - V_t)] - 1. \tag{58}$$

Note that if $\lambda > 0$, then the household would prefer to be in the risk-free regime, and *vise versa*. The higher the λ, the lower the welfare. We refer to the Appendix B for more details on the computation of λ.

Next, I evaluate welfare across alternative monetary policy rules, the results are reported in Table 2. In response to the economy-wide technology shock, it is clear from Table 2 that the interest rate rule with CPI inflation yields the highest level of welfare, followed by the rule with nominal exchange rate smoothing, the monetary policy rule with domestic inflation performs the worst in terms of welfare. For example, there exists a welfare improvement of about 0.005% consumption if the central bank implements an interest rate policy that explicitly targets the CPI inflation rate instead of domestic inflation. In addition, the ranking of alternative monetary policy rules does not change if one considers other exogenous shocks. Thus, the results suggest that monetary policy that targets CPI inflation outperforms alternative policies. Note that this result is consistent with the volatility view that is discussed previously.

To check the robustness of the result, I then explore the welfare effects of varying the response to inflation in the Taylor rule, as shown in Table 2. This is meant to quantify the potential welfare gains associated with an aggressive monetary policy. There are several important results that are worth mentioning. First, there is no surprise that an aggressive interest rate policy yields a higher level of welfare. For instance, if the central bank targets CPI inflation, in response to the economy-wide shock, there is a welfare improvement of 0.01% consumption if the central bank increases ϕ_π from 1.5 to 2.5.

Second, interestingly enough, the previous ranking does not carry over if monetary policy becomes relatively aggressive. For example, if the central bank chooses ϕ_π at 2 or 2.5, the policy that targets *domestic* inflation now outperforms alternative policies. And the ranking is actually the *reverse* of the previous one. This is because the Taylor rule with domestic inflation targeting is very effective at mitigating the volatilities of macroeconomic variables.

Third, for the productivity shock on non-traded goods sector, however, monetary policy is in general not very effective at mitigating volatilities, despite the specific mandate of interest rate policy. The welfare improvement of aggressive monetary policy is shown to be very small. And now the interest rate rule that targets domestic inflation performs the worst. In sum, the results show that the ranking of alternative monetary policy rules depends crucially on the stance of monetary policy (being aggressive or not) and the source of exogenous shocks.

6 Ramsey optimal policy

To characterize optimal monetary policy, this section performs a rigorous Ramsey policy analysis, deriving the optimal allocations and price system. I also examine to what extent the Taylor-type interest rate policy is able to replicate the dynamics implied by the Ramsey planner. The Ramsey policy is the process $\{R_t\}$ associated with the competitive equilibrium that yields the highest level of utility to the representative household, that is, that maximizes (1). In addition, I assume that the authorities have sufficient credibility to commit to the policy rules they announce at date 0.[13] In this study, I focus on optimal commitment policy, adopting Woodford's (2003) "timeless perspective".[14]

Figure 5 displays dynamic responses of macroeconomic variables to an economy-wide technology shock, for both interest rate rule (the benchmark) and the Ramsey policy. We can see that the Ramsey planner dislikes inflation in both production sectors and chooses to stabilize Π_t^H and Π_t^N. It is interesting to note that the planner, however, can tolerate the CPI inflation rate and the price changes in the tradable goods. This behavior is completely different from a Taylor-type central banker where he chooses to control CPI inflation. Furthermore, the Ramsey planner chooses a higher nominal interest rate, compared to the benchmark case. This tends to increase the real interest rate. But the higher CPI inflation rate by the Ramsey planner also puts downward pressure on the real rate. Overall, the real rate falls, causing consumption to increase. On the one hand, the increase in aggregate demand has to be met by the increase in supply-side factors (output and employment). One the other hand, it causes the real exchange rate to depreciate by more. The movements in real exchange rates can also be decomposed by more terms of trade depreciation and the increase in the relative price of tradable to non-tradable goods. This suggests that the Ramsey optimal policy allows for relatively volatile exchange rates. In sum, the Ramsey planner is shown to choose very different allocations.

[13] Many authors have claimed that central banks have either described their current monetary policy as policy under commitment, or come very close to doing so, see Svensson (2009) and Adolfson et al. (2011).

[14] This approach is widely adopted in the literature, see, for instance, Schmitt-Grohé and Uribe (2004) and Kirsanova and Wren-Lewis (2012)

The story is similar for the other two productivity shocks, as in Figure 6 and Figure 7. There are, however, some interesting differences. For the productivity shock to traded goods sector, the Ramsey planner chooses a smaller Π_t^H, although he does not stabilize it. The planner then tolerates higher inflation rates for Π_t, Π_t^N, and Π_t^T. This result carries over for the productivity shock to non-traded goods sector, in which the Ramsey policy features a smaller Π_t^N but higher Π_t, Π_t^T, and Π_t^H. This partially explains why the Taylor rule is not very effective at mitigating volatilities and improving welfare, shown in Table 2. This is because the Taylor-type central banker targets either CPI inflation or domestic inflation, but the Ramsey planner chooses to tolerate both types of inflation and lower the inflation rate in the non-tradable sector.

For the demand shock, the Ramsey policy shows a complete stabilization of inflation in both production sectors, whereas allowing for volatile inflation rates for Π_t and Π_t^T, as depicted in Figure 8. The Ramsey planner sets lower nominal interest rates. The real rate, however, increases due to the large decline in CPI inflation. This in turn causes consumption to fall, leading to smaller adjustments in the supply side of the economy. The fall in consumption, compared with the benchmark, induces more volatile real exchange rates, terms of trade, and the relative price of tradable to non-tradable goods.

To sum up, the Ramsey planner is shown to choose very different allocations and prices, compared with the Taylor-type central banker. In particular, the Ramsey optimal policy typically tolerates Π_t and Π_t^T but features stabilization of Π_t^H and Π_t^N. While the Ramsey planner stabilizes the inflation rates in both production sectors, he allows for volatilities in the CPI inflation rate, real exchange rates, the terms of trade, and the relative price of tradable goods. This suggests that the interest rate rules targeting CPI inflation or exchange rates are suboptimal. And the interest rate policy that targets domestic inflation may outperform alternative monetary policy rules. In addition, the results show that in response to sector specific shocks, the Ramsey planner cares only about the inflation rate in the sector where the shock originates.

7 Sensitivity analysis

This section studies the effects of varying the weight on traded goods γ, and the elasticity of substitution between traded and non-traded goods ξ. These two parameters are deemed important for this small open economy model with non-tradable goods. In particular, I choose a lower value of γ ($\gamma = 0.55$) and a higher value of ξ ($\xi = 2$). Both parameter values are used in the literature, see, for example, Benigno and Thoenissen (2008). In this section, I study the Ramsey economy and provide welfare-based analysis.

7.1 The weight on tradable goods

The impulse responses to exogenous shocks with a lower γ ($\gamma = 0.55$) are reported in Figure 9 to Figure 12. In Figure 9, as agents consume more non-traded goods, the supply side of the economy has to catch up, implying an increase (a smaller drop) in employment in the non-traded goods sector, compared with the benchmark Ramsey policy. The Ramsey planner is shown to lower the nominal interest rate, despite the small increases in Π_t^H and Π_t^N. This in turn increases aggregate demand, causing output to go up. The increase in consumption also depreciates real exchange rates by more, which induces more volatile terms of trade and the relative price of tradable goods. The story is the same for shocks to non-traded goods sector, as shown in Figure 11.

