Technology diffusion and international business cycles

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Abstract

This paper shows that the cross-country diffusion of innovations forms a critical channel through which macroeconomic shocks are transmitted across economies. This inference is obtained from a two country, medium scale DSGE model that includes an endogenous growth mechanism. R&D activity and innovation are the main components of this mechanism and they are introduced through a labor-augmenting technology. The model features international diffusion of technologies as the innovations by a firm are not only adopted by other firms within a country but also by those in the other country. Estimating the model with US and Euro Area data, I observe that foreign shocks contribute a high share to the macroeconomic volatility in each economy. By contrast, foreign shocks make a negligible contribution when the model is estimated after shutting down technology diffusion. The results, more generally, show that it is not technology shocks, nor any other shock, but the transmission of shocks through the diffusion of new technologies that is the key driver of international business cycles.

Keywords: Research and development, international business cycles, endogenous growth, DSGE, Bayesian estimation.

JEL Classification: F42, F44, O30, O33.

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1 Introduction

In the past three decades, most countries in the world have experienced a head-spinning pace of technological change and adoption across every industry and platform. Despite its apparent benefits, this development has also brought forth macroeconomic challenges. The most prominent of these being the adverse effects on income inequality due to the widening wedge between the earnings of high-skill and low-skill workers. In this paper, I consider a relatively unclear consequence of the world-wide trend by investigating how it has changed the macroeconomic linkages across economies. In particular, I determine how the technology creation process affects the transmission of shocks, that are not necessarily related to technology, from one country to the other. This exercise is important since determining whether economies have become more interconnected or more independent would have critical implications for formulation and the international coordination of policies.

One reason why the relationship between technological change and international business cycles is relatively obscure is that the standard tools that are used to study the two topics in economics are fundamentally different. While technology is a subject that is commonly studied in the growth literature within endogenous growth frameworks, the cross-country drivers of business cycles are usually identified by multiple-country, dynamic new Keynesian setups in the international macroeconomics literature. In this paper, I combine the two methods by incorporating an endogenous growth mechanism into an otherwise standard two country, dynamic stochastic general equilibrium (DSGE) model. In my discussion of the related literature below, I point out why this approach makes a unique contribution.

The endogenous growth mechanism is introduced in the model via a labor augmenting efficiency term in intermediate good producers' production function. This term depends on the amount of R&D (research and development) activity conducted by high-skill workers. Specifically, R&D activity adds to the knowledge stock in the economy and increases the efficiency of low-skill production workers if it successfully produces a new technology. The amount of R&D activity and the efficiency term also determine the growth of the economies along the balanced growth path under a symmetric equilibrium. In addition to conducting internal R&D, firms also adopt the innovations of other firms within their country and those originating in the other country. This cross country diffusion of technology and the technology process in general play a central role for the analysis in this paper. They not only allow country specific technology shocks, modelled as an exogenous change in the success rate of R&D activity, to be transmitted across countries but they also form a channel through which any country specific shock can affect the other country. My findings demonstrate that the latter role is more important.

Modelling both economies symmetrically, linearizing model equations around a steady state and reasonably calibrating the model to US data, I first find that R&D activity is procyclical. The higher demand for production labor during expansions, for example, increase the marginal benefit to R&D activity (with the elasticity of substitution between the two types of labor fixed to a reasonable value). The positive response of R&D is more muted since its marginal product is much higher in the model compared to that of production labor. This disparity between the two labor services generates a countercyclical income inequality (both at home and in the other country). The relative income of high-skill workers decrease and increase during economic upswings and downswings, respectively.

The more central result is that the improvements in efficiency, the by-product of higher R&D activity, spillover to the other country and induce a symmetry across the two economies. The strength of cross-country transmission, however, varies by type of shock as the model also features linkages through trade and bond holdings. Domestic price, wage and monetary policy shocks originating in one country, for example, generate a weaker output response in the other country since their effects through technology and trade are partially offset by their effects on inflation and the policy rate. The technology diffusion process, nevertheless, plays a crucial role for linking the two economies in the model as foreign responsiveness to domestic shocks decrease substantially when the process is shut-down. The correlation of output between the two economies in the simulated model is 0.72 (not too different from the correlation coefficient of 0.86 in the data). This value drops to 0.43 without technology creation and diffusion. This effect of technology is comparable, if not larger, than that of trade as the correlation coefficient drops to 0.52 under minimal bilateral trade (one-tenth the trade volume under the baseline calibration). Further demonstrating the strength of the technology diffusion mechanism, the model without technology diffusion requires an exogenously determined cross-country correlation coefficient of 0.3 between every pair of shocks in the model (10 pairs in total) to replicate the degree of output correlation in the model with technology.

The transmission mechanism depends on various other model characteristics. Sensitivity analyses reveal a stronger transmission of shocks from one economy to the other under higher R&D and wage adjustment costs, higher market power of intermediate good producers, low consumer habit persistence and asymmetric monetary policy formulation. Given the heterogeneity in the responses to different shocks and parameterizations of the model, I proceed by estimating the shock process and structural parameters to more accurately quantify the degree of transmission across countries. I do so by using a Bayesian methodology and quarterly data from the Euro Area (19 economies excluding Croatia) and the US, spanning 1998Q1 to 2019Q4.[1] The data set includes 21 variables that represent the demand, supply and the financial parts of the model and allow me to identify the 20 region-specific shocks and a common currency depreciation shock. The reason I use the two regions is that their economies are roughly similar in size and more importantly harmonized data are available for the Euro Area which allows me to circumvent aggregation issues.

To identify the significance of technology diffusion, I extend the model by assuming that each shock has a component that is common across the two regions and that exogenously generate macroeconomic symmetry. Estimating the model with and without technology and comparing the results, I then determine whether common shocks replace technology diffusion and play a more important role for the comovement of macroeconomic variables when technology is shut-down. To the contrary, I find that common shocks are more important drivers of macroeconomic volatility in the model with technology diffusion, implying that the technology diffusion mechanism reinforces the exogenous symmetry generated by a common shock specification.

[1]I exclude the period after 2019 to avoid the confounding effects of the nonlinearities governing the global pandemic.

The post-estimation inferences are based on two main statistics, historical variance decompositions and forecast error variance decompositions, that reflect the contribution of shock to the volatility of macroeconomic variables. These statistics, as well as, post-estimation impulse responses, more clearly show that the model without technology fails to replicate the degree of co-movement of Euro Area and US variables and that the responsiveness of macroeconomic variables in one country to the shocks originating in the other are relatively negligible. By contrast, foreign, domestic and common shocks make a roughly similar contribution to the economic volatility of each region in the model with technology diffusion. Further analysis reveals that technology diffusion operates more strongly in the direction from the US to the Euro Area as Euro Area shocks have a smaller impact on US efficiency growth and macroeconomic volatility than the other way around. More generally, however, the higher rate of technology adoption by the Euro Area opens a wider channel for US shocks, including but not limited to technology shocks, to transmit abroad through their effects on technology creation.

Following common practice, I impose symmetry across agents to solve the DSGE model. I should acknowledge however that this methodology does not allow me to include some realistic aspects of technology creation. In particular, the model does not include strategic behavior that can potentially change the inferences of the model especially given that one economy is relatively a technology creator and the other an adopter according to my estimation results. Incorporating firm heterogeneity into a two country open economy model with an endogenous growth mechanism is far from straightforward and confounds the analysis. I instead present a simple framework in the last part of the paper and postulate that strategic behavior could weaken the degree of technology creation and diffusion in my model. Specifically, the technology creating country could conduct less R&D when its innovations are more rapidly/cheaply diffuse to the adopting country. Nevertheless, the rapidly increasing technology diffusion in the world suggest that this mitigating effect of strategic behavior may not be large enough to change the inferences of my paper.

After Backus et al. (1992) documented the mismatch between the low cross-country output correlation in open economy models and the much higher positive correlation in the data, international macroeconomics literature incorporated frictions into standard open economy models to resolve the mismatch. These frictions, most notably, have been related to trade (Backus, et al.,1992; Zimmermann, 1997; Obstfeld and Rogoff, 2001; Ravn and Mazzenga, 2004) and financial markets (Kollmann, 1996; Heathcote and Perri, 2002; Kehoe and Perri, 2002; Davis, 2010; Devereux and Yetman, 2010; Kollmann, 2011; Alpanda and Aysun, 2014) and were mainly used to decrease the degree of risk sharing across countries. In my paper, I also demonstrate a standard two country model's inability to match the correlation of output growth across economies. The mechanism that enhances the degree of output correlation in my model, however, is not frictions. While the model has real and nominal frictions, these do not apply to trade and international finance. An endogenous technology creation process and its international diffusion instead plays the main role for linking the two economies. This endogenous mechanism makes a distinct contribution to the long-standing and well-documented literature on the role of productivity shocks for international business cycles. Specifically, studies such as Elliott and Fatás (1996), Stockman and Tesar (1995) and Kose and Yi (2001) show that a positive correlation between countries' total factor productivity (TFP) shocks significantly improves its ability to match the propagation of international business cycles. This literature, however, is silent on what the source of correlation could be. In this paper, I offer one method to generate the positive correlation and quantify its effects on international business cycles.

