# International business cycle comovement and vertical specialization reconsidered in multistage Bayesian DSGE model

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**Abstract**

Business cycle comovements across countries, for which vertical and sequential trade in intermediate input is empirically found to be one of the most important explanations, have been widely documented, and East Asian economies show no exception. We reevaluate the Bayesian estimated two-country real business cycle model with traded intermediates and New Keynesian model that incorporates vertical specialization using observable series of nine East and Southeast Asian economies, and generate counterfactual moments. The failure of these models stems not from the de facto unimportance but from the de jure formalization of vertical linkages. Because the available empirical findings rest trade-comovement nexus on back-and-forth trade in intermediate goods, the simple form of vertical specialization, we argue, is unable to capture the essence of vertical production and trade. We thus extend two-country New Keynesian model by considering three processing stages to authentically embrace vertical and sequential linkage at traded intermediate inputs. The Bayesian estimated model has been able to replicate the autocorrelation, cross and contemporaneous correlations over a large set of macroeconomic variables spectacularly well. Formalizing vertical and sequential linkage at intermediate goods through the lens of three processing stages is thus essential for an international business cycle model.

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## 1. Introduction

Explaining macroeconomic comovement across countries has been a longstanding task in international macroeconomics. Abrupt fall in world economy following the most recent U.S. recession has vividly demonstrated how countries across regions are tightly linked. A pressing question is thus to know what explains the business cycle comovement. International trade is certainly one of the empirically most established determinants of business cycle synchronization. Ever since Frankel and Rose (1998), and Clark and van Wincoop (2001), the profession generally agrees that countries that trade more to each other are more likely to co-move. Baxter and Kouparitsas (2005) add to the literature by proving that bilateral trade is one of the only few significant and robust determinants of business cycle comovement.

Of all the types of trade, particularly in between developed and developing nations, vertical trade in intermediates is potentially a mechanism too important to dispense with in accounting for the interaction between trade and business cycle comovement. As a matter of fact, it has no lack of empirical support on the role of vertical linkages. Based on a panel of 55 countries with 28 manufacturing over four decades, di Giovanni and Levchenko (2010), for instance, reach the conclusion that bilateral trade significantly enhances comovement should cross-border manufacturing pairs use each other as intermediate input. In particular, they infer that vertical trade can explain 73 percent of trade-comovement nexus among the advanced-developing country pairs (see, also, Burstein et al., 2008; Tesar, 2008).

At problem is that international business cycle models of transmission, even after incorporating vertical specialization, have difficulty to replicate the key macroeconomic correlations. Kose and Yi (2001), for instance, modify standard international real business cycle model of Backus et al. (1994) to incorporate a simple form of vertical specialization. Such model with high trade intensity, however, results in lower business cycle correlation due to the resource transferring towards country with favorable productivity shock that nullifies the positive impact of increasing trade intensity on business cycle comovement. The later Kose and Yi (2006) that use a three-country model with vertical specialization to take into account the fact that bilateral trade pairs are smaller vis-à-vis the rest of the world also obtain an unsatisfactory quantitative performance.

To shed light on this unmatched progress between empirical findings and theoretical modeling, this paper has two goals in succession. We first reevaluate the empirical ability of the Bayesian estimated two-country real business cycle model of Raffo (2008) with traded intermediate goods and New Keynesian model a-la Smets and Wouters (2003) that allows for trade in both intermediate and final goods. The latter model basically captures the simple form of vertical specialization put forward by Kose and Yi (2001), where home imports and remanufactures intermediate goods for which will be re-exported as consumer goods. Both models, however, fail to take up the task of coupling business cycle comovement with vertical trade linkage. The former generates counterfactual correlations, while the latter gives positive trade-comovement even when the channel of vertical specialization is shut off.

We hold the view that the failure of the early models with traded intermediates or vertical specialization stems not from the de facto unimportance but from the de jure formalization of vertical linkage. Drawn on di Giovanni and Levchenko (2010)'s finding that trade-comovement nexus is strengthened by back-and-forth trade in intermediate goods, which means importing and re-exporting intermediates, the simple form of vertical specialization, conceptualized as importing intermediates for re-export as consumer goods, we argue, incorrectly captures the essence of vertical production and trade.

The novelty of this paper is thus to extend two-country New Keynesian model with three processing stages so that it allows us to authentically embrace back-and-forth trade in intermediates. The quantitative performance of our Bayesian estimated model has been spectacular, as it very neatly accounts for autocorrelations as well as contemporaneous and cross-period business cycle comovement in East and Southeast Asia economies over a large set of macroeconomic time series, and survives from a battery of sensitive analysis. We, therefore, argue that vertical and sequential trade linkage formalized in three-stage production structure is essential and sufficient in understanding the interaction between international trade and business cycle synchronization.

The discussion is structured as follows. Section 2 takes stock on the quantitative performances of two-country real business cycle model and New Keynesian model in mimicking actual cross-region comovement. Section 3 lays out an extended vertical-specialization model by incorporating three stages of processing, which we call New Keynesian model with vertical production and trade (NKVPT). The model is then confronted to data using Bayesian estimation in Section 4, and tested on its ability to replicate East and Southeast Asian business cycle comovements. The mechanism of shock propagation is also investigated. Section 5 concludes.

## 2. A brief tour on two-country IRBC and VS model

In this section, we briefly outline the production and trade structure of a two-country real business cycle (IRBC) model and vertical-specialization (VS) model. The former is based on Raffo (2008), while the latter draws on the hugely influential Smets and Wouters (2003)[1].

[1] Interested readers can refer to working paper for technical details available upon request.

The IRBC model assumes two processing stages, in which home upstream firm exports a fraction of her output as intermediates for foreign downstream production. By the same token, home downstream firm utilizes both home and imported intermediates from foreign upstream firms with constant elasticity of substitution. The resultant final output does not cross the borders, and is only consumed and invested locally. In other words, only intermediate goods are traded, and such trade in intermediates cannot be considered as vertical and sequential due to the fact that export decision of upstream firm is unrelated to import decision of downstream firm.

The VS model clothed in Smets-Wouters (2003) model also assumes two processing stages. That makes VS model different from IRBC model is that both intermediate and final goods can be traded. Upstream firm uses Cobb-Douglas technology to produce for home and foreign market. Downstream firm then fabricates home and imported materials in constant elasticity of substitution to produce final goods for home and export market. Once downstream firm links her intermediates import to the final-good export decision, a simple vertical linkage is established.

Table 1 reports the model-generated cross-region macroeconomic correlations between Southeast Asian (SEA4) and East Asian economies (EA5) using the estimated IRBC and VS model[2]. In comparison to the actual cross-region contemporaneous correlations, performance of the baseline IRBC model apparently falls short of expectation. The model-generated SEA4 and EA5 are inversely correlated, implying that resource-shifting effect enabled by perfect market integration in the face of shocks overshadows the trade-link effect through intermediate inputs trade. Even when we consider persistent innovation to preference shocks, inspired by Stockman and Tesar (1995), capital stock with investment adjustment cost, and lower elasticity of substitution between home and imported foreign materials, meaningful macroeconomic comovement remains virtually absent.

[2] Discussion on data and Bayesian approach in model estimation is detailed in Section 4.

**[INSERT TABLE 1 ABOUT HERE]**

The last second vertical panel of Table 1 shows cross-region correlation for eleven macroeconomic variables generated by the estimated VS model. The VS model certainly outperforms IRBC model as a model of international business cycle. Higher log marginal likelihood for VS baseline model (2733.3) as compared to IRBC baseline model (1367.7) signifies the usefulness of expanding data set and better model specifications[3]. Most interestingly, the VS model is able to replicate the contemporaneous cross-region correlations surprisingly well in that the macroeconomic comovements are apparently accompanied by strong trade comovement[4].

But how robust is the positive trade-output comovement? Can the comovement be driven not by vertical trade link? We address the robustness by equating the share of imported intermediates for final goods production in both SEA4 and EA5 to zero to shut down the intermediates trade channel. As a result, only trade in final goods is allowed. The last vertical panel of Table 1 makes the fragility of trade-output comovement evident. A Bayes factor of 196.63 implies that the empirically unfit baseline model with vertical trade has to possess a prior probability of $2.48 \times 10^{85}$ in excess of the model without vertical trade for equivalent empirical fit. Such probability simply denies the potential role of vertical trade. More damaging is the fact that output comovement remains strong – though weaker – despite the negatively correlated trade dynamics. Rates of inflation co-move more tightly amid stronger negative correlations in monetary policy stance and exchange rates variability. The VS model thus fails to seal the

[3] IRBC model has thirty eight structural equations with twenty eight parameters for estimation, out of which eleven is standard deviation of home and foreign shocks. It uses eleven observable series. Meanwhile, there are sixty two structural equations and fifty three parameters, including standard deviation of shocks, for estimation in VS model using nineteen observable series.

[4] Of dubious is the magnitude of the contemporaneous comovement. Specifically, consumption co-moves too weakly, exports and imports are too strongly correlated, and rates of inflation, particularly CPI inflation, are questionably correlated despite the counterfactual negative comovement in nominal exchange rates and monetary policy stance.

regional macroeconomic comovement on vertical trade. Trade-comovement puzzle remains unsolved.

## 3. A two-country, three-processing stage New Keynesian model

The New Keynesian model with vertical production and trade (NKVPT model thereafter) considers a production process that has to be completed throughout upstream-middlestream-downstream production. Both upstream home and foreign firms partially export their outputs as materials for subsequent manufactures held abroad. In combination with local inputs, middlestream plants fabricate the imported parts and components. A fraction of remanufactured intermediates is then reexported for final assembly to downstream production. The final goods are lastly consumed and invested locally as well as exported to trading partners. This back-and-forth trade in intermediate inputs – importing-material-for-exporting-material linkage – by middlestream firms, in addition to importing-material-for-exporting-final linkage at downstream production, is the key property that differentiates NKVPT model from VS model.