Indeed, the model with a lower γ seems to generate a more volatile environment, suggesting a lower level of welfare. This result is also consistent with those obtained in Table 3. For example, if we compare the first column in Table 3 with that in Table

2, we see a loss in welfare. This result remains largely for other exogenous shocks, except for the shock to home produced tradable goods sector which I tend to the discussion. In Figure 10, the economy with more non-traded goods demand features more volatilities in Π_t^H, but less volatilities in the other types of inflation. The Ramsey planner chooses a higher nominal interest rate, compared with the benchmark Ramsey policy. Tightening monetary policy in turn cools down the economy. Similarly, the Ramsey planner tightens monetary policy in response to the demand shocks, as shown in Figure 12.

In addition, considering interest rate rules and welfare, the results are shown in Table 3. It is interesting to note that some of the results in Table 2 do not carry over. For example, when monetary policy is less aggressive (i.e., $\phi_\pi = 1.5$), CPI inflation targeting may not dominate alternative rules. It depends on the underlying exogenous forces. In response to the productivity shock in tradable sector or the demand shock, the interest rate rule with exchange rate smoothing performs the best in welfare terms. Also, when monetary policy becomes aggressive (i.e., $\phi_\pi = 2.5$), domestic inflation targeting may not outperform other monetary policy rule. The interest rate rule with CPI targeting yields the highest level of welfare in response to sector-specific shocks.

Overall, compared with the benchmark Ramsey policy, the model with a lower γ displays very different dynamics for most of the macroeconomic variables, including inflation and real exchange rates. To understand the model dynamics, the key lies on the Ramsey planner in setting monetary policy. If the planner tightens monetary policy, the economy tends to feature less volatilities, whereas if the planner chooses to loosen monetary policy, the model tends to generate more volatilities.

7.2 The elasticity of substitution between traded and non-traded goods

Finally, we examine the dynamics effects of a higher elasticity of substitution between traded and non-traded goods ξ ($\xi = 2$), shown in Figure 13 to Figure 16. In Figure 13, in response to the economy-wide technology shock, we see the Ramsey planner does not change the stance of monetary policy, so the real interest rate remains largely unchanged. This means aggregate demand remains unaffected, so do real exchange rates, terms of trade, and the relative price of tradable to non-tradable goods.

Note that there are, however, interesting changes in the supply side of the economy. According to (7) and (8), a higher elasticity of substitution between tradable and non-tradable goods would imply, everything else being equal, a lower demand for non-traded goods and home produced tradable goods. Thus, we see the falls in employment and output in the tradable sector. However, as the price of non-traded goods falls, it tends to increase the demand for non-tradable goods. The overall effect is shown to be positive for the non-traded goods sector. The same results holds for the technology shock in the non-traded goods sector, shown in Figure 15.

It is also interesting to note that, in Figure 15, the Ramsey planner loosens monetary policy by reducing nominal interest rates. However, the real rate increases due to the fall in expected CPI inflation. As a result, consumption falls. And we see real exchange rate depreciations. In Figure 14 and Figure 16, the fall in employment in the non-traded goods sector implies that there is an increase in employment in the traded goods sector. This is because aggregate level of employment does not move according to the intratemporal condition.

Next, I compare the performance of alternative monetary policy rules, shown in Table 4. The results are very similar to those obtained in Table 2. That is, when the monetary authority sets ϕ_π to 1.5, the interest rate rule targeting CPI inflation performs the best, whereas when monetary policy becomes relatively aggressive, the rule that targets domestic inflation yields the highest level of welfare. In addition, by comparing the results with those in Table 2, it is interesting to note that the model with a higher ξ typically features a higher level of welfare.

8 Concluding remarks

A prominent feature of an open economy is the existence of non-tradable goods. This paper introduces non-traded goods into a small open economy New Keynesian DSGE model and studies optimal monetary policy. The introduction of non-traded goods is shown to have important implications for the transmission of shocks and monetary policy arrangements. This paper makes contributions to the existing literature by providing several novel findings. First, the results show that positive technology shocks need not lead to deflation. It depends on the nature of exogenous forces (economy-wide or sector-specific) and the particular interest rate policy. In response to all types of technology shocks, real exchange rate and the terms of trade depreciate. The relative price of tradable to non-tradable goods may increase or decrease, depending on the shocks.

Second, based on welfare analysis, this paper evaluates the performance of different interest rate rules. The results show that if monetary policy is not very aggressive, the Taylor-type interest rate policy that targets CPI inflation performs the best. However, as monetary policy becomes relatively aggressive, the policy that targets domestic inflation is shown to yield the highest level of welfare. In addition, the interest rate policy that explicitly allows for exchange rate smoothing performs the worst in terms of welfare. This suggests that the monetary authority should not stabilize exchange rates.

Third, this paper studies the Ramsey policy and optimal allocations. The results indicate that the Ramsey optimal policy stabilizes the inflation rates in both production sectors, while allowing for volatilities in the CPI inflation rate, real exchange rates, the terms of trade, and the relative price of tradable goods. This suggests that the interest rate rules targeting CPI inflation or exchange rates are suboptimal. The results also show that in response to sector specific shocks, the Ramsey planner cares only about the inflation rate in the sector where the shock originates.

References

Adolfson, M., Laséen, S., Lindé, J., Svensson, L., 2011. Optimal monetary policy in an operational medium-sized DSGE model. Journal of Money, Credit, and Banking 43, 1287-1331.

Benigno, G., Thoenissen, C., 2003. Equilibrium exchange rates and supply-side performance. Economic Journal 113, C103–C124.

Benigno, G., Thoenissen, C., 2008. Consumption and real exchange rates with incomplete markets and non-traded goods. Journal of International Money and Finance 27, 926–948.

Bernanke, B., Mishkin, F., 1997. Inflation targeting: a new framework for monetary policy. Journal of Economic Perspectives 11, 97–116.

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

Betts, C., Kehoe, T., 2006. U.S. real exchange rate fluctuations and relative price fluctuations. Journal of Monetary Economics 53, 1297–1326.

Burstein, A., Eichenbaum, M., Rebelo, S., 2006. The importance of nontradable goods' prices in cyclical real exchange rate fluctuations. Japan and The World Economy 18, 247–253.

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

Campolmi, A., 2014. Which inflation to target? A small open economy with sticky wages. Macroeconomic Dynamics 18, 145–174.

Chari, V. V., Kehoe, P., McGrattan, E., 2002. Can sticky price models generate volatile and persistent real exchange rates? Review of Economic Studies 69, 533–563.

Clarida, R., Galí, J., Gertler, M., 2001. Optimal monetary policy in open vs. closed economies: an integrated approach. American Economic Review 91, 248–252.

Corsetti, G., Dedola, L., Leduc, S., 2008. International risk sharing and the transmission of productivity shocks. Review of Economic Studies 75, 443–473.

Corsetti, G., Pesenti, P., 2001. Welfare and macro-economic interdependence. Quarterly Journal of Economics 116, 421–446.

De Paoli, B., 2009a. Monetary policy and welfare in a small open economy. Journal of International Economics 77, 11–22.

De Paoli, B., 2009b. Monetary policy under alternative asset market structures: the case of a small open economy. Journal of Money, Credit and Banking 41, 1301–1330.