Also a common finding in the literature on the estimation of two country DSGE models, unlike the inferences from calibrated models mentioned above, is that technology shocks originating in one region play a relatively small role for the output volatility in the other region (e.g., Alpanda and Aysun, 2014; Aysun, 2016; Aysun, 2022). The results in this paper show that its not shocks to technology but the channel that technology forms between countries, allowing for every type of shock to transmit more strongly, is what drives the comovement of economies. Estimation results also reveal, consistent with the literature (e.g. Schmitt-Grohe, 1998; Ambler et al., 2002; Canova and de Nicolo, 2003; Kose et al., 2008; Crucini et al., 2011; Rey, 2013; Miranda-Agrippino and Rey, 2020), that common/global shocks' contribution to economic volatility has been increasing in the post-Bretton Woods era.

Following the productivity slow down after the Great Recession, there has been efforts to combine long-term growth mechanisms with short-run dynamics. These studies have mostly investigated the impact of business cycles on productivity and long-term growth in closed economy frameworks (e.g., Broda and Weinstein, 2010; Christiano et al., 2015; Fernald, 2015; Kung and Schmid, 2015; Queraltó, 2019; Bilbiie et al., 2012, 2019; Anzoategui et al., 2019; Bianchi et al., 2019; Aysun, 2020). In my paper, I approach the issue from the opposite direction and determine how productivity driven by R&D activity affects business cycles. Furthermore, the central focus in my paper is on the international, and not domestic, effects of technology creation and diffusion. It should however be noted that I model R&D as a contributing factor to the knowledge stock in an economy so that the firms consider not only current period contribution of R&D activity to production but also its discounted future contributions. This is an important aspect of my analysis that ties in with the literature mentioned above as it introduces persistence in the responses to macroeconomic shocks that is useful when describing the long-run growth effects of short-run economic fluctuations.

Microeconomic analyses of R&D activity demonstrate that R&D is conducted mostly by large firms (see, Foster and Grim, 2010; Foster et al., 2016), diffusion rate of innovations has been increasing (e.g. Chesbrough, 2003; Azoulay, 2004; Cassiman and Veugulers, 2006; Higón, 2016; Knott, 2017) mostly through R&D outsourcing (i.e., open innovation) and that R&D spending is relatively smooth along the business cycle (Brown et al., 2012; Hall et al., 2016; Aysun and Kabukcuoglu, 2019). The construction of my model is informed by these observations. In my model, R&D activity is conducted by intermediate good producers with market power, innovations of firms diffuse not only domestically but also across-countries, and R&D's high marginal product and its effects on future productivity generate a relatively smoother R&D activity in my model.

2 R&D and international linkages

In this section, I describe the technology process that forms a link between the two economies as well as the more conventional linkages through trade and financial markets. For brevity, I mostly describe the domestic economy as the foreign economy is modelled symmetrically.

2.1 R&D and the innovation process

R&D activity in the model is conducted by intermediate goods producers that are monopolistically competitive. The production of firm j is described by the following neoclassical function:

$$Y_{j,t} = \varepsilon_t^a \left(Z_{j,t} K_{j,t}\right)^{\alpha} M_{j,t}^{1-\alpha} \tag{1}$$

The firm rents capital, $K_{j,t}$, from households and combines it with labor input, $M_{j,t}$, to produce $Y_{j,t}$ units of an intermediate good that is then sold to final good producers. Here ε_t^a is a TFP shock that follows an AR(1) process, $Z_{j,t}$ is the utilization rate of capital and α is the labor share of capital income. I assume that the production function includes a labor augmenting technology. Specifically, the labor input is the product of an efficiency term, $\mu_{j,t}$, and production labor, $L_{j,t}^p$, so that

$$M_{j,t} = \mu_{j,t} L_{j,t}^p. \tag{2}$$

The efficiency term $\mu_{j,t}$ is the focal point of my paper as it describes the technological linkage across the two economies. This variable is the output of the innovation process. Each period, the intermediate good producer allocates $L_{j,t}^{rd}$ units of its labor force to R&D activities and $L_{j,t}^p$ units to the production process. If successful, R&D activities augment the firms' stock of knowledge, $S_{j,t}$, that in turn evolves according to the following expression:

$$S_{j,t} = S_{j,t-1} + \nu_t L_{j,t}^{rd} \tag{3}$$

where ν_t is an exogenous hazard rate variable that determines the probability that R&D activity successfully yields an innovation. This variable is also interpreted as the stepping on toes effects of technology creation in the literature and it is treated as a shock with a mean value of ν.

The efficiency of labor is related to the stock of knowledge as follows:

$$\mu_{j,t} = \left[\left(e^{S_{j,t}} \right)^{\eta} \left(e^{S_t} \right)^{1-\eta} \right]^{\eta_d} \left(e^{S_t^*} \right)^{1-\eta_d} \tag{4}$$

where e represents Euler's number. I assume that firm j's labor efficiency is a function of three factors: internal innovations, $e^{S_{j,t}}$, and innovations adopted from other domestic and foreign firms, e^{S_t} and $e^{S_t^*}$, respectively. The parameter η regulates the share of innovation due to company specific and external R&D within the domestic economy, and η_d regulates the source of efficiency by country. The corresponding expression for the foreign economy is given,

$$\mu_{j,t}^* = \left[\left(e^{S_{j,t}^*} \right)^{\eta^*} \left(e^{S_t^*} \right)^{1-\eta^*} \right]^{\eta_d^*} \left(e^{S_t} \right)^{1-\eta_d^*} \tag{5}$$

The country-specific stocks of knowledge, S_t and S_t^*, above are the following aggregates:

$$S_t = \int_0^1 S_{k,t} dk \quad for \;\; k \neq j \tag{6}$$

$$S_t^* = \int_0^1 S_{l,t}^* dl \quad for \;\; l \neq j \tag{7}$$

Notice here that e^{S_t} and $e^{S_t^*}$ for firm j represent the positive externalities common to technology creation with the latter forming a conduit through which shocks in one country can be transmitted to the other. The mass of domestic and foreign intermediate good producers in the expressions above are set equal to 1 without loss of generality so that under symmetry across firms within a country, $\mu_t = \left(e^{S_t} \right)^{\eta_d} \left(e^{S_t^*} \right)^{1-\eta_d}$ and $\mu_t^* = \left(e^{S_t^*} \right)^{\eta_d^*} \left(e^{S_t} \right)^{1-\eta_d^*}$.

It is important to note here that the growth rates of these efficiency terms determine the growth rates of the economies along the balanced growth path. These growth rates are given by,

$$\gamma_t = \frac{\mu_t}{\mu_{t-1}} = \left(e^{\nu_t L_t^{rd}}\right)^{\eta_d} \left(e^{\nu_t^* L_t^{*,rd}}\right)^{1-\eta_d} \tag{8}$$

$$\gamma_t^* = \frac{\mu_t^*}{\mu_{t-1}^*} = \left(e^{\nu_t^* L_t^{*,rd}}\right)^{\eta_d^*} \left(e^{\nu_t L_t^{rd}}\right)^{1-\eta_d^*} \tag{9}$$

where the growth rate of an economy is determined by not only the amount of innovation originating in that economy but also those adopted from abroad. Also notice here that the source of growth in each economy includes both exogenous factors, ν_t and ν_t^*, and endogenous factors, L_t^{rd} and $L_t^{*,rd}$.

Before solving the model, all growing variables such as output, consumption and investment will be de-trended with the efficiency terms μ_t and μ_t^* to ensure stationarity.

2.2 Conventional linkages

In addition to the technology diffusion process described above, the two economies are interconnected through trade and bond holdings as in the standard two country model setup. The trade linkage is introduced through the following consumption and investment aggregates:

$$C_t = \left[(\theta_c)^{\frac{1}{\lambda_c}} \left(C_t^h\right)^{\frac{\lambda_c - 1}{\lambda_c}} + (1-\theta_c)^{\frac{1}{\lambda_c}} \left(C_t^f\right)^{\frac{\lambda_c - 1}{\lambda_c}} \right]^{\frac{\lambda_c}{\lambda_c - 1}} \tag{10}$$

$$I_t = \left[(\theta_i)^{\frac{1}{\lambda_i}} \left(I_t^h\right)^{\frac{\lambda_i - 1}{\lambda_i}} + (1-\theta_i)^{\frac{1}{\lambda_i}} \left(I_t^f\right)^{\frac{\lambda_i - 1}{\lambda_i}} \right]^{\frac{\lambda_i}{\lambda_i - 1}} \tag{11}$$

where consumption and investment goods in the domestic economy, C_t and I_t, are constant elasticity of substitution (CES) aggregates of home (C_t^h and I_t^h) and foreign goods (C_t^f and I_t^f). The lower values of the share parameters, θ_c and θ_i, and the elasticity parameters, λ_c and λ_i, enhance the potential transmission between the countries as they imply higher shares of imports in the consumption and investment baskets and a lower degree of substitutability between foreign and home goods.