### *3.1. Firm's problem throughout chains of production*

A unit mass of competitive firms indexed by $j$ at upstream has access to Cobb-Douglas production technology that uses plant-specific capital $K_{t-1}(j)$, $j \in J$, and differentiated labor $N_t(i)$ of a variety $i \in I$ to produce plant-specific materials $Y_{1t}(j)$ at date *t*. These firms can only alter its capital over time by varying the rate of investment $I_t(j)$ at a cost of $\mathrm{S}(I_t(j)/I_{t-1}(j))$. Technology for accumulating capital stock resembles the one in Mandelman et al. (2011).

$$K_t(j) = (1-\delta)K_{t-1}(j) + \mathrm{u}_t^I I_t(j)\left\{1 - \frac{\Psi}{2}\left(\frac{\mathrm{u}_{t-1}^I I_{t-1}(j)}{\mathrm{u}_t^I I_t(j)}\right)\left(\frac{u_t^I I_t(j)}{u_{t-1}^I I_{t-1}(j)} - \Lambda\right)^2\right\} \tag{1}$$

Firm's cost minimization problem can then be written in the following manner:

$$\min_{K_{t(j)},N_t,I_t(j)}\left(r_{K,t}(j)+\delta\right)K_{t-1}(j)+W_tN_t+\mathrm{u}_t^I I_t(j)\left\{\frac{\Psi}{2}\left(\frac{\mathrm{u}_{t-1}^I I_{t-1}(j)}{\mathrm{u}_t^I I_t(j)}\right)\left(\frac{u_t^I I_t(j)}{u_{t-1}^I I_{t-1}(j)}-\Lambda\right)^2\right\} \quad (2)$$

s.t.

$$Y_{1t}(j)=e^{A_t}(K_{t-1}(j))^{\alpha}(N_t)^{1-\alpha} \quad (3)$$

where $N_t=\left[\int_{i\in I}N_t(i)^{1/\mu_t^N}di\right]^{\mu_t^N}$ and $W_t=\left[\int_{i\in I}W_t(i)^{1/(1-\mu_t^N)}di\right]^{1-\mu_t^N}$. $A_t$ is Hicks-neutral total factor productivity (TFP) shock, and $\mathrm{u}_t^I$ is investment-specific technology (IST) shock. Both follow first-order autoregressive process. The parameter $\Psi$ denotes investment adjustment cost, and $\Lambda$ is the long-run gross rate of growth of investment along the balanced growth path. $r_{K,t}$ denotes the real return on capital, and $\mu_t^N$ is a measure of time-varying wage mark-up. The demand function for labor *i* is $N_t(i)=(W_t(i)/W_t)^{-\varepsilon_{N,t}}N_t$, where $\varepsilon_{N,t}(\equiv\mu_t^N/(\mu_t^N-1))$ denotes the wage elasticity of demand for labor $i$.

Let $RMC_{1t}(j)$ be the real marginal cost for upstream plant *j*. The efficiency conditions are

$$1+r_{K,t}(j)=\frac{\alpha RMC_{1t}(j)Y_t(j)}{K_{t-1}(j)}+1-\delta \quad (4)$$

$$W_t=\frac{(1-\alpha)RMC_{1t}(j)Y_{1t}(j)}{N_t} \quad (5)$$

$$RMC_{1t}(j)\left\{\frac{\mathrm{u}_t^I I_t(j)}{\mathrm{u}_{t-1}^I I_{t-1}(j)}-\Lambda\mathrm{u}_t^I\right\}=\beta E_t RMC_{1t+1}(j)$$

$$\left\{\left(\frac{u_{t+1}^I I_{t+1}(j)}{u_t^I I_t(j)}\right)^2-\Lambda\left(\frac{u_{t+1}^I I_{t+1}(j)}{u_t^I I_t(j)}\right)-\frac{1}{2}u_t^I\left[\left(\frac{u_{t+1}^I I_{t+1}(j)}{u_t^I I_t(j)}\right)^2-2\Lambda\left(\frac{u_{t+1}^I I_{t+1}(j)}{u_t^I I_t(j)}\right)-\Lambda^2\right]\right\} \quad (6)$$

Inserting Eqs. (4) and (5) into (3) will give us the firm's real marginal cost function:

$$RMC_{1t}(j)=\frac{\left(r_{K,t}(j)+\delta\right)^{\alpha}(W_t)^{1-\alpha}}{e^{A_t}\alpha^{\alpha}(1-\alpha)^{1-\alpha}} \quad (7)$$

The investment dynamics of Eq. (6) and the corresponding motion of capital stock in log linearized form can be written as

$$\hat{\iota}_t(j) = \left(\frac{1}{1+\beta}\right)\hat{\iota}_{t-1}(j) + \left(\frac{\beta}{1+\beta}\right)\hat{\iota}_{t+1}(j) + \left(\frac{\beta}{1+\beta}\right)\left(1 - \Lambda - \frac{1}{2}(1-\Lambda)^2\right)\widehat{rmc}_{1t+1}(j) -$$

$$\left(\frac{1-\Lambda}{1+\beta}\right)\widehat{rmc}_{1t}(j) + \left(\frac{\beta}{1+\beta}\right)\hat{u}^I_{t+1} + \left(\frac{1}{1+\beta}\right)\hat{u}^I_{t-1} - \left(\frac{2-\Lambda-\beta\left(1+\frac{1}{2}(1-\Lambda)^2\right)}{1+\beta}\right)\hat{u}^I_t \quad (8)$$

$$\hat{k}_t(j) = (1-\delta)\hat{k}_{t-1}(j) + \delta(\hat{\iota}_t(j) + \hat{u}^I_t) - \left(\frac{\delta\Psi\left(1-\Lambda-\frac{1}{2}(1-\Lambda)^2\right)}{1-\frac{1}{2}\Psi(1-\Lambda)^2}\right)(\hat{\iota}_t(j) - \hat{\iota}_{t-1}(j) + \hat{u}^I_t - \hat{u}^I_{t-1}) \quad (9)$$

where the circumflex indicates log deviation from steady state. Once the process is completed, the processed outputs will be demanded by differentiated middlestream firms $j$ located domestically $\left(Y^j_{1H,t}\right)$ and abroad $\left(M^{j*}_{1H,t}\right)$ as materials. For the sake of simplicity, we assume that output market for upstream production is tightly competitive. In consequence, elasticity of substitution between varieties is close to infinity, and thus, price approximates real marginal cost. The pricing decision is further assumed to be symmetry across manufacturing plants.

A mass continuum of middlestream monopolistically competitive firm $j$, $j \in J$, imports upstream processed materials $M^j_{1F,t}\left(= \left[\int_{j\in J} M^j_{1F,t}(j)^{(\varepsilon_{2t}-1)/\varepsilon_{2t}} dj\right]^{\frac{\varepsilon_{2t}}{\varepsilon_{2t}-1}}\right)$ of plant $j$ for remanufacture. The demand function for $M^j_{1F,t}(j)$ is thus $\left(P^j_{1F,t}(j)/P^j_{1F,t}\right)^{-\varepsilon_{2t}} M^j_{1F,t}$, where $P^j_{1F,t}$ is the home price of imported materials and $\varepsilon_{2t} > 1$ is the time-varying demand elasticity of substitution between varieties. In combination with local inputs $Y^j_{1H,t}\left(= \left[\int_{j\in J} Y^j_{1H,t}(j)^{(\varepsilon_{2t}-1)/\varepsilon_{2t}} dj\right]^{\frac{\varepsilon_{2t}}{\varepsilon_{2t}-1}}\right)$, of which the demand function takes the form $\left(P^j_{1H,t}(j)/P^j_{1H,t}\right)^{-\varepsilon_{2t}} Y^j_{1H,t}$, firm $j$'s problem can be formulated as minimizing the cost of using local input $P^j_{1H,t}$ and imported materials subject to the following CES production technology:

$$Y^j_{2t} = \left[(1-\kappa_2)^{1/\vartheta}\left(Y^j_{1H,t}\right)^{(\vartheta-1)/\vartheta} + {\kappa_2}^{1/\vartheta}\left(M^j_{1F,t}\right)^{(\vartheta-1)/\vartheta}\right]^{\vartheta/(\vartheta-1)} \quad (10)$$

The parameter $\kappa_2$ indicates the share of imported materials, and the parameter $\vartheta > 0$ denotes the elasticity of substitution between home and imported intermediate inputs. Optimal demand function for home and imported materials can be derived in the following form

$$Y_{1H,t}^{j} = (1-\kappa_2)\left(\frac{P_{1H,t}^{j}}{P_{1t}^{j}}\right)^{-\vartheta} Y_{2t}^{j} \tag{11}$$

$$M_{1F,t}^{j} = \kappa_2\left(\frac{P_{1F,t}^{j}}{P_{1t}^{j}}\right)^{-\vartheta} Y_{2t}^{j} \tag{12}$$

$P_{1t}^{j}\left(=\left[(1-\kappa_2)\left(P_{1H,t}^{j}\right)^{1-\vartheta}+\kappa_2\left(P_{1F,t}^{j}\right)^{1-\vartheta}\right]^{1/(1-\vartheta)}\right)$ is the flexible producer price for middlestream production. Analogous to the case of upstream producer, a fraction of processed output $\left(Y_{2H,t}^{j*}\right)$ will be exported for further processing.