Dotsey, M., Duarte, M., 2008. Nontraded goods, market segmentation, and exchange rates. Journal of Monetary Economics 55, 1129–1142.

Duarte, M., Obstfeld, M., 2008. Monetary policy in the open economy revisited: the case for exchange-rate flexibility restored. Journal of International Money and Finance 27, 949–957.

Engle, C., 2011. Currency misalignments and optimal monetary policy: a re-examination. American Economic Review 101, 2796–2822.

Faia, E., Monacelli, T., 2007. Optimal interest rate rule, asset prices, and credit frictions. Journal of Economic Dynamics and Control 31, 3228–3254.

Faia, E., Monacelli, T., 2008. Optimal monetary policy in a small open economy with home bias. Journal of Money, Credit and Banking 40, 721–750.

Galí, J., 2015. Monetary Policy, Inflation, and Business Cycle. 2nd ed., Princeton University Press, Princeton.

Galí, J., Monacelli, T., 2005. Monetary policy and exchange rate volatility in a small open economy. Review of Economic Studies 72, 707–734.

Galí, J., Monacelli, T., 2016. Understanding the gains from wage flexibility: the exchange rate connection. American Economic Review 106, 3829–3868.

Gertler, M., Karadi, P., 2011. A model of unconventional monetary policy. Journal of Monetary Economics 58, 17–34.

Jia, P., 2020. The macroeconomic impact of monetary-fiscal policy in a "fiscal dominance" world. Macroeconomic Dynamics 24, 670–707.

Kirsanova, T., Leith, C., Wren-Lewis, S., 2006. Should central banks target consumer prices or exchange rate? Economic Journal 116, 208–231.

Kirsanova, T., Wren-Lewis, S., 2012. Optimal fiscal feedback on debt in an economy with nominal rigidities. Economic Journal 122, 238–264.

Kollmann, R., 2001. The exchange rate in a dynamic optimizing current account model with nominal rigidities: a quantitative investigation. Journal of International Economics 55, 243–262.

Lester, R., Pries, M., Sims, E., 2014. Volatility and welfare. Journal of Economic Dynamics and Control 38, 17–36.

Lombardo, G., Ravenna, F., 2014. Openness and optimal monetary policy. Journal of International Economics 93, 153–172.

Mendoza, E., 1995. The terms of trade, the real exchange rate, and economic fluctuations. International Economic Review 36, 101–137.

Monacelli, T., 2004. Into the Mussa puzzle: monetary policy regimes and the real exchange rate in a small open economy. Journal of International Economics 62, 191–217.

Monacelli, T., 2005. Monetary policy in a low pass-through environment. Journal of Money, Credit and Banking 37, 1048–1066.

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

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

Rabanal, P., 2009. Inflation differentials between Spain and the EMU: a DSGE perspective. Journal of Money, Credit and Banking 41, 1141–1166.

Rabanal, P., Tuesta, V., 2013. Nontradable goods and the real exchange rate. Open Economies Review 24, 495–535.

Schmitt-Grohé, S., Uribe, M., 2004. Solving dynamic general equilibrium models using a second-order approximation to the policy function. Journal of Economic Dynamics and Control 28, 755–775.

Stockman, A., Tesar, L., 1995. Tastes and technology in a two-country model of the business cycle: explaining international comovements. American Economic Review 85, 168–185.

Svensson, L., 2009. Transparency under flexible inflation targeting: experiences and challenges. Sveriges Riksbank Economic Review 1, 5–44.

Woodford, M., 2003. Interest and Prices: Foundations of a Theory of Monetary Policy. Princeton University Press, Princeton.

Table 1
Benchmark Parameterization: Key Parameter Values

Parameter	**Value**	**Description**
β	0.99	Discount factor
σ	1	Inverse elasticity of intertemporal substitution
φ	5	Inverse Frisch elasticity of labor supply
θ_H	0.75	Price stickiness parameter for traded goods
ϵ_H	9	Elasticity of substitution between domestically produced traded goods
θ_N	0.75	Price stickiness parameter for non-traded goods
ϵ_N	9	Elasticity of substitution between domestically produced non-traded goods
γ	0.87	Weight on traded goods
ξ	0.7	Elasticity of substitution between traded and non-traded goods
υ	0.26	Weight on foreign goods
η	2	Elasticity of substitution between domestic and foreign goods
ϕ_π	1.5	Response of nominal interest rate to inflation deviations
ρ_a	0.9	Persistence of technology shocks
σ_a	0.01	Standard deviation of innovation to technology shocks
ρ_z	0.8	Persistence of demand shocks
σ_z	0.01	Standard deviation of innovation to demand shocks

Table 2

Compensating Variations λ

Monetary policy	A_t	A_t^H	A_t^N	Z_t
interest rate rule: CPI inflation				
$\phi_\pi = 1.5$	0.0152	0.0129	0.0058	0.0159
$\phi_\pi = 2$	0.0065	0.0070	0.0056	0.0088
$\phi_\pi = 2.5$	0.0047	0.0058	0.0056	0.0070
interest rate rule: domestic inflation				
$\phi_\pi = 1.5$	0.0202	0.0175	0.0078	0.0212
$\phi_\pi = 2$	0.0048	0.0068	0.0072	0.0093
$\phi_\pi = 2.5$	0.0013	0.0047	0.0070	0.0060
interest rate rule with nominal exchange rate				
$\phi_\pi = 1.5$	0.0194	0.0145	0.0063	0.0158
$\phi_\pi = 2$	0.0121	0.0100	0.0060	0.0111
$\phi_\pi = 2.5$	0.0088	0.0080	0.0059	0.0088

Note: λ is the % fraction of consumption required to equate welfare under any given state to the risk-free deterministic steady state. Compensating variations are calculated for different values of ϕ_π, for different interest rate rules, and for different exogenous shocks.

Table 3

Compensating Variations λ, $\gamma = 0.55$

Monetary policy	A_t	A_t^H	A_t^N	Z_t
interest rate rule: CPI inflation				
$\phi_\pi = 1.5$	0.0242	0.0093	0.0157	0.0258
$\phi_\pi = 2$	0.0095	0.0063	0.0117	0.0133
$\phi_\pi = 2.5$	0.0063	0.0057	0.0111	0.0099
interest rate rule: domestic inflation				
$\phi_\pi = 1.5$	0.0300	0.0262	0.0376	0.0314
$\phi_\pi = 2$	0.0090	0.0195	0.0308	0.0140
$\phi_\pi = 2.5$	0.0042	0.0185	0.0279	0.0091
interest rate rule with nominal exchange rate				
$\phi_\pi = 1.5$	0.0277	0.0081	0.0197	0.0242
$\phi_\pi = 2$	0.0171	0.0066	0.0158	0.0166
$\phi_\pi = 2.5$	0.0120	0.0059	0.0140	0.0128

Note: λ is the % fraction of consumption required to equate welfare under any given state to the risk-free deterministic steady state. Compensating variations are calculated for different values of ϕ_π, for different interest rate rules, and for different exogenous shocks.