The aggregate price indices that correspond to the consumption and investment functions above are given by,

$$P_t = \left[\theta_c \left(P_t^h \right)^{1-\lambda_c} + (1-\theta_c) \left(P_t^f \right)^{1-\lambda_c} \right]^{\frac{1}{1-\lambda_c}} \tag{12}$$

$$P_t^i = \left[\theta_i \left(P_t^{i,h} \right)^{1-\lambda_i} + (1-\theta_i) \left(P_t^{i,f} \right)^{1-\lambda_i} \right]^{\frac{1}{1-\lambda_i}} \tag{13}$$

and they provide an additional channel through which shocks can propagate between countries. Here, P_t^h and P_t^f denote the prices of the home and foreign consumption goods, and $P_t^{i,h}$ and $P_t^{i,f}$ denote the prices of the home and foreign investment goods.

The consumers in each economy hold both domestic and foreign government bonds. The discount rates on these bonds, R_t and R_t^*, are also the monetary policy rates in the economies and they are linked through an uncovered interest parity (UIP) condition given by,

$$E_t \left[\beta \frac{\lambda_{t+1}}{\lambda_t \pi_{t+1}} \left(R_t - \varepsilon_t^d \frac{ER_{t+1}}{ER_t} R_t^* \right) \right] = 0 \tag{14}$$

where E is the expectations operator, β is the time discount factor and λ_t and π_{t+1} are the Lagrange multiplier on the consumers' budget constraint and the inflation rate in period $t+1$, respectively. The exchange rate, ER_t, is expressed as local currency per unit of foreign currency and ε_t^d is a default risk (depreciation) shock that follows an AR(1) process. This expression allows for monetary policy and depreciation shocks to propagate between the two economies through financial markets.

When obtaining inferences from the model, I will compare the strength of the cross-country transmission of shocks that operate through technology and the other channels.

3 Rest of the model

In this section, I describe the optimization problems of households, final goods, intermediate goods, and capital producers, and importers. I specify monetary and fiscal policy. I explain market clearance. In so doing, I similarly confine the discussion to the domestic economy as the foreign economy is identical.

3.1 Households

The economy is populated by a unit measure of infinitely-lived households who maximize the following utility function:

$$U_{i,t} = E_0 \sum_{t=0}^{\infty} \beta^t \frac{\varepsilon_t^c}{1-\sigma} \left[\{C_{i,t} - \zeta C_{t-1}\} \exp\left(-\xi \frac{L_{i,t}^{1+\sigma_l}}{1+\sigma_l} \right) \right]^{1-\sigma} \tag{15}$$

where i indexes the households, and $C_{i,t}$ and $L_{i,t}$ denote the amount of final goods consumption and labor supply for household i. The parameter ζ determines the importance of external habit formation in the utility function, and σ_l and σ regulate the inverse elasticity of labor supply and the intertemporal elasticity of substitution, respectively. The parameter ξ is calibrated to fix the steady state amount of labor supply to 1 without loss of generality, and β is the time discount factor. The variable ε_t^c is a preference shock that follows an AR(1) process. Positive values of this variable represent a greater preference for today's consumption over next period's consumption. All shocks introduced hereafter also follow an AR(1) process.

I assume that households have two types of members. Those possessing high skills supply $L_{i,t}^{rd}$ units of labor and those possessing low skills supply $L_{i,t}^{p}$ units of labor. Households' total supply of labor is the following CES (constant elasticity of substitution) aggregate of the two services:

$$L_{i,t} = \left(\theta_l^{\frac{1}{\lambda_l}} \left(L_{i,t}^{rd} \right)^{\frac{\lambda_l - 1}{\lambda_l}} + (1-\theta_l)^{\frac{1}{\lambda_l}} \left(L_{i,t}^{p} \right)^{\frac{\lambda_l - 1}{\lambda_l}} \right)^{\frac{\lambda_l}{\lambda_l - 1}} \tag{16}$$

where θ_l and λ_l represent the share of R&D labor and the elasticity of substitution between the two labor types. I assume that the households labor services are heterogenous within each skill category and they are hired by perfectly competitive labor intermediaries. These firms combine labor services as follows:

$$L_t^p = \left[\int_0^1 \left(L_{i,t}^p\right)^{\frac{\varphi_t^p}{\varphi_t^p - 1}} di\right]^{\frac{\varphi_t^p - 1}{\varphi_t^p}} \tag{17}$$

$$L_t^{rd} = \left[\int_0^1 \left(L_{i,t}^{rd}\right)^{\frac{\varphi_t^{rd}}{\varphi_t^{rd} - 1}} di\right]^{\frac{\varphi_t^{rd} - 1}{\varphi_t^{rd}}} \tag{18}$$

where the variables φ_t^p and φ_t^{rd} represent time-varying elasticities of substitution between the different labor services within each category and they are related to wage mark-up rates, $\varepsilon_t^{w,p}$ and $\varepsilon_t^{w,rd}$ as follows: $\varepsilon_t^{w,p} = \frac{\varphi_t^p}{\varphi_t^p - 1}$ and $\varepsilon_t^{w,rd} = \frac{\varphi_t^{rd}}{\varphi_t^{rd} - 1}$. The two variables represent wage mark-up shocks in the model and I assume that they are symmetric across the two types of labor. After aggregation, the intermediaries sell labor services to intermediate good producers at the wage rates W_t^p and W_t^{rd}. Labor intermediaries' profits are given by $W_t^p L_t^p - \int_0^1 W_{i,t}^p L_{i,t}^p di$ and $W_t^{rd} L_t^{rd} - \int_0^1 W_{i,t}^{rd} L_{i,t}^{rd} di$. Using the equations above and maximizing profits with respect to $L_{i,t}^p$ and $L_{i,t}^{rd}$ yields the following labor demand functions:

$$L_{i,t}^p = \left[\frac{W_{i,t}^p}{W_t^p}\right]^{-\varphi_t^p} L_t^p \tag{19}$$

$$L_{i,t}^{rd} = \left[\frac{W_{i,t}^{rd}}{W_t^{rd}}\right]^{-\varphi_t^{rd}} L_t^{rd} \tag{20}$$

The budget constraint that household i faces when maximizing her life-time utility is given by,

$$\begin{aligned} C_{i,t} + \frac{B_{i,t}^h}{R_t P_t} + ER_t \frac{B_{i,t}^f}{\varepsilon_t^d R_t^* P_t} + Q_t K_{i,t+1} + \frac{T_{i,t}}{P_t} + \sum_{z=lp,rd} \frac{\kappa_w^z}{2} \left(\frac{W_{i,t}^z / W_{i,t-1}^z}{\gamma \pi_{t-1}^{\iota_w} \pi^{1-\iota_w}}\right) \frac{W_t^z}{P_t} L_t^z \\ \leq \frac{W_{i,t}^p}{P_t} L_{i,t}^p + \frac{W_{i,t}^{rd}}{P_t} L_{i,t}^{rd} + \frac{B_{i,t-1}^h}{P_t} + ER_t \frac{B_{i,t-1}^f}{P_t} + \frac{R_t^k Q_{t-1} K_{i,t}}{\varepsilon_{t-1}^k} + \Pi_{i,t}^h + \Pi_{i,t}^m \end{aligned} \tag{21}$$

Households are the owners of capital in the domestic economy. They buy capital, K_{t+1}, at the price of Q_t from capital producers and lend these units to intermediate goods producers. These loans yield the rate of return R_t^k. Returns to capital are subject to a default risk shock, ε_t^k. Positive values of this shock represent an exogenous increase in credit spreads[2]. Households are also the owners

[2]This shock is commonly interpreted as the change in the volatility of idiosyncratic returns to capital shock that

of domestic intermediate good producing and importing firms from which they receive profits Π_t^h and Π_t^m, respectively. As explained above they hold domestic bonds, B_t^h, and foreign bonds, B_t^f. These bonds pay the interest rates R_t and R_t^*, respectively. The model features wage-stickiness that is introduced via the quadratic wage adjustment cost formulation in Rotemberg (1982) for each type of labor service.[3] In this formulation, given by the last two terms on the left hand side of the budget constraint, P_t is the aggregate price level, π_t is the inflation rate given by P_t/P_{t-1}, and γ is the steady state growth rate of the economy. In addition to wage adjustment costs, the households also pay lump-sum taxes, T_t, to the government.

3.2 Producers and importers

Final consumption goods, Y_t, are produced by a representative perfectly competitive firm that combines intermediate goods according to the following CES function:

$$Y_t = \left(\sum_{j=1}^{N} Y_{j,t}^{\frac{\varphi_t}{\varphi_t - 1}} \right)^{\frac{\varphi_t - 1}{\varphi_t}} \tag{22}$$

where φ_t is the elasticity of substitution between intermediate goods that determines price mark-up and N is the number of these goods. Prices are subject to a mark-up shock, $\varepsilon_t^p = \frac{\varphi_t}{\varphi_t - 1}$, that follows an AR(1) process. The final good producer's profit maximization problem yields the following demand function for intermediate good j:

$$Y_{j,t} = Y_t \left(\frac{P_{j,t}}{P_t^h} \right)^{-\varphi_t} \tag{23}$$

where $P_{j,t}$ is the price of the intermediate good j. Intermediate good producers play the central role in technology creation as described in the previous section. The life-time profit maximization

capital owners face in the literature.