Lastly at downstream production, monopolistically competitive producers $j$ of measure $J$ combines a variety of home $Y_{2H,t}^{j}\left(=\left[\int_{j\in J} Y_{2H,t}^{j}(j)^{(\varepsilon_{3t}-1)/\varepsilon_{3t}}dj\right]^{\frac{\varepsilon_{3t}}{\varepsilon_{3t}-1}}\right)$ and imported intermediate goods $M_{2F,t}^{j}\left(=\left[\int_{j\in J} M_{2F,t}^{j}(j)^{(\varepsilon_{3t}-1)/\varepsilon_{3t}}dj\right]^{\frac{\varepsilon_{3t}}{\varepsilon_{3t}-1}}\right)$ using the following CES technology

$$Y_{3t}^{j} = \left[(1-\kappa_3)^{1/\vartheta}\left(Y_{2H,t}^{j}\right)^{(\vartheta-1)/\vartheta} + {\kappa_3}^{1/\vartheta}\left(M_{2F,t}^{j}\right)^{(\vartheta-1)/\vartheta}\right]^{\vartheta/(\vartheta-1)} \tag{13}$$

The parameter $\kappa_3$ denotes the share of imported intermediates.

Solving for firm's cost minimization problem, the respective optimal demand function for home and imported intermediated goods can be inferred as below:

$$Y_{2H,t}^{j} = (1-\kappa_3)\left(\frac{P_{2H,t}^{j}}{P_{2t}^{j}}\right)^{-\vartheta} Y_{3t}^{j} \tag{14}$$

$$M_{2F,t}^{j} = \kappa_3\left(\frac{P_{2F,t}^{j}}{P_{2t}^{j}}\right)^{-\vartheta} Y_{3t}^{j} \tag{15}$$

$P_{2t}^{j}\left(=\left[(1-\kappa_3)\left(P_{2H,t}^{j}\right)^{1-\vartheta}+\kappa_3\left(P_{2F,t}^{j}\right)^{1-\vartheta}\right]^{1/(1-\vartheta)}\right)$ is the sticky utility-based producer price index (PPI) for downstream producers. Market clearing condition requires the final output to be consumed locally $\left(C_{H,t}^{i}\right)$, shipped abroad $\left(Y_{3H,t}^{j*}\right)$, and reinvested $(I_t)$ .

*3.2. Modeling trade cost*

Ravn and Mazzenga (2004) measure transportation cost as the wedge between c.i.f value and f.o.b. value of imports. Following this train of thought, our measure of trade cost takes the following form

$$\tau_t=\frac{M_{1F,t}}{Y_{1F,t}}-1=\frac{M_{2F,t}}{Y_{2F,t}}-1=\frac{C_{F,t}}{Y_{3F,t}}-1 \qquad (16)$$

The first two equalities refer to the trade cost incurred in exporting and importing processed materials in second-stage and final-stage productions, while the last equality refers to the trade cost involved in transporting consumer goods.

*3.3. Optimal pricing decision with U.S dollar pricing in export*

Pricing decision is assumed to be time dependent. The ability of domestic firms at second and third chain of production to reoptimize its price is subject to the signal received at probability $1-\theta_{Pn}$, $n=2,3$. Firm *j* that receives signal chooses $\mathbb{P}_{nH,t}^{j}$ to maximize the expected discounted profits $E_t\Pi_t$ for sales in home and export markets. For home market, the pricing decision is formulated as

$$E_t\Pi_t^{home}=E_t\sum_{i=0}^{\infty}(\theta_{Pn}\beta)^i\Lambda_{t+i}\left[\frac{\mathbb{P}_{nH,t+i}^{j,home}(j)-MC_{n,t+i}}{P_{n,t+i}}\right]\left[\frac{\mathbb{P}_{nH,t+i}^{j,home}(j)}{P_{nH,t+i}}\right]^{-\varepsilon_{n,t}}Y_{nH,t+i} \qquad (17)$$

Deviated from producer-currency pricing decision in typical New Keynesian model, we consider U.S. dollar pricing (DP) strategy in exports. DP strategy resembles the characteristics of the often-formulated local currency pricing in that the variability of exchange rates $S_{HD,t}$ between local currency and U.S. dollar will not be passed through into foreign price of home export, but rather, it will be passed through into local-currency denominated export earnings. Firm's expected profit in home currency under DP strategy is thus

$$E_t\Pi_t^{DP} = E_t \sum_{i=0}^{\infty}(\theta_{Pn}^{ex}\beta)^i\Lambda_{t+i}\left[\frac{S_{HD,t}\mathbb{P}_{nH,t+i}^{j,D}(j)-MC_{n,t+i}}{P_{n,t+i}}\right]\left[\frac{S_{FD,t}^{\psi^*}\mathbb{P}_{nH,t+i}^{j,D}(j)}{P_{nH,t+i}^*}\right]^{-\varepsilon_{n,t}} Y_{nH,t+i}^* \tag{18}$$

where $\psi^*$ denote the exchange rate pass-through into foreign import prices.

In what follows we assume that all firms producing all types of goods are symmetric in price setting. Solving for optimal reset price for both home and export markets for middlestream and downstream production gives us

$$\mathbb{P}_{nH,t+i}^{home} = \mu_{n,t+i}\frac{\sum_{i=0}^{\infty}(\theta_{Pn}\beta)^i\Lambda_{t+i}MC_{n,t+i}\left(Y_{nH,t+i}/P_{nH,t+i}\right)}{\sum_{i=0}^{\infty}(\theta_{Pn}\beta)^i\Lambda_{t+i}\left(Y_{nH,t+i}/P_{nH,t+i}\right)} \tag{19}$$

$$\mathbb{P}_{nH,t+i}^{DP} = \mu_{n,t+i}\frac{\sum_{i=0}^{\infty}\left(\theta_{Pn}^{ex}\beta\right)^i\Lambda_{t+i}MC_{n,t+i}(Y_{nH,t+i}^*/P_{nH,t+i})}{S_{HD,t}\sum_{i=0}^{\infty}\left(\theta_{Pn}^{ex}\beta\right)^i\Lambda_{t+i}(Y_{nH,t+i}^*/P_{nH,t+i})} \tag{20}$$

Firms that have received signal for price reoptimization will reset their log-linearized price ($\widehat{\mathbb{P}}_{nH,t}^{new}$) to approximate the optimal Eq. (20) for export market and Eq. (19) home market. The remaining firms that do not receive signal for readjustment will stick to last-period price, out of which a fraction of them ($\gamma_{Pn}$) will index to last-period inflation. The corresponding dynamics of PPI inflation ($n$ = 2) and GDP deflator inflation ($n$ = 3) for home, as well as export price inflation for intermediate and consumer goods, are respectively derived in the following manner

$$\pi_{nH,t}^{home} = \left(\frac{\gamma_{Pn}}{1+\theta_{Pn}\beta\gamma_{Pn}}\right)\pi_{nH,t-1}^{home} + \left(\frac{\beta}{1+\theta_{Pn}\beta\gamma_{Pn}}\right)E_t\pi_{nH,t+1}^{home} + \lambda\left(\widehat{rmc}_{n,t} + \hat{\mu}_{n,t}\right) \tag{21}$$

$$\pi_{nH,t}^{export} = \left(\frac{\gamma_P}{1+\theta_{Pn}\beta\gamma_{Pn}}\right)\pi_{nH,t-1}^{export} + \left(\frac{\beta}{1+\theta_{Pn}\beta\gamma_{Pn}}\right)E_t\pi_{nH,t+1}^{export} + \lambda\left(\widehat{rmc}_{n,t} - \hat{s}_{HD,t} + \hat{\mu}_{n,t}\right) \tag{22}$$

where $\lambda = (1-\theta_{Pn})(1-\theta_{Pn}\beta)/\big(\theta_{Pn}(1+\theta_{Pn}\beta\gamma_{Pn})\big)$, and $\hat{\mu}_{n,t}$ is an i.i.d price markup shock for $n = 2,3$. $\widehat{rmc}_{n,t}$ is the log-deviation of real marginal cost, in which $\widehat{rmc}_{2,t} = \hat{p}_{1,t}$ and $\widehat{rmc}_{3,t} = \hat{p}_{2,t}$.

*3.4. Consumer preference, nominal wage inflation, and monetary policy*

Suppose there is a continuum of infinitely-lived households, represented and indexed by $i \in [0,1]$, who maximizes the utility function of

$$U = E_t\left\{\sum_{t=0}^{\infty}\beta^t \mathrm{u}_t^C\left[\frac{(C_t^i - H_t)^{1-\sigma}}{1-\sigma} - \mathrm{u}_t^N\frac{(N_t^i)^{1+\chi_N}}{1+\chi_N}\right]\right\} \tag{23}$$

where

$$C_t^i = \left[(\gamma)^{1/\varphi}\left(C_{H,t}^i\right)^{(\varphi-1)/\varphi} + (1-\gamma)^{1/\varphi}\left(C_{F,t}^i\right)^{(\varphi-1)/\varphi}\right]^{\varphi/(\varphi-1)} \tag{24}$$