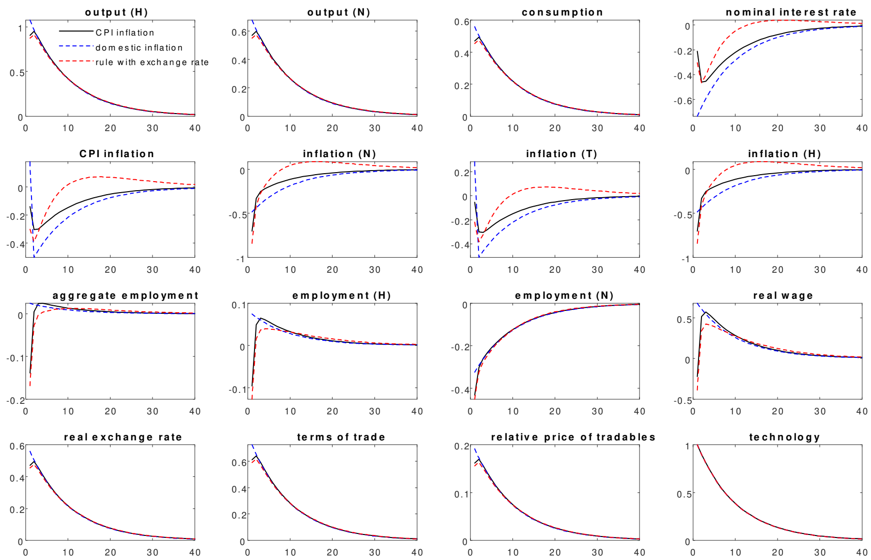
Table 4

Compensating Variations λ, $\xi = 2$

Monetary policy	A_t	A_t^H	A_t^N	Z_t
interest rate rule: CPI inflation				
$\phi_\pi = 1.5$	0.0142	0.0120	0.0024	0.0152
$\phi_\pi = 2$	0.0057	0.0059	0.0022	0.0083
$\phi_\pi = 2.5$	0.0040	0.0047	0.0022	0.0065
interest rate rule: domestic inflation				
$\phi_\pi = 1.5$	0.0193	0.0162	0.0040	0.0205
$\phi_\pi = 2$	0.0042	0.0051	0.0035	0.0088
$\phi_\pi = 2.5$	0.0008	0.0029	0.0033	0.0057
interest rate rule with nominal exchange rate				
$\phi_\pi = 1.5$	0.0183	0.0142	0.0026	0.0150
$\phi_\pi = 2$	0.0112	0.0094	0.0024	0.0104
$\phi_\pi = 2.5$	0.0080	0.0072	0.0023	0.0083

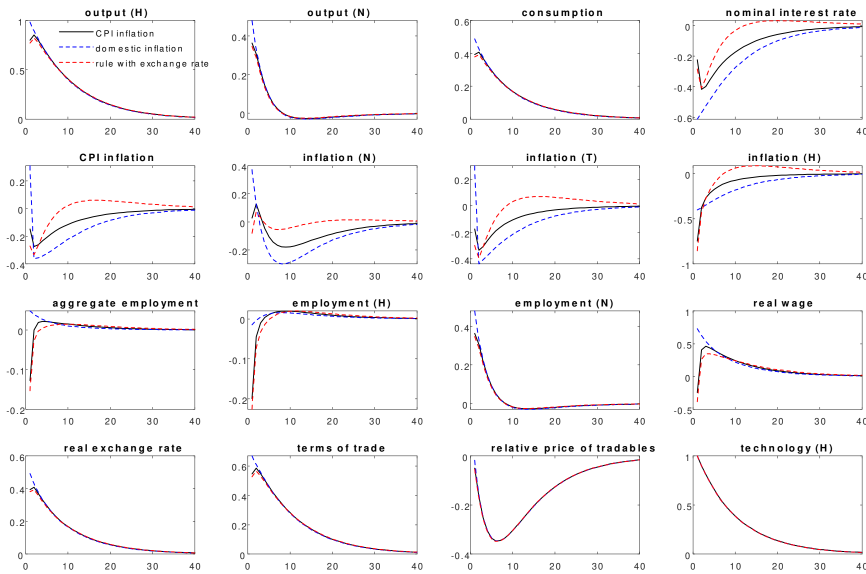
Note: λ is the % fraction of consumption required to equate welfare under any given state to the risk-free deterministic steady state. Compensating variations are calculated for different values of ϕ_π, for different interest rate rules, and for different exogenous shocks.

Figure 1
Dynamic Responses to a Technology Shock
Various Interest Rate Rules



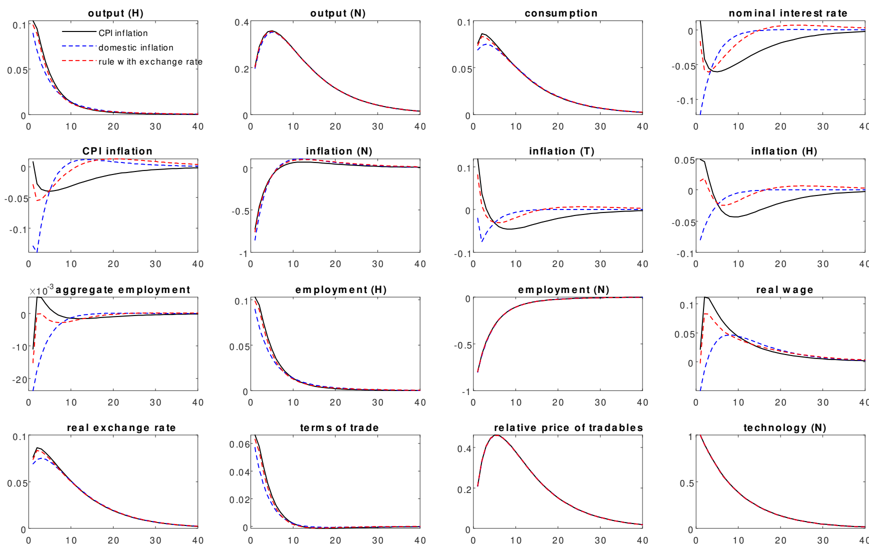
Notes: impulse responses to a one percent increase in technology. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 2
Dynamic Responses to a Technology Shock (Home)
Various Interest Rate Rules



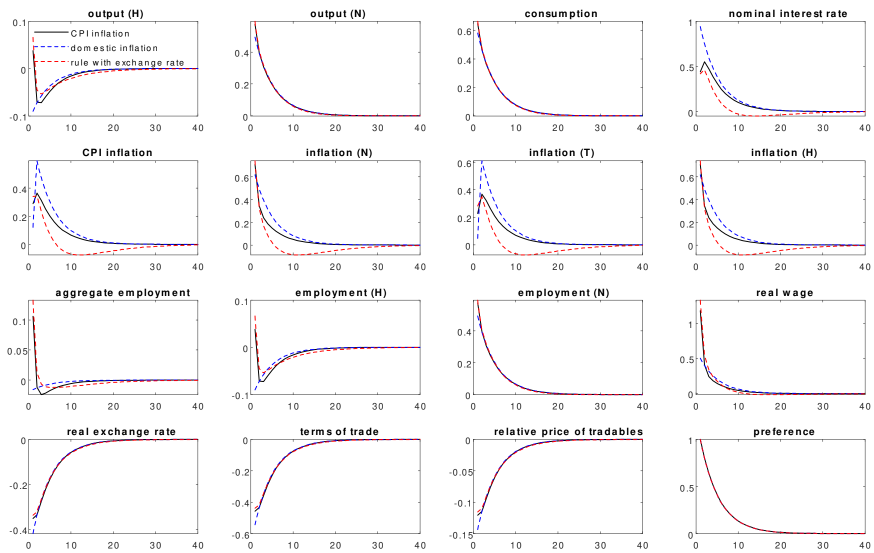
Notes: impulse responses to a one percent increase in technology (home). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 3
Dynamic Responses to a Technology Shock (Non-tradables)
Various Interest Rate Rules