[3] I assume that wage adjustment costs are symmetric across the two types of labor so that $\kappa_w^p = \kappa_w^{rd} = \kappa_w$. The parameter κ_w is set equal to $\frac{6\xi_w(1+\iota_w\beta)}{(1-\xi_w)(1-\xi_w\beta)(\varphi-1)}$ following standard practice (e.g., Smets and Wouters, 2007) with ξ_w denoting the probability that wages do not change and ι_w and φ representing the wage indexation parameter and the mean value of the elasticity of substitution between the different labor services, respectively. I assume that the latter is also the same for R&D and production labor.

problem of the intermediate good producer j is given by:

$$\max_{K_{j,t},L^{p}_{j,t},S_{j,t},Z_{j,t},P_{j,t}} E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \frac{\Pi_{j,t}}{P_t} \tag{24}$$

$$\begin{aligned}
s.t.\ \frac{\Pi_{j,t}}{P_t} = & \frac{P_{j,t}}{P_t} Y_{j,t} - \frac{W^{rd}_t}{P_t} L^{rd}_{j,t} - \frac{W^p_t}{P_t} L^p_{j,t} - R^k_t Q_{t-1} K_{j,t} - \frac{\kappa_z}{1+\varpi}\left[Z^{1+\varpi}_{j,t} - 1\right] K_{j,t} \\
& - \frac{\kappa_p}{2}\left(\frac{P_{j,t}/P_{j,t-1}}{\left(\pi^h_{t-1}\right)^{\iota_p}\pi^{1-\iota_p}} - 1\right)^2 \frac{P^h_t}{P_t} Y_t - \frac{\kappa_{rd}}{2}\left(\frac{L^{rd}_{j,t}}{L^{rd}_{j,t-1}} - 1\right)^2 \frac{W_t}{P_t} L^{rd}_t \\
s.t.\ \ & Y_{j,t} = \varepsilon^a_t \left(Z_{j,t} K_{j,t}\right)^{\alpha} M^{1-\alpha}_{j,t} \\
s.t.\ \ & M_{jt} = \mu_{j,t} L^p_{j,t} \\
s.t.\ \ & \mu_{j,t} = \left[\left(e^{S_{j,t}}\right)^{\eta}\left(e^{S_t}\right)^{1-\eta}\right]^{\eta_d}\left(e^{S^*_t}\right)^{1-\eta_d} \\
s.t.\ \ & S_{j,t} = S_{j,t-1} + \nu_t L^{rd}_{j,t} \\
s.t.\ \ & Y_{j,t} = Y_t \left(\frac{P_{j,t}}{P_t}\right)^{-\varphi_t}
\end{aligned}$$

where $\lambda_t = \varepsilon^c_t \left(C_t - \zeta C_{t-1}\right)^{-\sigma} \exp\left(\frac{\sigma-1}{1+\sigma_l} \xi L^{1+\sigma_l}_t\right)$ is the Lagrange multiplier on the households' budget constraint and $\Pi_{j,t}$ denotes profits. In addition to labor and capital costs, the producer also incurs capital utilization costs and quadratic costs to adjusting prices and the level of R&D labor. The parameters κ_z, κ_p and κ_{rd} determine the level of these costs, respectively, ϖ represents the elasticity of utilization costs, and ι_p regulates the price indexation to past inflation.[4]

The remaining constraints have been described in previous sections. It is, however, important to point out some aspects of the firm's problem that relate to these contraints. As illustrated by the last restriction, the firm hires $L_{j,t}$ units of labor in each period and allocates these to production and R&D activities. In doing so, the firm compares the marginal products of the two forms of labor. This comparison favors R&D services for two reasons. While marginal returns to production labor exhibit the usual diminishing returns, R&D services do not. In addition, R&D services augment

[4]The level parameter κ_p is set equal to $\frac{3.5\xi_p\left(1+\iota_p\beta\right)}{\left(1-\xi_p\right)\left(1-\xi_p\beta\right)(\varphi-1)}$ where ξ_p represents the probability of keeping prices constant.

the production process not only today but also in future periods. Despite these advantages of R&D labor over production labor, firms' problem does not have a corner solution since R&D is meaningless without production labor according to the labor augmenting technology. The firms, therefore, have to strike a balance between the two types of labor services. R&D services, nevertheless, are less responsive to the changes in the demand for the firm's output given the higher marginal returns. Quadratic adjustment costs further insulate R&D labor from the changes in demand. As explained above, the implied smoothness of R&D labor matches the relatively low volatility of R&D spending, especially compared to fixed investment, over the business cycle. This feature of the model is consistent with the predictions and findings in studies such as Brown et al. (2012), Hall et al. (2016) and Aysun and Kabukcuoglu (2019).

The economy is also populated by perfectly competitive capital producers that use undepreciated capital and final investment goods, I_t, to produce new capital. These new capital units are then sold to consumers at the price of Q_t. The producers' problem of maximizing life-time profits subject to the evolution of capital is as follows:

$$\max\ E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[Q_t K_t - Q_{t-1} (1-\delta) K_{t-1} - I_t \right] \tag{25}$$
$$s.t. \qquad K_t = (1-\delta) K_{t-1} + \left[1 - \frac{\kappa_i}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] \varepsilon_t^i I_t.$$

where δ is the depreciation rate and κ_i determines the level of investment adjustment costs. ε_t^i is an investment shock that represents an exogenous change in the technology that converts investment goods into capital. The consumer's realized rate of return on their capital holdings is given by,

$$R_t^k = \frac{(1-\delta) Q_t + MPK_t}{Q_{t-1}} \tag{26}$$

where MPK_t denotes the marginal product of capital.

The importers are monopolistically competitive firms that buy imported goods at the price of $P_t^{h,*}$ ($ER_t P_t^{h,*}$ in local currency units), differentiate these goods and sell them at a mark-up to perfectly competitive aggregators in local currency. The aggregators then combine the heterogenous import goods to manufacture a homogenous import good. The importers, indexed by k, maximize their life-time profits by choosing prices, $P^f_{k,t}$, and the amount of imports, $Y^f_{k,t}$:

$$\max\ E_0 \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[\left(P^f_{k,t} - ER_t P^{h,*}_t\right) Y^f_{k,t} - \frac{\kappa_f}{2} \left(\frac{P^f_{k,t}/P^f_{k,t-1}}{\left(\pi^f_{t-1}\right)^{\iota_f} (\pi)^{1-\iota_f}} - 1 \right)^2 P^f_t Y^f_t \right] \tag{27}$$

In so doing, they face the following demand function for their goods:

$$Y^f_{k,t} = \left(\frac{P^f_{k,t}}{P^f_t} \right)^{-\varphi^f_t} Y^f_t \tag{28}$$

where φ^f_t is the time-varying elasticity of substitution between the heterogenous import goods. This variable is related to import price mark-up rates as follows: $\varepsilon^f_t = \frac{\varphi^f_t}{\varphi^f_t - 1}$ and they are similarly subject to a shock. The importers face quadratic price adjustment costs which, in addition to introducing prices rigidities, allows for imperfect exchange rate pass-through. The parameters κ_f and ι_f regulate the level of these adjustment costs and the degree of price indexation, respectively, and Y^f_t and $\pi^f_t = P^f_t / P^f_{t-1}$ denote the aggregate amount of imports and import price inflation, respectively.[5] It should also be noted that the stochastic discount factors of all producers and importers are identical to that of households.

3.3 Monetary and fiscal policy, and market clearing

The central bank in each country formulates monetary policy by following a Taylor-rule. This rule for the domestic central bank is given by,

$$R_t = \rho R_{t-1} + (1-\rho) \left(\log R + \gamma_\pi \log \frac{\pi_t}{\pi} + \gamma_y \log Y_t \right) + \varepsilon^r_t \tag{29}$$

[5] The parameter κ_f is rescaled similar to the price adjustment cost parameter by following the Kimball aggregator formulation: $\kappa_f = \left(1-\xi_f\right)\left(1-\xi_f \beta\right)/3.5\xi_f$ with ξ_f representing the probability of keeping prices constant.

where ρ, γ_π and γ_y regulate the relative importance of interest rate smoothing, inflation and output in the Taylor-rule, and R is the steady state level of the policy rate. I assume that the policy rate is subject to a shock, ε_t^r.

Government spending, ε_t^g, is introduced in the model as a shock variable with a mean value of G. The government finances its expenditures with the lump-sum taxes it collects from households and by issuing discount bonds and selling them to domestic and foreign households,

$$P_t \varepsilon_t^g + B_{t-1}^h + B_{t-1}^{*,f} = T_t + \frac{B_t^h}{R_t} + \frac{B_t^{*,f}}{R_t} \tag{30}$$

where B_t^h and $B_t^{*,f}$ are the domestic and foreign households' holdings of domestic government bonds, respectively.