$\mathrm{u}_t^C$ and $\mathrm{u}_t^N$, respectively, is i.i.d preference and labor supply shock. $H_t(= bC_{t-1}^i)$ indicates external habit formation in which $b$ is the parameter that governs the extent of habit persistence. $0 < \beta < 1$ refers to subjective discount factor, $\sigma$ measures the coefficient of relative risk aversion, and the reciprocal of $\chi_N$ indicates the wage elasticity of labor supply. Household *i*'s consumption bundle consists of home $\left(C_{H,t}^i\right)$ and imported consumer goods $\left(C_{F,t}^i\right)$, with elasticity of substitution between home and imported consumer goods $(\varphi > 1)$. The parameter $\gamma$ measures home bias. Household *i*'s constrained optimization problem can be illustrated as utility maximization of Eq. (23) subject to Eq. (24) and the following budget constraint

$$P_{H,t}C_{H,t}^i + P_{F,t}C_{F,t}^i + \left(\frac{S_{HD,t}}{P_tRP_t}\right)\left(\frac{B_t^*}{R_t^*}\right) + \frac{B_t}{P_tR_t} = W_t^iN_t^i + \Pi_t + \left(\frac{S_{HD,t}B_{t-1}^* + B_{t-1}}{P_t}\right) \tag{25}$$

where $P_{H,t}$ and $P_{F,t}$, respectively, denotes domestic price of home and imported consumer goods. Household facing exchange-rate risk ($RP_t$) in foreign asset market has access only to imperfect international asset market. Efficiency conditions can then be derived as

$$C_{H,t}^{i} = \gamma\left(P_{H,t}/P_t\right)^{-\varphi} C_t^{i} \tag{26}$$

$$C_{F,t}^{i} = (1-\gamma)\left(P_{F,t}/P_t\right)^{-\varphi} C_t^{i} \tag{27}$$

$$P_t = \left[\gamma P_{H,t}^{1-\varphi} + (1-\gamma) P_{F,t}^{1-\varphi}\right]^{1/(1-\varphi)} \tag{28}$$

$$\left(C_t^{i} - bC_{t-1}^{i}\right)^{-\sigma} E_t P_{t+1} \mathrm{u}_t^{C} = \beta R_t \left(E_t C_{t+1}^{i} - bC_t^{i}\right)^{-\sigma} P_t E_t \mathrm{u}_{t+1}^{C} \tag{29}$$

$$\left(N_t^{i}\right)^{\chi_N} \left(C_t^{i} - bC_{t-1}^{i}\right)^{\sigma} \mathrm{u}_t^{N} = W_t^{MRS} \tag{30}$$

$$S_{HD,t} = E_t S_{HD,t+1} (R_t^{US}/R_t) RP_t \tag{31}$$

Eqs. (26) and (27) are optimal demand functions, Eq. (28) is utility-based consumer price index (CPI), Eq. (29) is the Euler condition for intertemporal consumption smoothing with habit persistence, Eq. (30) shows the marginal rate of substitution between leisure and consumption, and Eq. (31) refers to uncovered interest parity condition (UIPC). We assume that UIPC shock ($RP_t$) is i.i.d white noise. Since household is a monopoly supplier of differentiated service, nominal wage is set in Calvo-style, which results in nominal wage inflation dynamics as what follows:

$$\pi_t^{w} = \left\{\frac{\gamma_w}{1+\theta_w\beta\gamma_w}\right\} \pi_{t-1}^{w} + \left\{\frac{\beta}{1+\theta_w\beta\gamma_w}\right\} E_t \pi_{t+1}^{w} + \left\{\frac{(1-\theta_w)(1-\theta_w\beta)}{\theta_w(1+\theta_w\beta\gamma_w)}\right\} (markup_t + \mathrm{u}_t^{w}) \tag{32}$$

where $\theta_w$ denotes wage stickiness, $\gamma_w$ is wage indexation, and $markup_t = \widehat{w}_t^{MRS} - \widehat{w}_t$. $\mathrm{u}_t^{W}$ is i.i.d wage markup shock.

All the budget constraints and market clearing conditions considered, aggregate demand of the model economy can be defined as

$$AD_t = C_t + I_t + \underbrace{\textstyle\sum_{n=1}^{3} Y_{nH,t}^{*}}_{export,f.o.b} - \underbrace{\textstyle\sum_{n=1}^{3}(1+\tau_{n,t})Y_{nF,t}}_{import,f.o.b} \tag{33}$$

The model is closed by considering a general form of monetary policy reaction as below:

$$r_t = \rho_R r_{t-1} + (1-\rho_R)\left(r_t^n + V_\pi \pi_{CPI,t} + V_{AD}\widehat{ad}_t + V_S \Delta s_{HD,t}\right) + \mathrm{u}_t^R \tag{34}$$

where $r_t^n\left(= \mathrm{u}_t^C + \sigma(u_t^I + \hat{a}_t)\right)$ is the natural rate of interest, $\rho_R$ measures the interest rate persistence, $V_\pi, V_{AD}$, and $V_S$ indicates central bank's responsiveness toward variability in CPI inflation, aggregate demand variability, and rate of change in nominal exchange rates between home currency and U.S. dollar, respectively. $\mathrm{u}_t^R$ refers to i.i.d white noise to the conduct of monetary policy.

## 4. Bayesian evaluation of New Keynesian model with vertical production and trade

East and Southeast Asian economies have been the natural candidates for study on the importance of vertical linkage as conduit that couples international trade and business cycle comovement. This is grounded on a widely recognized fact that the most complex vertical production networks occur in this region. For instance, in a study of 79 countries, over 121 categories of goods within the period of 1967-2005, Amador and Cabral (2009) show that out of top ten vertically most specialized countries, eight is located in East Asia. Of 22 countries in East, Southeast, South, and Central Asia in 2003, Sawyer et al. (2010) document that Southeast Asian countries and the high-income economies in East Asia exhibit the highest level of intra-product trade, followed closely by China (see, also, Athukorala and Yamashita, 2006).

In light of this evidence, we study nine East and Southeast Asian economies, including Japan, Republic of Korea, Hong Kong, Taiwan, Singapore, Malaysia, Thailand, Indonesia, and Philippines. Because the systematic formation of regional vertical production and trade link is widely viewed as the consequence of the massive outflow of vertical foreign direct investment from Japan in the aftermath of Plaza Accord and subsequently other first-tier Newly Industrializing Economies to Southeast Asia, we focus on year 1987, rather than the earlier available data, onward and categorize the nine economies into developing Southeast Asian economies (SEA4), which consists of Indonesia, Malaysia, Philippines, and Thailand, and advanced East Asian economies (EA5) for the rest.

*4.1. Bayesian estimation*

The model is confronted with the data using Bayesian method. As the literature on Bayesian estimation and evaluation has been growing tremendously, its estimation procedure is briefly sketched here[5]. The procedure is principally built around the likelihood function of the data derived from the model in conjunction with the prior belief on the probability distribution of the parameters. Bayesian estimation is thus about finding a set of parameters that maximizes the posteriors.

According to Bayes's theorem, the posterior distribution of model parameters $\mathcal{P}(\mathbb{X}|\Upsilon,\mathcal{M})$ is formed by combining the likelihood function $\mathcal{P}(\Upsilon|\mathbb{X},\mathcal{M})$ and prior density $\mathcal{P}(\mathbb{X},\mathcal{M})$ in following manner:

$$\mathcal{P}(\mathbb{X}|\Upsilon,\mathcal{M}) = \frac{\mathcal{P}(\Upsilon|\mathbb{X},\mathcal{M})\mathcal{P}(\mathbb{X},\mathcal{M})}{\mathcal{P}(\Upsilon,\mathcal{M})} \tag{35}$$

where $\mathcal{P}(\Upsilon,\mathcal{M})$ is the marginal density of the data, given a specific model:

$$\mathcal{P}(\Upsilon,\mathcal{M}) = \int_{\mathbb{X}} \mathcal{P}(\Upsilon|\mathbb{X},\mathcal{M})\mathcal{P}(\mathbb{X},\mathcal{M})\, d\mathbb{X} \tag{36}$$

[5]See, for instance, Smets and Wouters (2003, 2005), Rabanal and Rubio-Ramirez (2005) for skillful application of Bayesian method. More recent Fernandez-Villaverde (2010) and Schorfheide (2011) provide for in-depth discussion on Bayesian estimation of DSGE model.

Suppose that the marginal density of the data is a constant or equals certain parameter, the posterior kernel can be derived from the numerator of the posterior density

$$\mathcal{K}(\mathbb{X}|\Upsilon,\mathcal{M}) \equiv \mathcal{P}(\mathbb{X}|\Upsilon,\mathcal{M}) \propto \mathcal{P}(\Upsilon|\mathbb{X},\mathcal{M})\mathcal{P}(\mathbb{X},\mathcal{M}) \tag{37}$$

where $\propto$ denotes proportionality. Posterior kernel is simulated to generate draws using Markov Chain Monte Carlo (MCMC) method. The resultant findings provide the point estimates, standard deviations and probability density region.

Because we intend to compare empirical fit of the NKVPT model across a variety of different specifications, as well as vis-à-vis IRBC and the simple VS model, Bayesian approach that allows us to compare marginal likelihood of each model, even when they are misspecified or not nested, is clearly very convenient. In line with Rabanal and Rubio-Ramirez (2005), how well these models fit the observable series can be compared using Bayes factors. Specifically, the Bayes factor of model $\mathcal{M}$ over model $\mathcal{N}$ is

$$\hat{B} = exp\{ln(\mathcal{P}(\Upsilon|\mathcal{M})) - ln(\mathcal{P}(\Upsilon|\mathcal{N}))\} \tag{38}$$

where $ln(\mathcal{P}(\Upsilon|\mathcal{M}))$ is the log marginal likelihood of Eq. (36) for model $\mathcal{M}$ that comprises the sum of the log likelihood of the data and the sum of all log prior distributions:

$$ln\mathcal{P}(\Upsilon|m) = \mathcal{L}(\Upsilon|\mathbb{X},\mathcal{M}) + \int_{i=1}^{J} ln\mathcal{P}(\mathbb{X}_i,\mathcal{M}) \tag{39}$$

An estimated model that shows higher log marginal likelihood over the competitive models is either employing better set of observable series or is better specified. In other words, given similar set of observable series, the Bayes factor informs us a prior probability that the empirically relative unfit model has to possess in excess of the prior probability over better fit model.