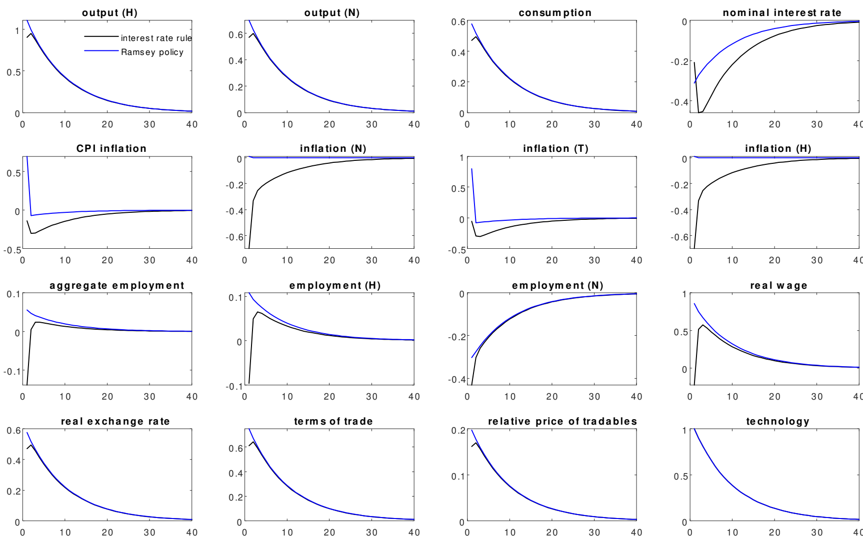
Notes: impulse responses to a one percent increase in technology (non-tradables). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 4
Dynamic Responses to a Demand Shock
Various Interest Rate Rules



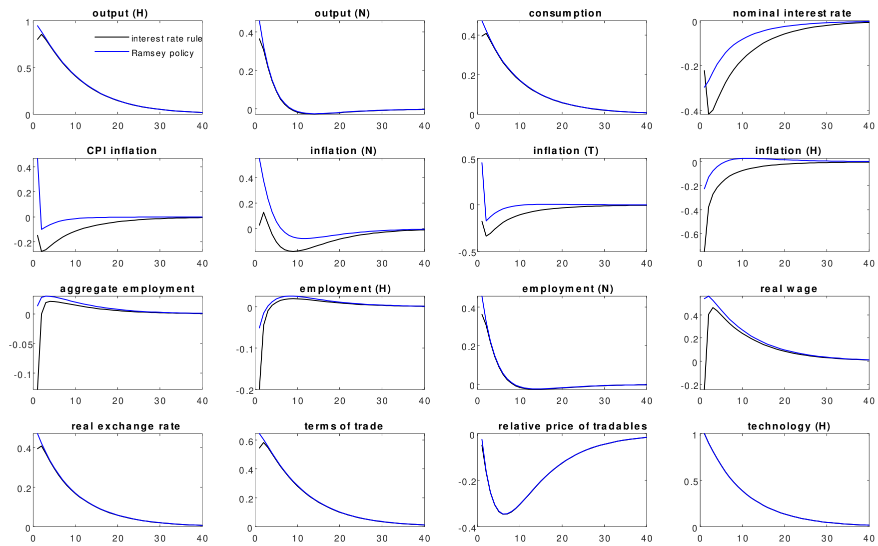
Notes: impulse responses to a one percent increase in preference. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 5
Dynamic Responses to a Technology Shock
Interest Rate Rule and Ramsey Policy



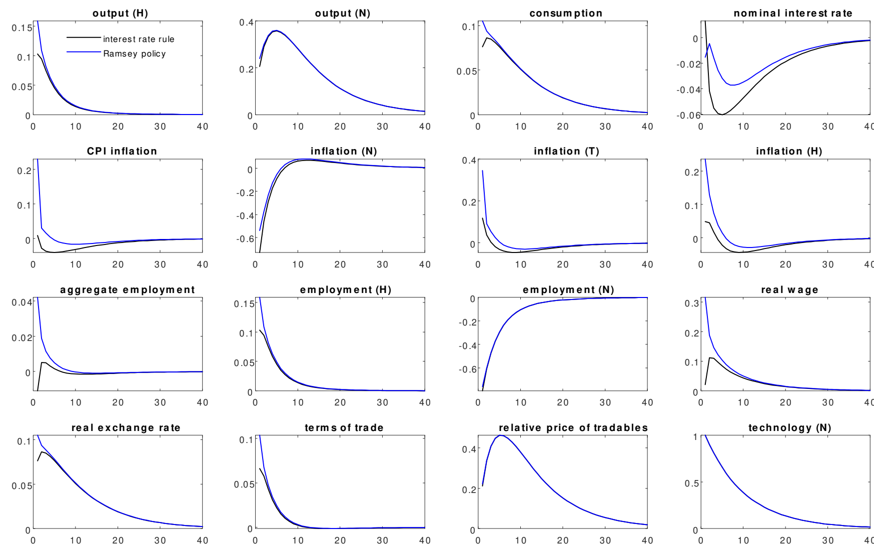
Notes: impulse responses to a one percent increase in technology. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 6
Dynamic Responses to a Technology Shock (Home)
Interest Rate Rule and Ramsey Policy



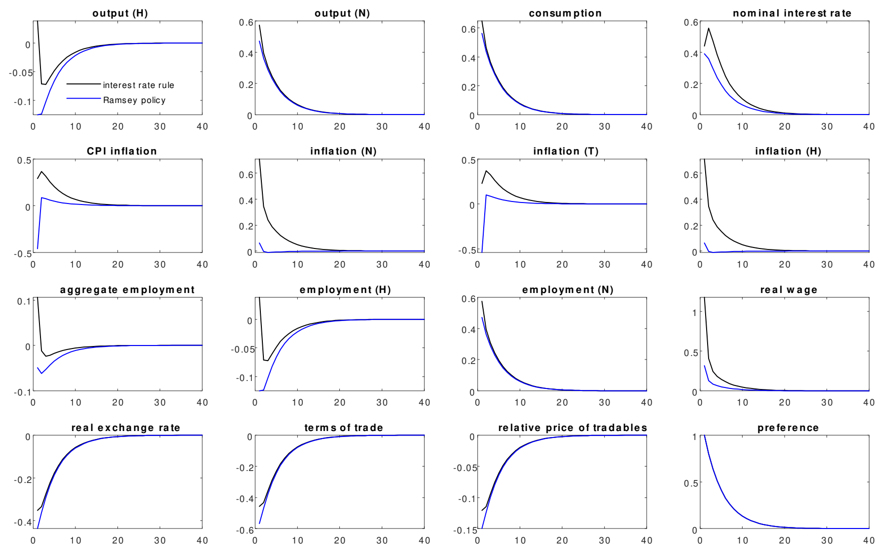
Notes: impulse responses to a one percent increase in technology (home). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 7
Dynamic Responses to a Technology Shock (Non-tradables)
Interest Rate Rule and Ramsey Policy