Treating capital utilization costs as transfers to households, the resource constraint of the economy can be described as follows:

$$C_t^h + I_t^h + \varepsilon_t^g + Y_t^{*,f} = Y_t \tag{31}$$

where domestic production equals consumption, investment, government spending and foreign export expenditure. Total amount of imports equals imports of consumption and investment goods so that

$$C_t^f + I_t^f = Y_t^f \tag{32}$$

4 Optimality conditions

Below, I first list the optimality conditions obtained from the maximization problem of intermediate goods producers that play the central role for the innovation process. In so doing, I consider a symmetric equilibrium and de-trend the growing variables. I do the same when describing the optimality conditions obtained from the problems of the other agents in the economy. The following conditions, and their log-linearized form under a symmetric equilibrium, describe the intermediate good producers' optimal decisions:

Capital:

$$\Omega_t \alpha \frac{Y_{j,t}}{K_{j,t}} = R_t^k + \frac{\kappa_z}{1+\varpi}\left(Z_{j,t}^{1+\varpi} - 1\right) \tag{33}$$

$$\widehat{\Omega}_t + \widehat{y}_t - \widehat{k}_t = \widehat{r}_t^k + \widehat{z}_t \tag{34}$$

where the lower case variables with hats represent deviations of from steady state or balanced growth path values and Ω_t is the Lagrange multiplier on the firms' production function.

Production labor:

$$(1-\alpha)\,\Omega_t \frac{P_{j,t}Y_{j,t}}{P_t L_{j,t}^p} = \frac{W_t^p}{P_t} \tag{35}$$

$$\widehat{\Omega}_t + \widehat{y}_t - \widehat{l}_t^p = \widehat{w}_t^p \tag{36}$$

where w_t^p denotes real wages given by W_t^p/P_t.

R&D labor:

$$\left[1 + \kappa_{rd}\left(\frac{L_{j,t}^{rd}}{L_{j,t-1}^{rd}} - 1\right)\frac{L_t^{rd}}{L_{j,t-1}^{rd}}\right]\frac{W_t^{rd}}{P_t} = \tag{37}$$

$$\psi_{j,t} + \kappa_{rd} E_t\left[\left(\beta\frac{\lambda_{t+1}}{\lambda_t}\right)\left(\frac{L_{j,t+1}^{rd}}{L_{j,t}^{rd}} - 1\right)\left(\frac{L_{j,t+1}^{rd}}{L_{j,t}^{rd}}\right) L_{t+1}^{rd}\frac{W_{t+1}^{rd}}{P_{t+1}}\right]$$

$$\widehat{w}_t^{rd} + \kappa_{rd}\left(\widehat{l}_t^{rd} - \widehat{l}_{t-1}^{rd}\right) = \psi_{j,t} + \kappa_{rd} E_t\left[\widehat{l}_{t+1}^{rd} - \widehat{l}_t^{rd}\right] \tag{38}$$

Knowledge stock:

$$\psi_{j,t} = E_t\left[\left(\beta\frac{\lambda_{t+1}}{\lambda_t}\right)\psi_{j,t+1}\gamma_{t+1}\right] + \Omega_t\,(1-\alpha)\,\eta\,\eta_d\,\nu_t\frac{Y_{j,t}P_{j,t}}{P_t} \tag{39}$$

$$\widehat{\psi}_t = \beta E_t\left[\widehat{\psi}_{t+1} + \widehat{\gamma}_{t+1} - (\widehat{r}_t - \widehat{\pi}_{t+1})\right] + (1-\beta)\left(\nu_t + \widehat{w}_t^p + \widehat{l}_t^p\right) \tag{40}$$

where $\psi_{j,t}$ is the Lagrange multiplier on the evolution of firm j's knowledge stock. This variable captures the marginal benefits of R&D labor and demonstrates that it not only increases production in the current period but also in the future through its effects on the stock of knowledge and future labor efficiency.

Capacity utilization:

$$\Omega_t \alpha \frac{Y_{j,t}}{Z_{j,t}} = \kappa_z Z_{j,t}^{\varpi} K_{j,t} \tag{41}$$

$$\widehat{z}_t = \frac{1}{\varpi} \widehat{r}_t^k \tag{42}$$

Prices:

$$\begin{aligned} &\left(\frac{\pi_{j,t}}{\left(\pi_{t-1}^h\right)^{\iota_p} \pi^{1-\iota_p}} - 1 \right) \frac{\pi_{j,t}}{\left(\pi_{t-1}^h\right)^{\iota_p} \pi^{1-\iota_p}} \\ &= E_t \left[\left(\beta \frac{\lambda_{t+1}}{\lambda_t} \right) \left(\frac{\pi_{j,t+1}}{\left(\pi_t^h\right)^{\iota_p} \pi^{1-\iota_p}} - 1 \right) \frac{\pi_{j,t+1}}{\left(\pi_t^h\right)^{\iota_p} \pi^{1-\iota_p}} \frac{Y_{t+1}}{Y_t} \right] - \frac{\varphi_t - 1}{\kappa_p} \left(1 - \Omega_t \varepsilon_t^p\right) \end{aligned} \tag{43}$$

$$\widehat{\pi}_t^h = \frac{\iota_p}{1+\beta\iota_p} \widehat{\pi}_{t-1}^h + \frac{\beta}{1+\beta\iota_p} E_t \left(\widehat{\pi}_{t+1}^h \right) + \frac{\varphi - 1}{(1+\beta\iota_p)\kappa_p} \left[\widehat{w}_t - \left(\widehat{y}_t - \widehat{l}_t^p \right) + \widehat{\varepsilon}_t^p \right] \tag{44}$$

A majority of the remaining optimality conditions are obtained from the maximization problem of the households.

Risk-free bond holdings:

$$1 = E_t \left[\left(\beta \frac{\lambda_{i,t+1}}{\lambda_{i,t}} \right) \frac{R_t}{\pi_{t+1}} \right], \tag{45}$$

$$\begin{aligned} \widehat{c}_t = &\frac{\zeta/\gamma}{1+\zeta/\gamma} (\widehat{c}_{t-1} - \widehat{\gamma}_t) + \frac{1}{1+\zeta/\gamma} E_t [\widehat{c}_{t+1} + \widehat{\gamma}_{t+1}] \\ &- \frac{1-\zeta/\gamma}{\sigma(1+\zeta/\gamma)} \left[(\sigma - 1)\xi \left(\widehat{l}_t - E_t \left\{ \widehat{l}_{t+1} \right\} \right) - (\widehat{r}_t - E_t \{\widehat{\pi}_{t+1}\}) \right] + \varepsilon_t^c \end{aligned} \tag{46}$$

The arbitrage between foreign and domestic bond holdings produce the interest rate arbitrage condition in equation (14) above.

Capital holdings:

$$1 = E_t \left[\left(\beta \frac{\lambda_{i,t+1}}{\lambda_{i,t}} \right) \frac{(1-\delta) Q_{t+1} + R_{t+1}^k}{Q_t} \right] \tag{47}$$

$$\widehat{q}_t = \frac{(1-\delta)\beta}{\gamma} E_t\left[\widehat{q}_{t+1}\right] + \left(1 - \frac{(1-\delta)\beta}{\gamma}\right) E_t\left[\widehat{r}^k_{t+1}\right] - \left(\widehat{r}_t - E_t\left\{\widehat{\pi}_{t+1}\right\}\right) \tag{48}$$

Equations (46) and (48) above represent the Euler condition and the expression for the returns to capital, respectively. Combining the first order conditions with respect to bond holdings and capital yields the following expression for credit spreads:

$$E_t\left[\beta \frac{\lambda_{i,t+1}}{\lambda_{i,t}} \left(\frac{E_t\left\{R^k_{t+1}\right\}}{\varepsilon_{k,t}} - \frac{R_t}{\pi_{t+1}}\right)\right] = 1 \tag{49}$$

$$E_t\left(\widehat{r}^k_{t+1}\right) = \widehat{r}_t - E_t\left(\widehat{\pi}_{t+1}\right) + \varepsilon^k_t \tag{50}$$