*4.2. Data, prior, and posterior distribution for NKVPT model*

The medium-scale NKVPT mode contains seventy nine structural equations with twenty two forward-looking variables and sixty five parameters, which include twenty five structural shocks. There are altogether twenty three macroeconomic time series over the periods of 1987Q1 through 2008Q4, which comprise trade-weighted real GDP, real consumption, real investment, labor force, nominal interest rate, exchange rates, trade-weighted PPI inflation, GDP deflator inflation, export deflator inflation, and CPI inflation for SEA4 and EA5, and U.S. federal funds rate. All the quantity variables are deflated by respective deflator, and all data, except for rates of inflation and interest, are logged and detrended using Hodrik-Prescott Filter with smoothing parameter $\lambda = 1600$. The regional series for SEA4 and EA5, as in previous estimation on IRBC and VS model, are constructed using time-varying fraction of national total trades over aggregate regional trades. We treat SEA4 as home while EA5 as foreign.

**[INSERT FIG. 1 ABOUT HERE]**

Given that the data set is limited (88 observations) relatively to the model parameters available for estimation, we use identical priors for both SEA4 and EA5, except for price indexation and stickiness, share of imported materials, monetary policy reaction functions, and standard deviation of structural shocks. We use Dynare 4.2.1 algorithms for model estimation, and adjust the number of Markov chains to ensure that estimates for mean and standard deviation across the Markov chains are satisfactorily consistent.

Guided by the principle of allowing equal probability for all potential parameter values within the range in the face of uncertainty about the true value, prior standard deviation of shocks is in uniform distribution with a range of (0,1). All structural shocks are well identified. Despite a handful of parameters, for instance, SEA4 policy reaction toward output fluctuation and home biasness, and EA5 export price indexation and policy reaction toward change in exchange rates, all important parameters are also nicely identified as evinced by the proximity between posterior mode and mean.

Table 2 reports the priors, probability density function, and posteriors for model parameters and shocks. Due to the space constraints, here we only pay attention to the posterior mean of the share of imported materials in middlestream and downstream production. Priors for the share of imported materials in middlestream and downstream productions of both SEA4 and EA5 are assumed to be uniform distributed. Evidently, SEA4 and EA5 are vertically and sequentially tied. For instance, as shown in Table 2, almost one fourth of materials for middlestream productions in SEA4 are sourced from EA5 ($\vartheta_2 = 0.242$). The fraction is even higher in downstream production ($\vartheta_3 = 0.484$). Following Yi (2003), the degree of vertical specialization of total export for country $i$ over sector $k$ can actually be measured by

$$VS_i = \frac{\sum_k \vartheta_k Export_k}{\sum_k Export_k} \tag{40}$$

Given the structure of NKVPT model, for index $i$ denotes SEA4 and $j$ denotes EA5, the vertical-specialization index is reformulated as

SEA4: $VS_i = \frac{\vartheta_1^i y_{1i}^j + \vartheta_2^i y_{2i}^j + \vartheta_3^i y_{3i}^j}{y_{1i}^j + y_{2i}^j + y_{3i}^j}$ EA5: $VS_j = \frac{\vartheta_1^j y_{1j}^i + \vartheta_2^j y_{2j}^i + \vartheta_3^j y_{3j}^i}{y_{1j}^i + y_{2j}^i + y_{3j}^i}$

Because upstream production uses only labors and capital stocks, we get $\vartheta_1 = 0$. The fraction of intermediates and final goods in total export of both SEA4 and EA5 is calibrated, respectively, at $\frac{y_{2i}^j}{Ex_i} = 0.35$, $\frac{y_{3i}^j}{Ex_i} = 0.3$, $\frac{y_{2j}^i}{Ex_j} = 0.3$, and $\frac{y_{3j}^i}{Ex_j} = 0.3$. In conjunction with the posterior mean of $\vartheta_2$ and $\vartheta_3$, it can be easily calculated that the vertical-specialization index for SEA4 is 0.23, and is 0.31 for EA5. This index is generally in line with the estimates in Amador and Cabral (2010) that obtain 0.22 for Malaysia, Philippines and Thailand combined and 0.19 for Singapore, Taiwan, Republic of Korea, and Hong Kong combined on average over the periods of 1987 through 2005 (see also Uchida, 2008).

**[INSERT TABLE 2 ABOUT HERE]**

*4.3. Quantitative performance of NKVPT model*

A first glance at Table 3 gives an overwhelming impression that NKVPT model works spectacularly well as an international business cycle model. The log marginal likelihood of the baseline NKVPT model (3753.07) is so much better than the baseline IRBC model (1367.7) and VS model (2733.3), even after penalizing for larger set of parameters to estimate. Such a huge difference between log marginal likelihood implies that the probability for IRBC and VS model to dominate NKVPT model as international business cycle model is basically zero.

Most importantly, the baseline NKVPT model replicates the actual cross-region contemporaneous correlations almost perfectly. For instance, strong trade-comovement is reproduced. The simulated cross-region correlations in real GDP, consumption, export, and import are all almost equally strong as the one in data, despite the inability to replicate the weaker cross-region correlation in output than that of consumption. In addition, the estimated model works well in mimicking the inflation dynamics. Strong correlations in PPP inflation and export price inflation in conjunction with weaker CPI inflation and the weakest GDP deflator inflation comovement shown in the data are all approximated subtly by the model-generated moments. Last but not least, the model also nicely imitates the non-trivial comovement in policy-controlled interest rate and nominal exchange rate vis-à-vis U.S. dollar.

**[INSERT TABLE 3 ABOUT HERE]**

For concreteness, we further examine the goodness of fit of NKVPT model by comparing model-generated cross correlations between SEA4 and EA5, and autocorrelations for SEA4 with the data over 12 quarters. Figure 1 illustrates the model-generated correlations of eleven important macroeconomic variables between SEA4 and EA5 at twelve lags and leads in comparison with the data. Obviously, the NKVPT model has also been relatively successful in replicating the lead-lag relationship between SEA4 and EA5 over a large set of variables simultaneously. Figure 2 compares the model-generated autocorrelation of identical set of macroeconomic variables for SEA4 with the data over twelve lags, and the nearly perfectly matched autocorrelations have further confirmed the validity of NKVPT model.

To the best of our knowledge, this is the first medium-scale estimated international business cycle model with vertical trade and production that can jointly explain contemporaneous comovement and dynamics over time for such a large set of variables over different countries in such remarkable accuracy. This is also the first estimated international business cycle model that accounts for the trade and macroeconomic interdependence between the developed East Asia and developing Southeast Asia economies.

**[INSERT FIG.1 & FIG. 2 ABOUT HERE]**

*4.4. What can we learn from sensitivity analysis?*

In this section the NKVPT model is put into a battery of sensitivity analysis to take stock on how robust its quantitative performance is when certain frictions are changed. We know how fragile the role of vertical trade in simple VS model has been in instigating trade-comovement. We test for this fragility in NKVPT model by setting the share of imported materials at middlestream and downstream production to zero to give us a complete absence of vertical specialization$(VS_{SEA4} = VS_{EA5} = 0)$.

The forth vertical panel of Table 3 convincingly calls for the role of vertical trade in generating international business cycle comovement. Without vertical trade in intermediates, cross-region correlations in export and import turn trivial, while real GDP, consumption, investment, and PPI inflation of SEA4 are now inversely correlated with those of EA5. Besides, a significantly smaller log marginal density for the re-estimated model indicates how unlikely the model without vertical trade is to outperform the baseline NKVPT model. It thus cannot be overstated to conclude that SEA4 and EA5 are coupled by vertical trade in intermediates, and that vertical production and trade in three processing stages is a sufficient ingredient to generate positive macroeconomic comovement.

Arkolakis and Ramanarayanan (2009) uncover trade-comovement puzzle when simulating an international business cycle model with perfect competition, flexible price and vertical specialization that is endogenous to trade barriers. They thus speculate that allowing for sticky price along with imperfect competition could be the key to overcoming this puzzle. We re-estimate the model by choosing a prior Calvo stickiness for producer price, export price, and consumer goods price that result in price reoptimization in every 2 quarters. The fifth vertical panel in Table 3 reports the model-generated business cycle comovement. Obviously, greater price flexibility deteriorates the model fit, and substantially reduces output comovement, despite the equally strong trade comovement. As such, our finding complements Arkolakis and Ramanarayanan (2009) by showing that price stickiness is a necessary though not sufficient ingredient for overcoming trade-comovement puzzle.

Kose and Yi (2006), and Burstein et al. (2008) suggest low elasticity of substitution between home and foreign inputs as the key parameter underlying the positive trade-comovement relationship in a quantitative model. Our baseline NKVPT model that assumes high elasticity of substitution, however, defies its role as key parameter. Again, we reestimate the model by restricting prior elasticity of substitution to 0.9 with tight standard deviation of 0.01 as suggested by di Giovanni and Levchenko (2010). Through the lens of model-generated correlations reported in the sixth vertical panel of Table 3, one hardly finds any non-trivial improvements in terms of the quantitative ability to replicate the actual cross-region correlation. To the contrary, this low-elasticity-of-substitution model yields a weaker consumption comovement and turns a weakly positive cross-region correlation in GDP deflator inflation into a weakly negative one. It can thus be inferred that low elasticity of substitution between imported and home intermediate inputs is neither an essential nor sufficient condition for NKVPT model once vertical trade in intermediates is properly formalized.

Besides of having three processing stages, NKVPT model differs from VS model in terms of invoice currency in trade. Is dollar pricing equally important as vertical trade and production in NKVPT model to replicate the actual moments? We re-structure the model so that trade is now priced at producer currency, equating the export price inflation dynamics with domestic inflation dynamics. In consequence, the data set used for estimation exactly resembles the one for the estimation of VS model.