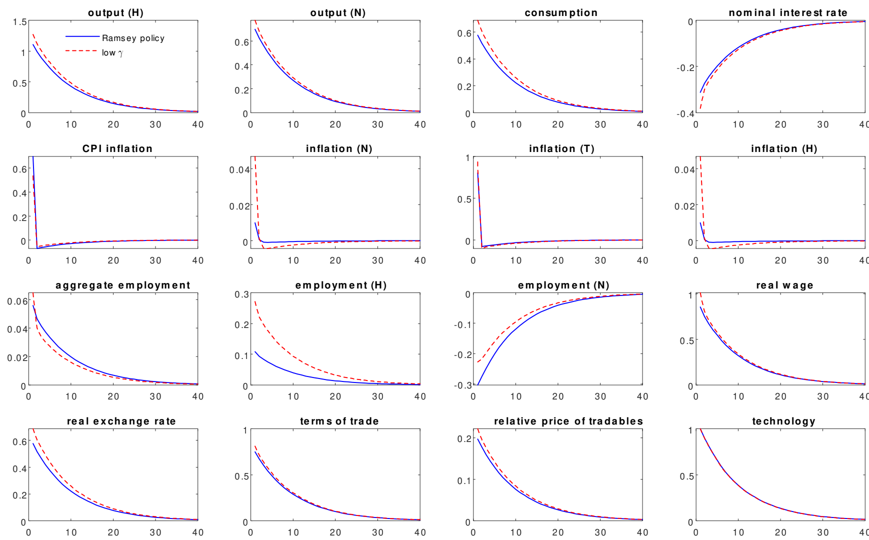
Notes: impulse responses to a one percent increase in technology (non-tradables). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 8
Dynamic Responses to a Demand Shock
Interest Rate Rule and Ramsey Policy



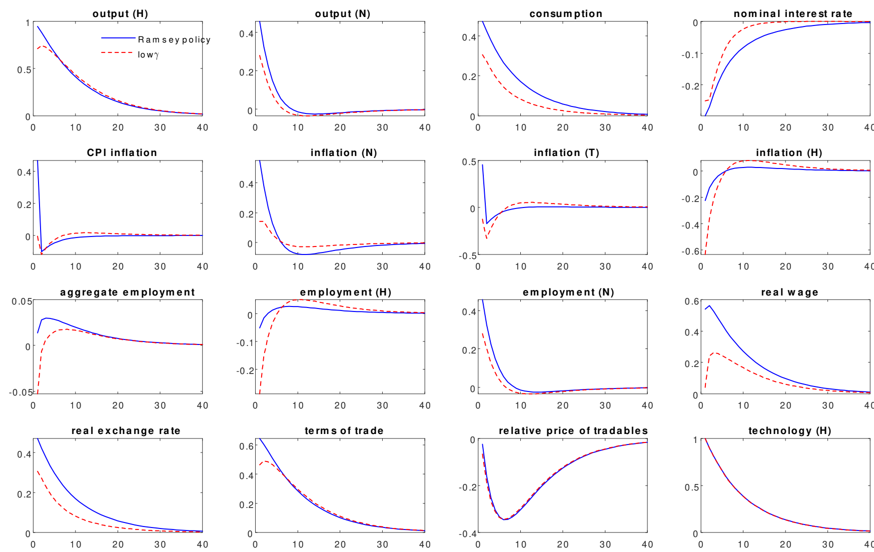
Notes: impulse responses to a one percent increase in preference. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 9
Dynamic Responses to a Technology Shock
Ramsey Policy, low γ



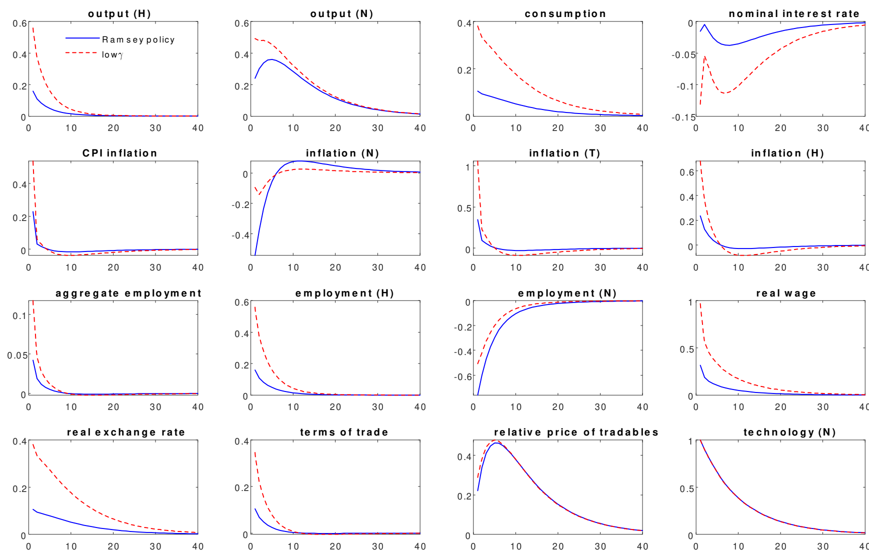
Notes: impulse responses to a one percent increase in technology. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 10
Dynamic Responses to a Technology Shock (Home)
Ramsey Policy, low γ



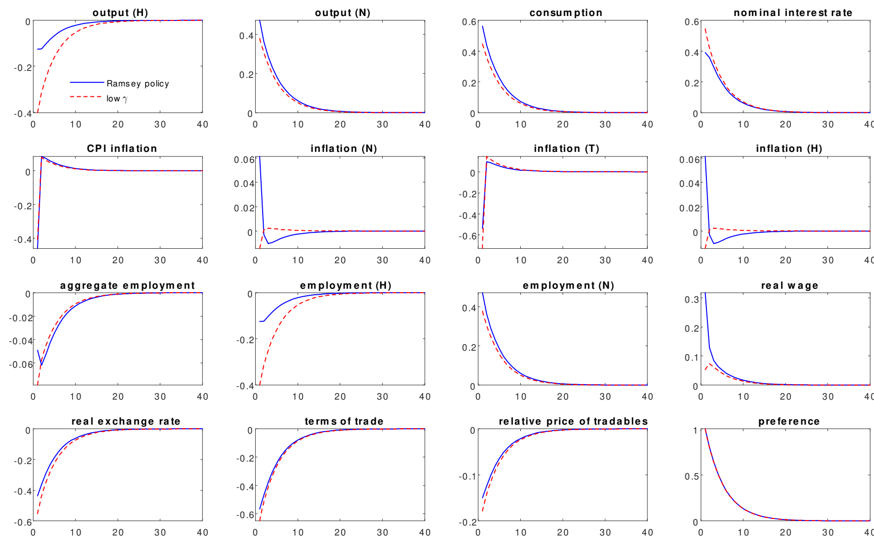
Notes: impulse responses to a one percent increase in technology (home). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 11
Dynamic Responses to a Technology Shock (Non-tradables)
Ramsey Policy, low γ