Labor supply and wages for each type of labor, index by $z = rd,\ p$:

$$\varepsilon^c_t \left[\left(C_{i,t} - \zeta C_{t-1}\right) \exp\left(\xi \frac{L^{1+\sigma_l}_{i,t}}{1+\sigma_l}\right)\right]^{1-\sigma} \xi L^{\sigma_l}_{i,t} \frac{\partial L_{i,t}}{\partial L^z_{i,t}} = \lambda_t \Omega^l_t \frac{W^z_t}{P_t} \tag{51}$$

$$\begin{gathered}\left(\frac{\pi^{w,z}_t}{\gamma \pi^{\iota_w}_{t-1} \pi^{1-\iota_w}} - 1\right) \frac{\pi^{w,z}_t}{\pi^{\iota_w}_{t-1} \pi^{1-\iota_w}} = \\ E_t\left[\beta \frac{\lambda_{t+1}}{\lambda_t} \left(\frac{\pi^{w,z}_{t+1}}{\gamma \pi^{\iota_w}_t \pi^{1-\iota_w}} - 1\right) \frac{\pi^{w,z}_{t+1}}{\gamma \pi^{\iota_w}_t \pi^{1-\iota_w}} \frac{\pi^{w,z}_{t+1}}{\pi_{t+1}} \frac{L^z_{t+1}}{L^z_t}\right] - \frac{\varphi^z_t - 1}{\kappa^z_w} \left(1 - \Omega^l_t \varepsilon^{w,z}_t\right)\end{gathered} \tag{52}$$

where Ω^l_t is the Lagrange multiplier on the labor demand function for households. These two equations can be combined and log-linearized to produce the following wage Phillips curve separately for each labor type indexed by z:

$$\begin{gathered}\widehat{\pi}^{w,z}_t - \iota_w \widehat{\pi}_{t-1} = \beta\left(E_t\left\{\widehat{\pi}^{w,z}_{t+1}\right\} - \iota_w \widehat{\pi}_t\right) \\ -\frac{\varphi^z - 1}{\kappa^z_w}\left[\widehat{w}^z_t - \left(\sigma_l \widehat{l}^z_t + \frac{\left(\widehat{l}_t - \widehat{l}^z_t\right)}{\lambda_l} + \frac{\left(\widehat{c}_t - \frac{\zeta}{\gamma}\left\{\widehat{c}_{t-1} - \gamma_t\right\}\right)}{1 - \zeta/\gamma}\right)\right] + \varepsilon^{w,z}_t\end{gathered} \tag{53}$$

where $\pi^{w,z}_t = W^z_t / W^z_{t-1}$ represents wage inflation. The linearized form of this inflation rate is related to real wages as follows: $\widehat{\pi}^{w,z}_t = \widehat{w}^z_t - \widehat{w}^z_{t-1} + \widehat{\pi}_t$.

Capital producer's problem (maximizing profits with respect to investment) yields an intertemporal condition for investment given by,

$$Q_{t-1}\varepsilon_t^i\left[1-\frac{\kappa_i}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2-\kappa_i\left(\frac{I_t}{I_{t-1}}-1\right)\frac{I_t}{I_{t-1}}\right] \\ +E_t\left[\left(\beta\frac{\lambda_{t+1}}{\lambda_t}\right)\kappa_i Q_t\varepsilon_{t+1}^i\left(\frac{I_{t+1}}{I_t}-1\right)\frac{I_{t+1}^2}{I_t^2}\right]-1=0 \tag{54}$$

$$\widehat{i}_t=\frac{1}{1+\beta}\widehat{i}_{t-1}+\frac{\beta}{1+\beta}E_t\left(\widehat{i}_{t+1}\right)+\frac{1}{(1+\beta)\,\kappa_i}\left(\widehat{q}_t-\widehat{\pi}_t^i+\varepsilon_t^i\right) \tag{55}$$

where $\widehat{\pi}_t^i$ is the deviation of investment good inflation (P_t^i/P_{t-1}^i) from its steady state value. The importer's first order condition with respect to prices is given by,

$$\left(\frac{\pi_t^f}{\left(\pi_{t-1}^f\right)^{\iota_f}\pi^{1-\iota_f}}-1\right)\frac{\pi_t^f}{\left(\pi_{t-1}^f\right)^{\iota_f}\pi^{1-\iota_f}}= \\ E_t\left[\beta\frac{\lambda_{t+1}}{\lambda_t}\left(\frac{\pi_{t+1}^f}{\left(\pi_t^f\right)^{\iota_f}\pi^{1-\iota_f}}-1\right)\frac{\pi_{t+1}^f}{\left(\pi_t^f\right)^{\iota_f}\pi^{1-\iota_f}}\frac{\pi_{t+1}^f}{\pi_{t+1}}\frac{Y_{t+1}^f}{Y_{t+1}}\right]+\left(\frac{\varphi_t^f-1}{\kappa_f}\right)\frac{E_tP_t^{*,h}}{\kappa_fP_t^f}\varepsilon_t^f \tag{56}$$

$$\widehat{\pi}_t^f-\frac{\iota_f}{1+\iota_f\beta}\widehat{\pi}_{t-1}^f=\frac{\beta}{1+\iota_f\beta}E_t\left(\widehat{\pi}_{t+1}^f\right)-\left(\frac{\varphi^f-1}{\kappa_f}\right)\left[\widehat{p}_t^f-\widehat{rer}_t-\widehat{p}_t^{*,h}\right]+\varepsilon_t^f \tag{57}$$

where import price inflation is given by $\pi_t^f=P_t^f/P_{t-1}^f$.[6] The linearized form of the real exchange rate, $\widehat{rer}_t$, above is equal to $\widehat{rer}_t=\widehat{er}_t+\widehat{p}_t^*-\widehat{p}_t$.

5 Technology diffusion and shock transmission

In this section, I calibrate the model to US data and identify the contribution of technology creation to the transmission of shocks across countries. I conduct various sensitivity analyses. I draw inferences from a Bayesian estimation exercise that uses Euro Area and US data. I assess the

[6] $\kappa_f=\frac{3.5\xi_f\left(1+\iota_f\beta\right)}{\left(1-\xi_f\right)\left(1-\xi_f\beta\right)\left(\varphi^f-1\right)}$ with ξ_f similarly denoting the probability that import prices do not change.

potential effects of strategic decision making on model results.

5.1 Calibration

Before calibrating the model, I first assume that there is symmetry across both the two countries and the agents within each country. I then use several data moments and macroeconometric findings to match the components of my model related to the R&D process. Assuming that the output growth rate is equal to 2.5% on an annual basis, and that the share of R&D labor in the labor force is 3%, imply that the stepping on toes parameter (i.e., the hazard rate) is 0.21 at steady state. This suggests that 21% of R&D efforts result in a successful innovation.[7] The 2.5% growth along the balanced growth path approximately matches the US real GDP (gross domestic product) growth rate in the past 40 years. The average ratio of scientists and engineers to total production workers in National Science Foundation's Business R&D and Innovation Survey (BRDIS) is approximately 2% from 2000 to 2018. While the number that I use is higher, it is not unreasonable as the 2% in the BRDIS surveys do not include any R&D support personnel who are neither classified as scientists nor engineers. I should also note that the percentage of R&D workers to production workers is much higher for R&D intensive sectors such as Chemicals, Transportation, Information, Computer and electronic products.

I assume a unit elastcity of substitution between the two labor types in the model. This is a reasonable value given the findings in the literature. While a large number of studies such as Ciccone and Peri (2005), Cantore et al. (2017) find an elasticity between 1 and 2, there also studies such as Havranek et al. (2020) that find an upward bias in these estimates and demonstrate that the elasticity, especially more recently, is less than 1 (implying that the two services are gross complements). If the skill premium between R&D and production activities is greater than the skill premium between the wages of college and high school graduates (the approach in a majority of the literature), than this would also be a reason why fixing the elasticity to 1 is a reasonable

[7] Empirical evidence shows that success rate of R&D activities depend on the industry and country. The estimated value for this hazard rate is as low as 8% and as high as 90% (e.g. Cooper, 1983; Cozijnsen et al., 2000; DiMasi et al., 2016; Välikangas et al. 2009).

strategy.

For the diffusion of technology, the macroeconometric finding that I use is the estimated value for the diffusion rate parameter in Bianchi et al. (2019). The study estimates a dynamic stochastic general equilibrium closed economy model and finds that the diffusion rate is 0.28. This diffusion corresponds to parameter η in my model. Setting the time discount rate β equal to 0.99, annual risk free interest rate of 4% (approximately matching the average annual yield on 10 year Treasury constant maturity securities in the past 40 years), and using the steady state expressions for the first order conditions with respect to R&D labor, knowledge stock and production labor implies that the cross-country technology diffusion parameter η_d is approximately 0.4. While there is no close match for this parameter in the data, R&D conducted domestically is roughly two-thirds of worldwide R&D for US companies in the BRDIS database between 2000 to 2018. The number of domestic R&D workers to worldwide R&D workers ratio is roughly the same during this period. While the parameter value that I use is slightly lower, if one considers R&D activity abroad as only one channel of technology diffusion (in addition but not limited to diffusion through trade for example), this is not an unreasonable parameterization.

Finally, I set the R&D labor adjustment cost parameter, κ_{rd}, initially to 0. Despite the absence of adjustment costs, R&D labor in model simulations is less volatile compared to investment, matching the fact that the growth rate of R&D spending has been approximately half as volatile as real business fixed investment growth in the past 75 years while exhibiting procyclical growth.[8]. I set the investment adjustment cost parameter $\kappa_i = 4$, a commonly-used value in the literature, so that the elasticity of investment with respect to the price of capital is approximately 0.125. I do, however, simulate the model by using an alternative calibration with positive costs to adjusting R&D in a sensitivity analysis.