As demonstrated in the seventh vertical panel of Table 3, the presence of dollar pricing certainly fits the NKVPT model more satisfactorily to the data, evidenced by the fact that in order to obtain an empirically better performing PCP model one needs to possess a very unlikely prior probability that is $2.4 \times 10^{173}$ $\left(= exp(3753.07 - 3353.84)\right)$ greater than the prior probability for the baseline NKVPT model. Without dollar pricing mechanism, cross-region consumption, domestic inflation and CPI inflation contrarily comove, although trade-output comovement remains intact. It is unsurprising to witness a role for dollar pricing in our model estimation given the dominance of U.S dollar as vehicle currency in international trade (Goldberg and Tille, 2008). In addition, a comparison between the log marginal density of PCP model (3353.84) and the VS model (2733.3), once again, confirms the empirical relevance of formalizing vertical and sequential trade in intermediates, regardless of the invoice currency.

Of all the estimated parameters, there are three that exhibit posteriors different from the available estimates based on the United States and Euro Area (see, for instance, Smets and Wouters, 2005). In particular for SEA4, the posterior mean for risk adverse coefficient is too low, policy reaction to inflation is smaller than one[6], and consumption habit is too persistent. Our concern is to what extent the empirical success of the baseline NKVPT model is de facto attributed to these estimates. In other words, would the nicely replicated cross-region international business cycle comovement disappear if the intertemporal substitution of consumption is a priori restricted to be inelastic $(\sigma > 1)$? What if prior policy reaction toward inflation is raised to 3.5, or there is no habit persistence $(b = 0)$? The model-generated comovements are reported in eighth through tenth vertical panel of Table 3. Overall, the reestimated NKVPT model remains capable in generating business cycle comovements that match the data at large, despite weak or inverse consumption and CPI inflation correlations. None the less, dramatically deteriorating Bayes factor indicates that prior belief of inelastic intertemporal substitution, "hawkish" monetary policy reaction toward inflation, or habit is not persistent is clearly at odd with the data on SEA4 and EA5.

*4.5. Inspecting the mechanism*

To provide a sense of how the shocks are propagated within and across region, in this section we present impulse responses of home (SEA4) and foreign economy (EA5) toward

6 Because monetary policy rule of Eq. (34) also reacts to rate of change in nominal exchange rate, which, by definition, measures the difference between home and foreign CPI inflation, the effective policy reaction toward inflation fluctuation is indeed $V_\pi + V_s$. Drawn from Table 2, the posterior mean sums up to 1.6041, and is thus in line with estimates of typical Taylor's rule that approximate 1.5.

shock to foreign total factor productivity. Figure 3 displays dynamic responses of the economy to a favorable foreign TFP shock. Solid blue lines with dots correspond to home, and dashed read lines correspond to foreign.

**[INSERT FIG. 3 ABOUT HERE]**

Positive foreign TFP shock raises investment, real wage, and natural interest rate that enters consumption Euler condition on the one hand, and reduces the real marginal cost for middlestream production on the other hand. Because policy-controlled interest rate hardly responds on impact due to the offsetting forces of rising natural rate and falling inflation rate, consumption also increases on impact to a lesser extent. Expansion in consumption and investment combined raises the demand for middlestream inputs, which, in turn, stimulates the demand for upstream inputs. Meanwhile, declining real marginal cost for middlestream production results in falling producer price for subsequent downstream production at home and decreasing intermediate export price for processing at foreign. Falling PPI inflation gradually feeds into lower domestic inflation and thus CPI inflation, which can partly be attributed to cheaper imported consumer goods thanks to nominal appreciation, and final export price inflation.

That matters the most as tie that binds home and foreign is the sequentially linked trade and production. Consumption expansion in foreign would raise the export of home final goods, which, of course, would bolster home middlestream and upstream production through input-output structure. This spillover effect is propagated by the foreign demand for home export of middlestream and upstream products in consequence of expansions in foreign downstream and middlestream production, respectively. Such multiple back-and-forth production linkage is the key characteristic that propagates the repercussion effect of a small shock across the borders.

Without corresponding TFP shock at home, positive foreign TFP shock that raises demand for home exports of all stages of production is expected to drive the prices up. From home PPI to CPI inflation, Figure 3 depicts that inflation rates and thus policy-controlled interest rate rise gradually over the time. The magnitude is, however, trivial as the inflationary pressure is partly counterbalanced by falling imported price[7].

## 5. Concluding remark

Mounting evidence has pointed to business cycle synchronization across countries, and East Asia economies show no exception. One of the empirically most solid reasons that instigate comovement is the international trade link, particularly vertical linkage in traded intermediate inputs. However, the early open-economy models with trade links have frustratingly failed to replicate the cross-country comovement shown in the data.

We reevaluate the two most prominent open-economy models, namely, international real business cycle model and two-country New Keynesian model, on the ground of historical comovement between East and Southeast Asia. The former, equipped with trade in intermediate inputs without vertical and sequential linkage, and the latter, which resembles a simple form of vertical-specialization model in a way such that downstream firms import materials from abroad and the resulting processed final goods will be partially exported abroad, have produced counterfactual correlations. In consequence, the international real business cycle model and two-

[7] The NKVPT model has many implications of which we are unable to explore here due to space constraint. One of the instances is Harrod-Balassa-Samuelson effect in response to aggregate productivity differentials. Not shown in Figure 3 is the fact that foreign currency appreciates against U.S dollar as well as home currency following favorable shock to foreign TFP even in the absence of nontraded sector and endogenous entry (see Ghironi and Melitz, 2005). The vertical and sequential trade mechanism through which productivity differentials effectuate Harrod-Balassa-Samuelson effect deserves serious attention in future research.

country New Keynesian model are self-invalidating as useful model to account for trade-comovement.

This paper contributes to the literature by laying out a two-country model with three processing stages that encompass vertical and sequential linkage in traded intermediate inputs and final goods. The numerical simulation generated from the Bayesian estimated NKVPT model, along with a variety of sensitivity analysis, has convincingly endorsed the quantitative ability of this model to produce autocorrelation as well as cross-region contemporaneous and cross-correlations that can spectacularly match a large set of observable East and Southeast Asian data. The sensitivity analysis also shows that dollar-invoiced vertical trade in intermediates at sequentially linked middlestream and downstream production is essential and sufficient ingredient for an empirically relevant international business cycle model. Other necessary though not sufficient conditions include sticky price, low risk aversion (elastic intertemporal substitution), and habit persistence in consumption. Low elasticity of substitution between home and imported inputs and strong policy response toward inflation response are neither essential nor sufficient properties for compelling trade-comovement.

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**Table 1**

Cross-region correlations in international real business cycle model and simple vertical-specialization model

| | | International real business cycle model | | | | Vertical-specialization model | |
|---|---|---|---|---|---|---|---|
| | | Role of shocks and frictions | | | | Role of vertical trade | |
| | Data | Baseline | AR(1) innovation to preference shock[1] | IST shock[2] | Low ELS[3] | Baseline | No trade in intermediates[4] |
| Output | 0.624 | -0.171 | 0.070 | 0.349 | -0.051 | 0.414 | 0.112 |
| Consumption | 0.659 | -0.420 | -0.224 | 0.130 | -0.256 | 0.095 | 0.102 |
| Investment | 0.532 | -0.356 | 0.122 | -0.127 | -0.178 | 0.281 | 0.170 |
| Export | 0.769 | -0.381 | -0.100 | 0.011 | -0.216 | 0.924 | -0.618 |
| Import | 0.849 | -0.381 | -0.100 | 0.011 | -0.216 | 0.976 | -0.618 |
| PPI inflation | 0.427 | - | - | - | - | 0.587 | 0.136 |
| Domestic inflation | 0.092 | - | - | - | - | 0.143 | 0.148 |
| Export price inflation | 0.422 | - | - | - | - | 0.587 | 0.148 |
| CPI inflation | 0.283 | -0.015 | -0.021 | -0.048 | -0.017 | 0.739 | -0.763 |
| Nominal exchange rates | 0.553 | - | - | | - | -0.057 | -0.151 |
| Interest rate | 0.581 | - | - | | - | -0.251 | -0.592 |
| Money growth | 0.262 | 0.028 | 0.017 | 0.003 | -0.023 | - | - |
| *Log marginal density* | | *1367.7* | *1348.03* | *1245.41* | *1342.88* | *2733.3* | *2929.93* |

Notes:

[1]Innovation to preference shock is assumed to follow AR(1) process with prior autocorrelation coefficient of 0.5 and standard deviation 0.2887 distributed uniformly. The average acceptance ratio over 8 chains is 0.23.

[2]Capital stock with investment adjustment cost is introduced. Adjustment cost parameter is calibrated at the value of 0.6. The prior autocorrelation coefficient for investment shock presumes beta distribution with mean of 0.7 and standard deviation of 0.1. The average acceptance ratio over 8 chains is 0.313.

[3]Prior mean elasticity of substitution between home and imported materials is reduced to 0.9, normally distributed with tight standard deviation 0.01. The average acceptance ratio over 8 chains is 0.23. The average acceptance ratio over 8 chains is 0.137.

[4]The share of imported materials for SEA4 and EA5 is set to zero. Only trade in final goods is allowed. The average acceptance ratio over 8 Markov chains is 0.331.