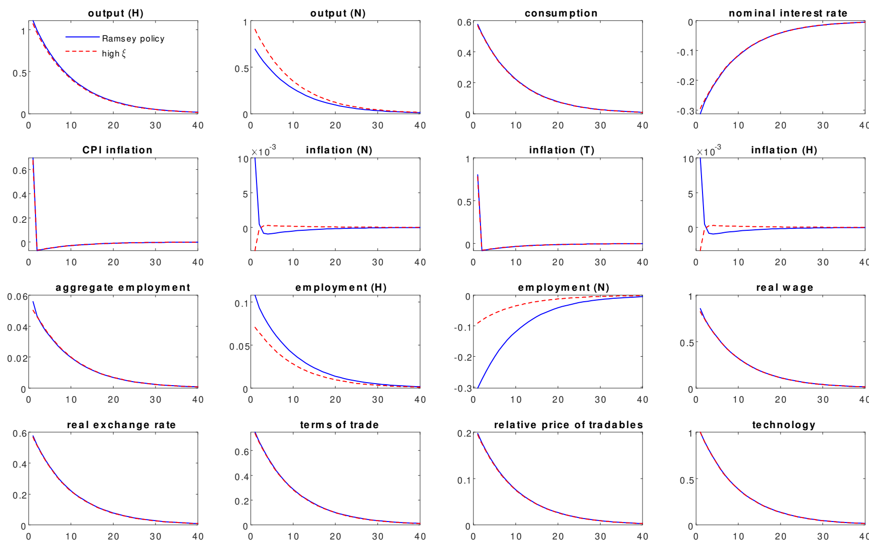
Notes: impulse responses to a one percent increase in technology (non-tradables). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 12
Dynamic Responses to a Demand Shock
Ramsey Policy, low γ



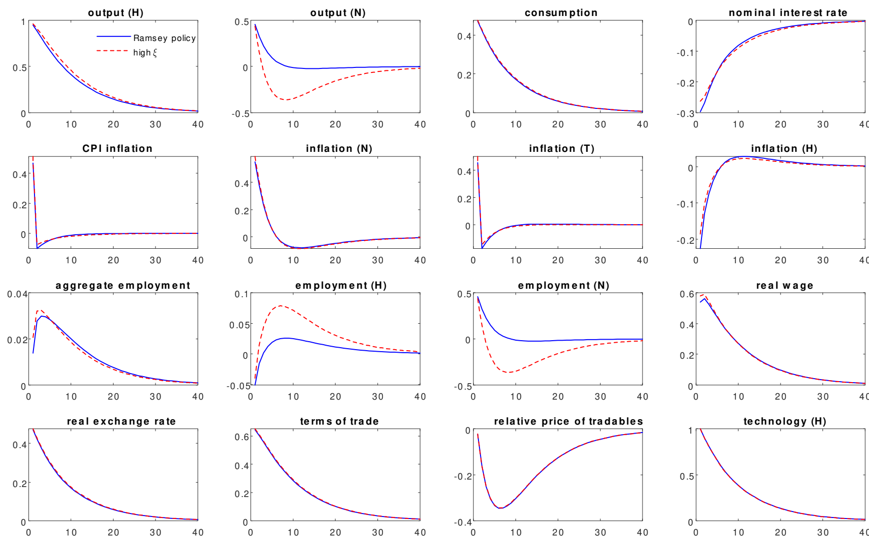
Notes: impulse responses to a one percent increase in preference. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 13
Dynamic Responses to a Technology Shock
Ramsey Policy, high ξ



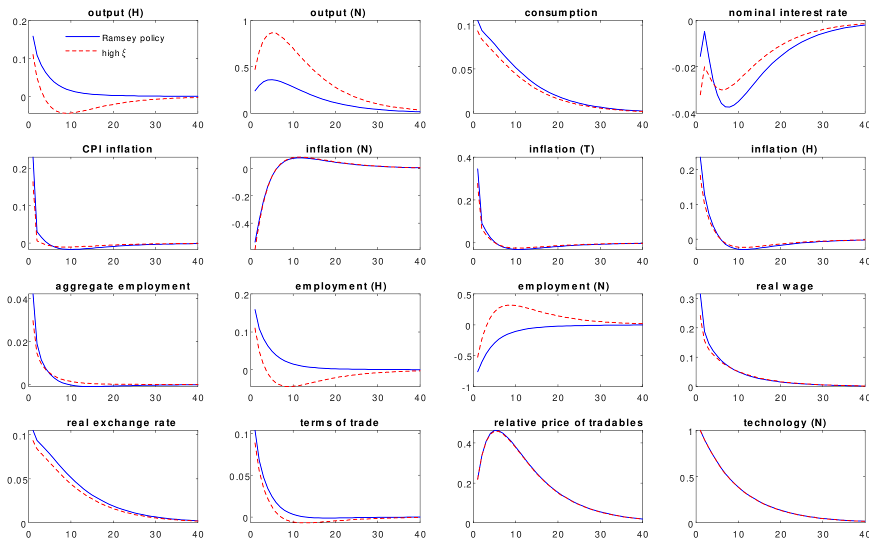
Notes: impulse responses to a one percent increase in technology. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 14
Dynamic Responses to a Technology Shock (Home)
Ramsey Policy, high ξ



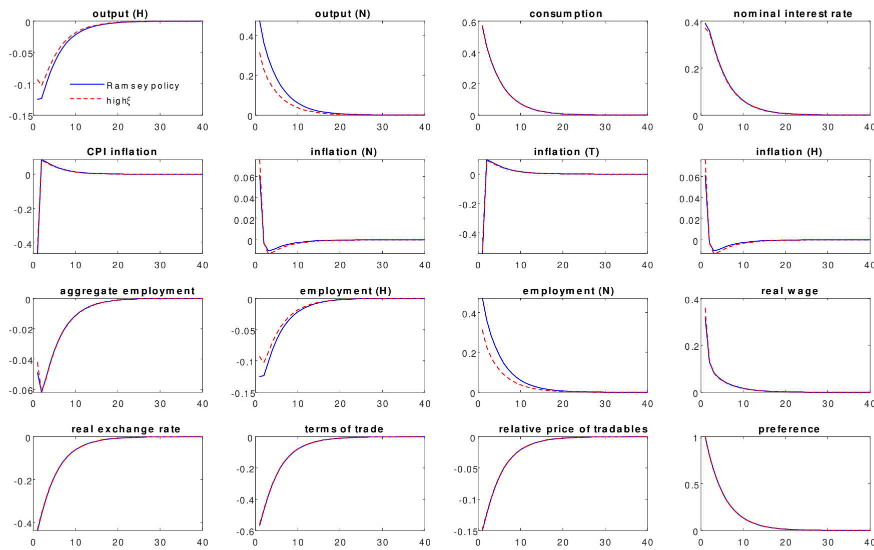
Notes: impulse responses to a one percent increase in technology (home). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 15
Dynamic Responses to a Technology Shock (Non-tradables)
Ramsey Policy, high ξ



Notes: impulse responses to a one percent increase in technology (non-tradables). Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

Figure 16
Dynamic Responses to a Demand Shock
Ramsey Policy, high ξ



Notes: impulse responses to a one percent increase in preference. Horizontal axes indicate quarters. Variables are expressed in percentage point deviations from steady state. The responses of inflation, policy rate, and spreads are annualized percentage point changes.

1 Appendix A: Equilibrium equations

1.1 Equilibrium

This appendix summarizes the equilibrium conditions of the small open economy model with traded and non-traded goods, as in the text.