To calibrate the remaining parts of my model, I use parameter values that are fairly standard. The habit persistence parameter, ζ, is set equal to 0.7. The Calvo pricing parameters ξ_w, ξ_p and

[8]The correlation between real R&D spending and real GDP growth rates is roughly 0.31 in the past 75 years. The standard deviations of the growth rates of real R&D spending, real GDP and real nonresidential fixed investment are 2.70, 5.38 and 14.39 between 1948Q1 and 2022Q4 (source: FRED).

ξ_f, and the indexation parameters ι_w, ι_p and ι_f are all set equal to 0.5 so that the probability of adjusting wages and prices (both domestic and foreign) is 50% and that wage and price contracts have a duration of two quarters. The steady state values of the price and wage mark-up variables, φ^p, φ^f and φ^w are set equal to 1.5. The Taylor rule, interest rate smoothing, inflation and output parameters ρ, γ_π, and γ_y are fixed to 0.75, 1.5 and 0.125, respectively. The steady state value of the the spread between the returns to capital and the risk free rate, $R^k - R$, is approximately 2% on an annual basis.[9]

Setting the depreciation rate, δ, equal to 0.025 and the share parameter α to 0.3, implies an annual depreciation rate of 10% and a 30% share of capital income at steady state. The capacity utilization elasticity parameter, ϖ, is set equal to 0.5, implying unit elasticity of utilization with respect to the marginal product of capital. The parameters representing the inverse elasticity of labor supply and the intertemporal elasticity of substitution in the utility function, σ_l and σ, are fixed to 2 and 1, respectively, with the latter implying unit elasticity. The utility parameter $\xi = \frac{(1-\alpha)}{\xi_w(1-\zeta)C/Y}$ so that the steady state level of labor is equal to 1. Here C/Y is the steady state share of consumption and it is fixed to 0.65. The share of government spending and investment in GDP, G/Y and I/Y, are equal to 0.2 and 0.15 at steady, matching historical data. The investment and consumption share parameters, θ_c and θ_i, are fixed to 0.9 implying that imports and exports are 10% of GDP along the balanced growth path. The corresponding elasticity of substitution parameters, λ_c and λ_i are set equal to 0.23 and 0.4 following Alpanda and Aysun (2015). Finally, following common practice, the persistence and standard deviation of all shocks are assigned the values 0.9 and 0.01, respectively, when measuring impulse responses.

5.2 Procyclicality of R&D and cross-country shock transmission

Before I proceed with measuring the transmission of shocks across countries and focusing on the innovation process, I should mention that the model demonstrates the standard responses of

[9] Approximately the average spread between BBB rate corporate bond yields and 10 year Treasury securities in historical data.

domestic variables to domestic shocks. The models moments also provide a reasonably close match to their data counterparts. The illustration of these responses and moments are deferred to Appendix A (Figure A.1 and Table A.1, respectively).

A key feature of the model is that R&D activity is procyclical. As displayed in Figure 1, firms increase their R&D activities when output expands and they do the opposite when output contracts. Larger amounts of production labor services that are hired to meet the higher demand during expansions, for example, increase the marginal benefits of and the demand for R&D labor. The responses of R&D labor is in general more muted compared to the responses of output since the R&D labor elasticity of output, $\frac{\partial Y_t/Y_t}{\partial l_t^{rd}/l_t^{rd}}$, is greater than 1 in the baseline calibration. Smaller adjustments in R&D, therefore, are sufficient to match the changes in the demand for intermediate goods.

Turning to the responses of foreign output to domestic shocks, displayed in Figure 2, the model demonstrates a strong cross-country transmission for the three demand shocks, foreign price shock and the depreciation shock. Specifically, the foreign variable responses, are often comparable, albeit smaller in magnitude, compared to the domestic responses, marked by the solid lines on the same graph. The transmission of domestic price, wage and monetary policy shocks are relatively weaker. The reason is that the effects of these shocks on foreign output through the changes in the real exchange rate are offset by their effects on inflation and the policy rate. A real appreciation in the domestic economy due to a positive price, wage and policy rate shocks, for example, prompts an increase the demand for foreign output and inflation simultaneously. The ensuing monetary tightening in the foreign economy partially offsets the increase in foreign output generated by the higher the demand for exports.

The results show that R&D labor is also procyclical when shocks originate outside of the country. The relative income of R&D workers, however, is countercyclical, as a result of the technology diffusion process. A domestic shock that increases the amount of innovations adopted by the foreign economy, for example, decrease the relative demand for R&D labor, prompting a decline in the relative wages and income of high-skill workers. The more general inference here is that external shocks impact not only the level but also the distribution of income in countries through technology diffusion.

5.3 The strength of cross-country linkages and other model characteristics

I proceed by more closely investigating the degree of international linkages. To do so, I first measure the effect of a domestic shock on foreign output under high and low degrees of technology spillover and without the technological process. To capture high and low degree of spillover I set the share of domestic innovations that the foreign economy adopts to 50 percent higher and lower than its baseline value. I then shut-off the technology process in each country by setting the mean value of the hazard rate to zero. The steady state growth rate of the economies are kept the same in these calibrations. The first plot of Figure 3, compares the responses of foreign output to a one standard deviation domestic investment shock under these scenarios with the baseline response. I choose to illustrate the responses to investment shocks here for brevity. The responses to the other domestic shocks are summarized in Table 1 and described below. With higher and lower spillover, the maximum response of foreign output is roughly 26 basis points higher and 32 basis points lower compared to the baseline response, respectively. Without the technology process, the maximum response is roughly half its size with technology.

Similar observations can be made for other domestic shocks and also for variables other than output. As summarized in Panel A of Table 1, for example, the amplitude of the responses are generally lower with low technology spillover. The foreign output response to a domestic consumption shock is roughly the same mainly due to monetary policy's reaction to inflation. Specifically, with a lower degree of diffusion, the smaller change in output and consumption in the domestic economy generate a smaller response in foreign inflation and the policy rate. This relatively accommodating monetary policy response then counteracts the smaller impact of the consumption shock on foreign output when the diffusion rate is low.[10]

[10]If I set the inflation paramater in the Taylor rule to lower values, I find that the response to a consumption shock also generates a smaller response in output when diffusion rate is low. When I set the parameter to 1.25, for example (.25 lower than its baseline value), the maximum response of foreign output with lower rate of diffusion is roughly 20

For other domestic shocks, the technology process and its diffusion introduces an amplification mechanism. Shocks that increase domestic output have a positive impact on foreign output not only through trade and the demand for foreign goods but also through its effects on labor efficiency and the supply of foreign goods. This amplification mechanism roughly doubles the strength of cross-country transmission of shocks to output. The correlation between foreign and domestic output in model simulations (with all shocks) is 0.86 with technology and 0.43 without it. This result demonstrates the significant role that technology plays in the model both by amplifying the domestic variable responses to domestic shocks and reinforcing the transmission of shocks originating in other countries.

A higher degree of trade also amplifies the effects of domestic investment shocks on foreign output as displayed in Figure 3. This is also true for consumption shocks (Table 1). To obtain the responses under low and high degree of trade openness, I set the share of both foreign consumption and investment goods in their corresponding CES aggregates to 0.99 and 0.3, respectively. With lower trade, the increase in the demand for foreign goods in response to positive preference and investment shocks is more muted. Furthermore, the response of domestic policy rates to inflation generated by the two shocks and the resulting real appreciation of the currency does not reinforce the demand for foreign goods as strongly as it does under higher trade. These observations, however, cannot be made for domestic price, wage and monetary policy shocks. For these shocks, foreign output responsiveness is higher with less trade (as reported in Table 1) for similar reasons. Specifically, the cross-country linkages of interest rates through the UIP condition becomes stronger under lower trade since the transmission of the changes in domestic interest rates (in response to the three shocks) to foreign interest rates and its negative effects on foreign output is not mitigated by the effects of a real appreciation on the demand for foreign goods. Panel B of Table 1 shows, consistent with this observation, that the drop in the correlation between domestic and foreign output under low trade is smaller compared to the drop in correlation when technology is shut-down.

basis points lower than the corresponding value under the benchmark calibration.

While the effects of trade openness on cross-country macroeconomic linkages depends on the type of shock, caibrations that shut-down technology and set bilateral trade to low levels unequivocally exhibit a much weaker link between the two economies. The maximum/minimum foreign output responses displayed in the fourth column of Table 1, Panel A are all much smaller in magnitude compared to the corresponding baseline values. The more general inference here is that the technology diffusion channel of shock transmission is much stronger for country pairs with high level of bilateral trade.