**Table 2**
Prior and posterior distributions for New Keynesian model with vertical production and trade

| | Prior distribution | | | Posterior distribution | | | |
|---|---|---|---|---|---|---|---|
| | Type | Mean | Std | Mode | 5% | Mean | 95% |
| *Parameters* | | | | | | | |
| Risk aversion coefficient | Uniform | 1 | 0.577 | 0.055 | 0.032 | 0.098 | 0.188 |
| Inverse wage elasticity of labor supply | Gamma | 2 | 1 | 2.055 | 2.030 | 2.127 | 2.230 |
| Habit persistence | Beta | 0.7 | 0.1 | 0.956 | 0.826 | 0.914 | 0.975 |
| Home bias in consumption | Beta | 0.7 | 0.1 | 0.624 | 0.601 | 0.673 | 0.747 |
| Els between home and imported intermediate goods | Normal | 1.5 | 0.5 | 1.418 | 1.335 | 1.441 | 1.543 |
| Share of imported materials at intermediate production | Uniform | 0.5 | 0.289 | 0.278<br>(0.305) | 0.097<br>(0.225) | 0.242<br>(0.372) | 0.386<br>(0.562) |
| Share of imported intermediate goods at final production | Uniform | 0.5 | 0.289 | 0.502<br>(0.694) | 0.401<br>(0.570) | 0.484<br>(0.672) | 0.565<br>(0.760) |
| employment indexation | Uniform | 0.5 | 0.289 | 0.000<br>(0.000) | 0.000<br>(0.000) | 0.014<br>(0.025) | 0.029<br>(0.059) |
| Producer price indexation | Uniform | 0.5 | 0.289 | 0.965<br>(0.968) | 0.895<br>(0.901) | 0.944<br>(0.947) | 1.000<br>(1.000) |
| Final goods price indexation | Uniform | 0.5 | 0.289 | 0.380<br>(0.895) | 0.203<br>(0.829) | 0.316<br>(0.869) | 0.425<br>(0.909) |
| Intermediate export price indexation | Uniform | 0.5 | 0.289 | 0.556<br>(0.275) | 0.438<br>(0.222) | 0.571<br>(0.336) | 0.712<br>(0.454) |
| Final goods export price indexation | Uniform | 0.5 | 0.289 | 0.843<br>(0.907) | 0.798<br>(0.894) | 0.886<br>(0.948) | 0.999<br>(1.000) |
| Employment stickiness | Uniform | 0.75 | 0.144 | 0.858<br>(0.893) | 0.842<br>(0.886) | 0.853<br>(0.895) | 0.865<br>(0.903) |
| Producer price stickiness | Uniform | 0.75 | 0.144 | 0.754<br>(0.827) | 0.739<br>(0.815) | 0.757<br>(0.830) | 0.774<br>(0.844) |
| Final goods price stickiness | Uniform | 0.75 | 0.144 | 0.837<br>(0.925) | 0.818<br>(0.914) | 0.833<br>(0.925) | 0.848<br>(0.939) |
| Intermediate export price stickiness | Uniform | 0.75 | 0.144 | 0.958<br>(0.770) | 0.951<br>(0.658) | 0.959<br>(0.762) | 0.967<br>(0.870) |
| Final export price stickiness | Uniform | 0.75 | 0.144 | 0.732<br>(0.828) | 0.711<br>(0.802) | 0.732<br>(0.817) | 0.753<br>(0.834) |
| Policy inertia | Beta | 0.7 | 0.1 | 0.702<br>(0.867) | 0.662<br>(0.828) | 0.711<br>(0.858) | 0.760<br>(0.884) |
| Policy response to inflation | Gamma | 1.5 | 1 | 0.929<br>(1.233) | 0.849<br>(0.979) | 0.929<br>(1.148) | 1.007<br>(1.299) |
| Policy response to output fluctuation | Gamma | 0.125 | 0.05 | 0.083<br>(0.066) | 0.052<br>(0.033) | 0.115<br>(0.072) | 0.176<br>(0.107) |
| Policy response to change in exchange rates | Gamma | 0.5 | 0.1 | 0.648<br>(0.632) | 0.588<br>(0.529) | 0.675<br>(0.582) | 0.768<br>(0.636) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| TFP shock persistence | Beta | 0.8 | 0.1 | 0.426 (0.503) | 0.339 (0.401) | 0.443 (0.587) | 0.548 (0.851) |
| IST shock persistence | Beta | 0.7 | 0.1 | 0.752 (0.813) | 0.678 (0.747) | 0.735 (0.808) | 0.794 (0.873) |
| *Shocks* | | | | | | | |
| Total factor productivity | Uniform | 0.5 | 0.289 | 0.021 (0.000) | 0.000 (0.000) | 0.024 (0.028) | 0.049 (0.054) |
| Investment-specific technology | Uniform | 0.5 | 0.289 | 0.055 (0.027) | 0.045 (0.020) | 0.059 (0.029) | 0.074 (0.038) |
| Labor supply | Uniform | 0.5 | 0.289 | 0.431 (0.508) | 0.339 (0.476) | 0.420 (0.610) | 0.507 (0.765) |
| Preference | Uniform | 0.5 | 0.289 | 0.051 (0.027) | 0.036 (0.020) | 0.046 (0.026) | 0.056 (0.031) |
| Producer price markup | Uniform | 0.5 | 0.289 | 0.641 (0.415) | 0.573 (0.359) | 0.655 (0.431) | 0.743 (0.507) |
| Final goods price markup | Uniform | 0.5 | 0.289 | 0.342 (0.794) | 0.252 (0.701) | 0.332 (0.812) | 0.414 (0.927) |
| Intermediate export price markup | Uniform | 0.5 | 0.289 | 0.838 (0.679) | 0.756 (0.567) | 0.860 (0.654) | 0.968 (0.748) |
| Final export price markup | Uniform | 0.5 | 0.289 | 0.435 (0.421) | 0.369 (0.310) | 0.452 (0.381) | 0.552 (0.452) |
| Transportation cost | Uniform | 0.5 | 0.289 | 0.427 (0.784) | 0.386 (0.686) | 0.442 (0.771) | 0.496 (0.851) |
| Monetary policy | Uniform | 0.5 | 0.289 | 0.010 (0.003) | 0.008 (0.003) | 0.010 (0.003) | 0.012 (0.004) |
| UIPC | Uniform | 0.5 | 0.289 | 0.118 (0.022) | 0.097 (0.016) | 0.118 (0.025) | 0.137 (0.035) |
| U.S monetary policy | Uniform | 0.5 | 0.289 | 0.012 | 0.011 | 0.012 | 0.014 |

Notes: Southeast Asian (SEA4) and East Asian economies (EA5) share identical priors for all parameters and shocks, and identical posteriors for the first five parameters. Remaining posteriors for EA5 are reported in bracket. The posterior distribution is obtained using the Metropolis-Hastings sampling algorithm based on 4 parallel chains of 50,000 draws, of which the first half was discarded as burn-in. The average acceptance rate is 0.281.

**Table 3**
Cross-region correlations in New Keynesian model with vertical production and trade

| | | | Role of frictions | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Data | Baseline | No vertical trade[1] | Flexible price[2] | Low ELS[3] | PCP[4] | Inelastic intertemporal substitution[5] | Hawkish monetary policy[6] | No habit persistence[7] |
| Output | 0.624 | 0.396 | -0.399 | 0.092 | 0.307 | 0.315 | 0.510 | 0.172 | 0.239 |
| Consumption | 0.659 | 0.217 | -0.099 | 0.429 | 0.089 | -0.206 | 0.087 | -0.005 | 0.151 |
| Investment | 0.532 | 0.506 | -0.332 | 0.539 | 0.341 | 0.368 | 0.496 | 0.228 | 0.078 |
| Export | 0.769 | 0.864 | 0.069 | 0.819 | 0.862 | 0.805 | 0.790 | 0.858 | 0.832 |
| Import | 0.849 | 0.864 | 0.069 | 0.819 | 0.862 | 0.805 | 0.790 | 0.858 | 0.832 |
| PPI inflation | 0.427 | 0.315 | -0.064 | 0.671 | 0.339 | 0.250 | 0.418 | 0.159 | 0.226 |
| Domestic inflation | 0.092 | 0.049 | 0.134 | 0.249 | -0.069 | -0.148 | 0.271 | 0.135 | -0.187 |
| Export price inflation | 0.422 | 0.368 | 0.274 | 0.469 | 0.311 | 0.188 | 0.331 | 0.398 | 0.501 |
| CPI inflation | 0.283 | 0.221 | 0.147 | 0.389 | 0.210 | -0.067 | 0.024 | -0.044 | -0.164 |
| Nominal exchange rates | 0.553 | 0.528 | 0.698 | 0.338 | 0.487 | 0.272 | 0.726 | 0.545 | 0.577 |
| Interest rate | 0.581 | 0.649 | 0.391 | 0.584 | 0.655 | 0.632 | 0.652 | 0.234 | 0.522 |
| *Log marginal density* | | *3753.07* | *3658.82* | *3262.96* | *3790.45* | *3353.84* | *3713.06* | *3697.92* | *3474.06* |

Notes:
[1]The share of imported materials at both intermediates and final goods production is set to zero. Only final goods are allowed to flow across borders. The vertical-specialization index is thus zero. The average acceptance ratio is 0.195.
[2]Prior Calvo price stickiness for all prices of intermediate and final goods for home and export markets of both SEA4 and EA5 is assumed to be beta distributed at 0.5 with tight standard deviation 0.01. The average acceptance ratio is 0.319.
[3]Prior elasticity of substitution between home and imported intermediates is normally distributed at mean of 0.9 with standard deviation of 0.01. The average acceptance ratio is 0.235.
[4]Exports of intermediates and final goods are priced in producer currency. Export price inflation dynamics for intermediate and final goods are thus identical to those for home market. The average acceptance ratio is 0.303.
[5]Prior risk aversion coefficient is assumed to be uniform distributed at 1.5 with the range [1,2]. The average acceptance ratio is 0.24.
[6]Prior mean of policy reaction toward inflation fluctuation is raised to 3.5, gamma distributed with standard deviation of 0.1. The average acceptance ratio is 0.381.
[7]The parameter for habit persistence is set to zero, and is thus not estimated. The acceptance ratio is 0.381.