- Households:

$$w_t = C_t^{\sigma} N_t^{\varphi} \tag{1}$$

$$\beta R_t E_t[(\frac{C_t}{C_{t+1}})^{\sigma}(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})] = 1 \tag{2}$$

- International risk-sharing:

$$C_t = Y_t^* Z_t^{\frac{1}{\sigma}} Q_t^{\frac{1}{\sigma}} \tag{3}$$

- Relative prices and inflation:

$$Q_t = (\frac{S_t}{q_t^S})(\frac{T_t}{h_t^T}) \tag{4}$$

$$q_t^S = [(1-\upsilon) + \upsilon S_t^{1-\eta}]^{\frac{1}{1-\eta}} \tag{5}$$

$$h_t^T = [(1-\gamma) + \gamma T^{1-\xi}]^{\frac{1}{1-\xi}} \tag{6}$$

$$\frac{T_t}{T_{t-1}} = \frac{\Pi_t^T}{\Pi_t^N} \tag{7}$$

$$\Pi_t^T = \Pi_t^H \frac{q_t^S}{q_{t-1}^S} \tag{8}$$

$$\Pi_t = \Pi_t^N \frac{h_t^T}{h_{t-1}^T} \tag{9}$$

- Price setting (traded goods):

$$K_t^H = \frac{A_t A_t^H N_t^H}{\Delta_t^H} + \beta\theta_H E_t\{(\frac{C_t}{C_{t+1}})^{\sigma}(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t}) K_{t+1}^H (\Pi_{t+1}^H)^{\epsilon_H}\} \tag{10}$$

$$F_t^H = \frac{N_t^H}{\Delta_t^H}\frac{w_t h_t^T q_t^S}{T_t} + \beta\theta_H E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})F_{t+1}^H(\Pi_{t+1}^H)^{\epsilon_H+1}\} \tag{11}$$

$$\tilde{p}_t^H = \frac{F_t^H}{K_t^H} \tag{12}$$

$$1 = \theta_H(\Pi_t^H)^{\epsilon_H-1} + (1-\theta_H)(\tilde{p}_t^H)^{1-\epsilon_H} \tag{13}$$

- Price setting (non-traded goods):

$$K_t^N = \frac{A_t A_t^N N_t^N}{\Delta_t^N} + \beta\theta_N E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})K_{t+1}^N(\Pi_{t+1}^N)^{\epsilon_N}\} \tag{14}$$

$$F_t^N = \frac{N_t^N}{\Delta_t^N}w_t h_t^T + \beta\theta_N E_t\{(\frac{C_t}{C_{t+1}})^\sigma(\frac{1}{\Pi_{t+1}})(\frac{Z_{t+1}}{Z_t})F_{t+1}^N(\Pi_{t+1}^N)^{\epsilon_N+1}\} \tag{15}$$

$$\tilde{p}_t^N = \frac{F_t^N}{K_t^N} \tag{16}$$

$$1 = \theta_N(\Pi_t^N)^{\epsilon_N-1} + (1-\theta_N)(\tilde{p}_t^N)^{1-\epsilon_N} \tag{17}$$

- Aggregate conditions:

$$\frac{A_t A_t^H N_t^H}{\Delta_t^H} = (1-\nu)(q_t^S)^\eta\gamma(\frac{h_t^T}{T_t})^\xi C_t + \nu S_t^\eta Y_t^* \tag{18}$$

$$\frac{A_t A_t^N N_t^N}{\Delta_t^N} = (1-\gamma)(h_t^T)^\xi C_t \tag{19}$$

$$N_t = N_t^H + N_t^N \tag{20}$$

$$\Delta_t^H = (1-\theta_H)(\tilde{p}_t^H)^{-\epsilon_H} + \theta_H(\Pi_t^H)^{\epsilon_H}\Delta_{t-1}^H \tag{21}$$

$$\Delta_t^N = (1-\theta_N)(\tilde{p}_t^N)^{-\epsilon_N} + \theta_N(\Pi_t^N)^{\epsilon_N}\Delta_{t-1}^N \tag{22}$$

- Monetary policy:

$$(\frac{R_t}{\bar{R}}) = (\frac{\Pi_t}{\bar{\Pi}})^{\phi_\pi}. \tag{23}$$

This is a system of 23 equations in 23 unknowns ($w_t, C_t, N_t, R_t, \Pi_t, Q_t, S_t, q_t^S, T_t, h_t^T$, $\Pi_t^T, \Pi_t^N, \Pi_t^H, K_t^H, F_t^H, \tilde{p}_t^H, N_t^H, K_t^N, F_t^N, \tilde{p}_t^N, N_t^N, \Delta_t^H, \Delta_t^N$).

1.2 Shock process

The processes for the shocks are given by:

$$A_t = \bar{A}^{1-\rho_a} A_{t-1}^{\rho_a} e^{\epsilon_t^a}$$

$$A_t^H = (\bar{A}^H)^{1-\rho_{a,H}} (A_{t-1}^H)^{\rho_{a,H}} e^{\epsilon_t^{a,H}}$$

$$A_t^N = (\bar{A}^N)^{1-\rho_{a,N}} (A_{t-1}^N)^{\rho_{a,N}} e^{\epsilon_t^{a,N}}$$

$$Z_t = \bar{Z}^{1-\rho_z} Z_{t-1}^{\rho_z} e^{\epsilon_t^z}.$$

In addition, I choose $\bar{A} = 1$, $\bar{A}^H = 1$, $\bar{A}^N = 1$, and $\bar{Z} = 1$ as a normalization.

1 Appendix B: Computation of the compensating variation parameter

This appendix describes the calculation of compensating variations for welfare evaluations. For the case of additively separable preferences and log utility over consumption, as assumed in the text, the value function evaluated at a particular point in the state space, V_t, can be written as:

$$V_t = E_0 \sum_{t=0}^{\infty} \beta^t [\ln C_t - \frac{N_t^{1+\varphi}}{1+\varphi}].$$

I then define two auxiliary value functions:

$$V_t = V_t^C + V_t^N$$

$$V_t^C = E_0 \sum_{t=0}^{\infty} \beta^t \ln C_t$$

$$V_t^N = E_0 \sum_{t=0}^{\infty} \beta^t (-\frac{N_t^{1+\varphi}}{1+\varphi}).$$

In addition, the value function evaluated at the risk-free deterministic steady state is given by $\tilde{V} = (\ln \tilde{C} - \frac{\tilde{N}^{1+\varphi}}{1+\varphi})/(1-\beta)$, where $\tilde{C}$ and $\tilde{N}$ are the steady state values of consumption and employment. And the conditional compensating variation λ for the regime V_t is defined by:

$$E_0 \sum_{t=0}^{\infty} \beta^t [\ln(1+\lambda)C_t - \frac{N_t^{1+\varphi}}{1+\varphi}] = \tilde{V}.$$

Using the definitions above and simplifying, one gets:

$$\begin{aligned} \tilde{V} &= \sum_{t=0}^{\infty} \beta^t \ln(1+\lambda) + E_0 \sum_{t=0}^{\infty} \beta^t \ln C_t + E_0 \sum_{t=0}^{\infty} \beta^t (-\frac{N_t^{1+\varphi}}{1+\varphi}) \\ &= \frac{1}{1-\beta} \ln(1+\lambda) + V_t^C + V_t^N \\ &= \frac{1}{1-\beta} \ln(1+\lambda) + V_t. \end{aligned}$$

Solving for λ yields:

$$\lambda = \exp[(1-\beta)(\tilde{V} - V_t)] - 1.$$