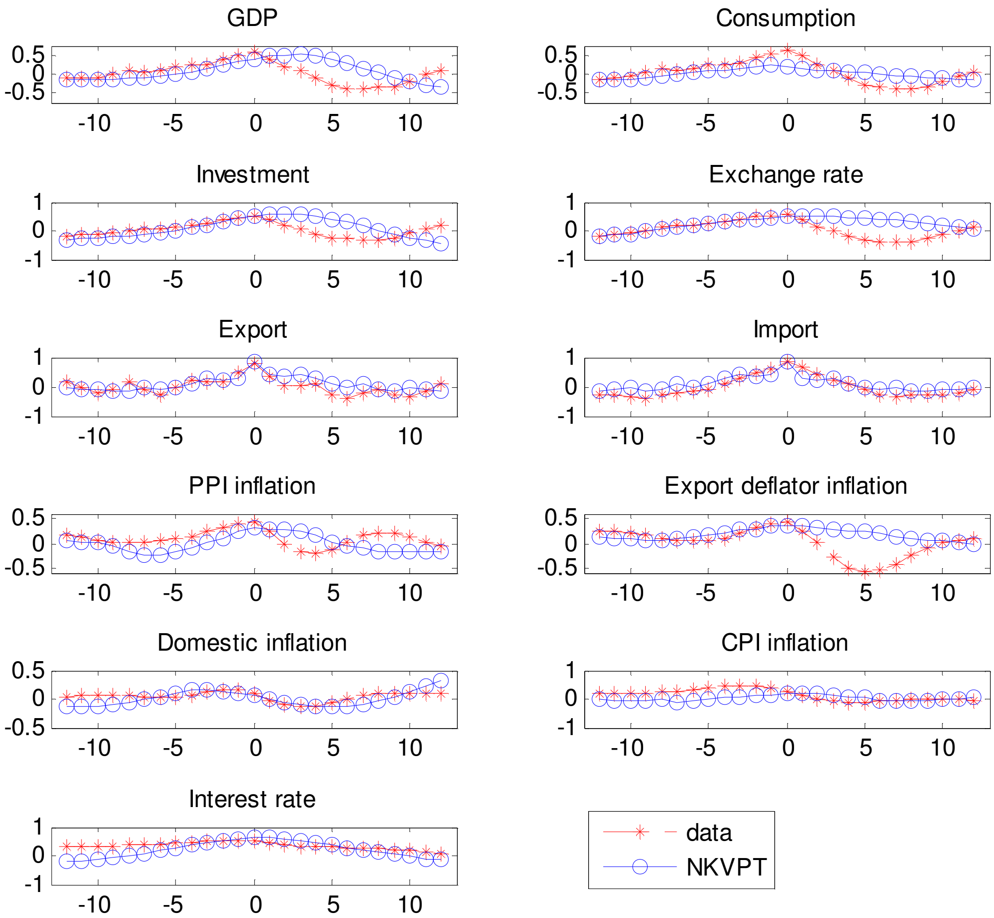


**Fig. 1** Cross correlations

Notes: *y*-axis is labeled as the number of quarters, and *x*-axis measures the extent of cross-correlation

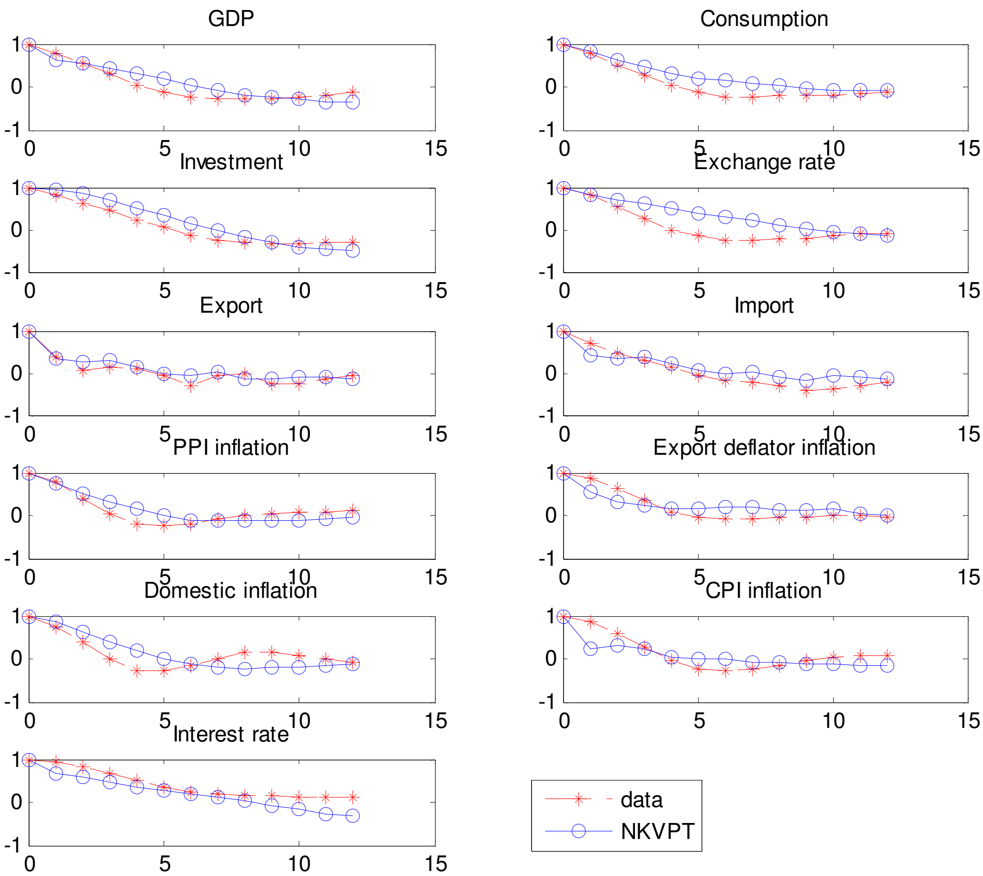


**Fig. 2** Autocorrelations

Notes: *y*-axis is labeled as the number of quarters, and *x*-axis measures the extent of autocorrelation

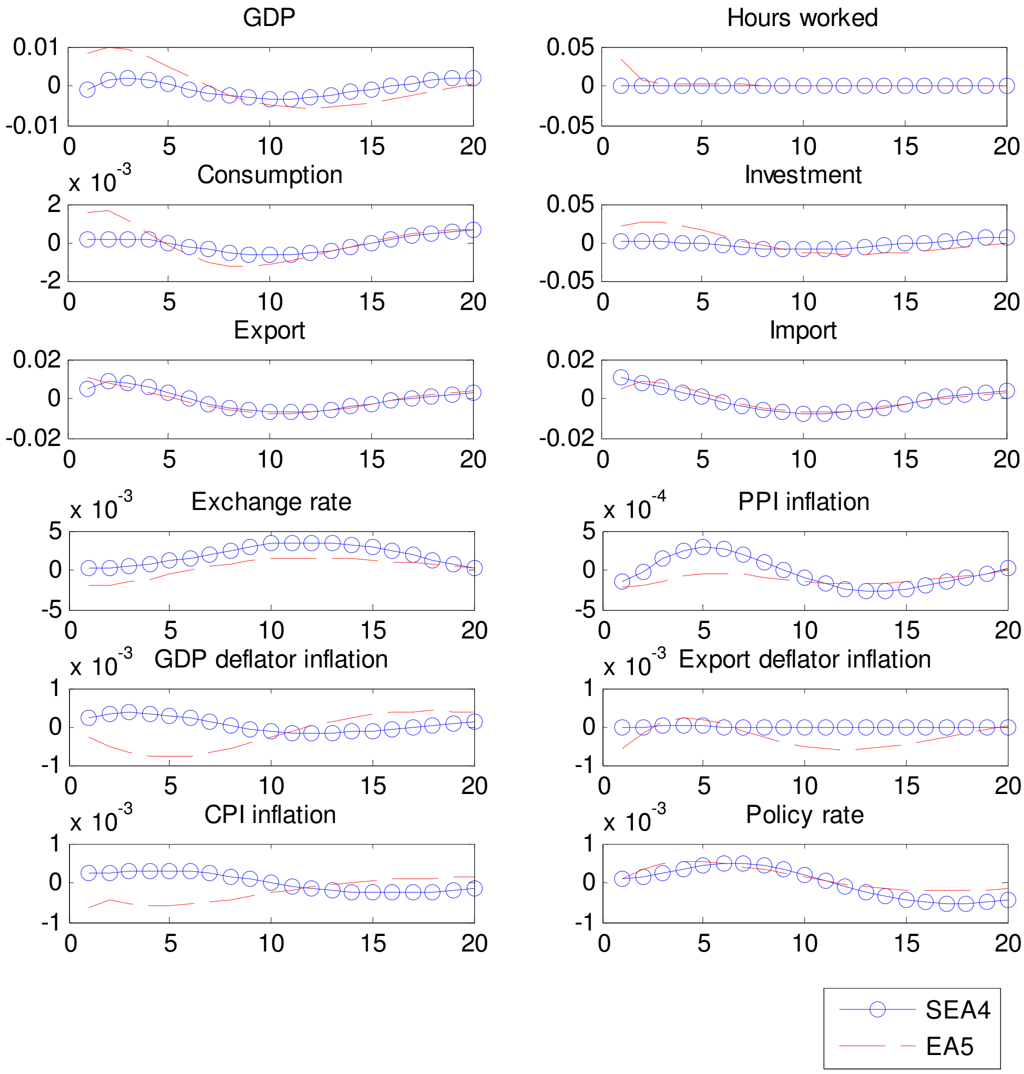


**Fig. 3** Dynamic responses to EA5 total factor productivity shock

Notes: *y*-axis is labeled as log-deviation in basic points, and x-axis is labeled as quarters.