I conduct three more experiments to identify the contribution of the technology process to the comovement of the two economies. For all three experiments I shut-down the technology process by setting the mean value of the hazard rate to zero in each country. First, I introduce a TFP shock that is perfectly correlated across the two economies as a substitute for the endogenous technology process. As reported in Panel B of Table1, I find that the introduction of this shock falls considerably short of replicating the comovement generated by technology as there is minimal increase in the correlation between domestic and foreign output relative to the calibration without technology. As a second experiment, I assume, for all ten shocks in the model except for the common depreciation shock, that there is a component that is common across the two countries. These shocks by design impact the two countries symmetrically and they also follow an AR(1) process with a persistence parameter equal to 0.9 and a variance equal to 0.01. As displayed in Table 1, I find that the contribution of these exogenous links between the two countries is approximately equal to the contribution made by the endogenous technology process in my model. I make a similar observation (as displayed in the last column of Panel B) when I allow for all shocks in the model to be positively correlated across the two countries. When I set the correlation coefficient to 0.3, I find that the increase in the correlation of domestic and foreign output is similar to the increase in correlation through technology. Overall, these experiments all point to the key role that technology plays in the transmission of shocks between economies.

Further analyses, displayed in Figures 3 and 4 and summarized in Table 1, show that the strength of cross-country transmission is generally stronger with higher R&D adjustment costs (setting the R&D adjustment cost parameter to 4 times that of investment adjustment costs), higher market power for intermediate good producers (setting the mark-up rate to 100 percent), higher wage adjustment costs (increasing the wage adjustment cost parameter by 20 percent) and it is lower when households cannot hold foreign bonds so that asset markets are incomplete and the link between the two interest rates through the UIP condition is severed.[11] These inference, however, cannot be drawn uniformly for each shock. The different effects of shocks on the cross-country transmission is more clearly observed for habit persistence. When I change the habit persistence parameter to 0.8, replacing its benchmark value of 0.7, it is not clear whether the overall impact of domestic shocks on foreign output is stronger. Finally, I assume that monetary policy across the two economies if asymmetrically formulated such that the Taylor rule of the foreign central bank only includes inflation. Under this calibration, I find that the foreign variable responses to domestic shocks are larger in magnitude. The reason is that the domestic shocks that generate supply side effects (first 6 shocks listed in Panel A), feeding through the diffusion of technology, are more strongly reinforced by a central bank that only considers inflation in policy formulation. Similarly, domestic shocks that generate inflationary pressures in the foreign economy (the last 4 shocks in Panel A) prompt a stronger monetary policy reaction in the foreign economy.

The general observation here is that the strength of cross-country transmission of shocks critically depends on parameter values and more importantly on the relative persistence and variance of shocks. While the results in this section are obtained from a reasonable calibration, the methodology falls short of obtaining precise quantitative results especially given the assumption that the shock persistence and variance parameter values are the same for each type of shock.

5.4 Inferences from a Bayesian estimation

In this section, I use macroeconomic data to estimate model parameters, both structural and those governing the shock processes, to quantify the degree of cross-country linkages through technology. To do so, I use the economies of the US and the Euro Area to represent the domestic and

[11] Under incomplete asset markets, exchange rate follows an AR(1) process in the model.

foreign economies in the model. The two economies are roughly similar in size and they do have strong linkages through trade, financial markets, and technology as in the model. Also, there are harmonized data for the Euro Area countries that make using a group of countries to represent one economy in the model less problematic.[12] For each economy, I obtain 10 macroeconomic data series and a common $/Euro nominal exchange rate variable to estimate the model. The ten data series are the quarterly growth rates of real GDP, real personal consumption expenditures, real private fixed investment, real government consumption expenditures and gross investment, total employment, import price index, GDP deflator, short-term interbank rates, hourly earnings, total employment in scientific research and development and professional services.[13,14] The data are from 1998Q2 to 2022Q4 and all series are demeaned prior to estimation. The data definitions and sources are provided in Appendix A.

The data allow me to estimate the parameters governing 20 country specific shocks (10 for each economy) and a common depreciation shock. The country specific shocks are the consumption, investment, government spending, total factor productivity, monetary policy, domestic price, foreign price, wage, cost of capital and the efficiency shocks described above. In addition and similar to the previous section, I introduce a shock component that affects each economy symmetrically (hereafter, a common shock) for each shock excluding the depreciation shock. I should note that it is not clear how commons shocks would contribute to the cross-country transmission of shocks through technology. On the one hand, since R&D activity is pro-cyclical they can amplify the responses to shocks by forming a closer link between the economic activity in the two regions. On the other hand, they can absorb the impulses that generate the comovement of macroeconomic variables and mitigate the linkages through technology. While it is uncertain which effect would prevail, the

[12] The most comprehensive aggregate data for the Euro Area represents a fixed composition of data from 19 countries (Austria, Belgium, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Slovak Republic, Slovenia and Spain). It should be noted that this group excludes Croatia, the 20th member.

[13] I use total employment instead of hours as the hours worked in professional, scientific and technical activities is available for only a short period of time for the Euro Area.

[14] Growth rates are computed through log differencing except for interest rates. The growth of interest rate represent the change in basis points over the previous period. All data series with the exception of interest rates, bond yields and the exchange rate are seasonally adjusted.

common shock specification also allows me to detect and quantify the amount of comovement that is not explained by the model (through trade, bond holdings and technology diffusion).

To estimate the model, I use a Bayesian methodology that consists of five stages. The state space form of the model is first represented by its reduced form in predetermined variables so that the residuals represent orthogonal shocks (see, Blanchard and Khan, 1980). These predetermined variables are then linked to data via measurement equations. As a third step, the data are combined with prior parameter distributions to construct a likelihood function via a Kalman filter. Posterior distribution functions for estimated parameters are then constructed by multiplying the likelihood function with the prior density functions. Finally, an optimization routine is used to estimate the parameter values that maximize this posterior density function.[15]

Appendix B, lists the prior distributions for both the structural and shock process parameters. The parameters that are not included in the appendix are level parameters that are set equal to their values that are described in the calibration section.[16] The prior distributions that I use are common in the literature (see, Smets and Wouters, 2007 and Gilchrist et al., 2009) and they are informed by logical restrictions and macro-econometric evidence. Appendix B also reports the posterior estimates of the parameters. Compared to their prior means the posterior mean values are considerably different for most parameters suggesting that the data are informative. I should note here that I estimate the mean value of the hazard rate variable only as the other parameters governing the technology process are obtained from the steady state equations of the model.

To identify the role of technology, I estimate two versions of the model, one with and one without the technological process. To shut-down technology, I assume that all labor units are allocated to production and that there is no R&D activity. The Euro Area output responses to US shocks under these two specifications are displayed in Figure 5. The main inference from the figure is that the responses with technology dwarf the ones without. While the confidence intervals demonstrate that US shocks have significant effect on Euro Area output and that the

[15] I use a Monte-Carlo based procedure in Dynare as the optimization routine.

[16] Some of these parameters are functions of the mean values of the observable variables. Since observables are demeaned prior to estimation, the values for these parameters cannot be estimated.

direction of the responses are similar across the two models, the responses without technology are considerably smaller in magnitude except for the depreciation shock. When I compare these results with the responses of US output to Euro Area shocks, displayed in Figure 6, I find a relatively smaller disparity between the responsiveness of domestic variables to foreign shocks across the two specifications. These findings imply that the diffusion of technology could be operating more strongly from the U.S. to the Euro Area compared to the other direction.

Consistent with the impulse responses, I find that the US shocks' contribution to the macroeconomic volatility in the Euro Area is larger in the model with technology. I draw this inference by first measuring the contribution of US shocks to the historical decomposition of Euro Area variables. As illustrated in Figure 7, the combined contribution of US shocks to Euro Area volatility is comparable to those of Euro Area specific shocks and common shocks in the model with technology, both during the whole sample period and in the last decade. By contrast, when technology is shut-down, Euro Area output volatility is predominantly driven by Euro Area shocks. In Panel A of Table 2, I show that this observation can also be made for other macroeconomic variables, albeit at different degrees of magnitude.[17] While the three types of shocks make a similar contribution in the model with technology on average, the contribution of US shocks to the Euro Area macroeconomic volatility in the model without technology is considerably small similar to the inferences obtained from impulse responses. Unlike impulse responses, however, the historical decompositions are period specific, representing the contribution of the current level of a shock and its lagged values to a variable's deviation from the balanced growth path for a given period. They are thus a better gauge of how international shock transmission has evolved historically. The results I obtain demonstrate that the relative shares of the contributions have been quite stable across the sample period.

Forecast error variance decompositions (FEVDs), reported in Panel B of Table 2, similarly demonstrate a stronger cross-country transmission of shocks through technology. FEVDs, a long-standing tool used in the literature (e.g., Gali, 1999) to identify the drivers of business cycles, are

[17] I first measure the contribution shares for the three types of shock for each time period and then compute the averages of these values across the sample period to obtain the figures in Table 2.

measured by feeding in smoothed shocks to the estimated model one at a time to measure the contribution of each shock to the volatility of a forecast error at a given horizon. Using 4 quarters for the forecast horizon, I find that the contributions of US, Euro Area and common shocks to the macroeconomic volatility in the Euro Area are roughly the same, similar to previous findings. Without technology, however, Euro Area shocks are more important sources of volatility according to FEVDs, while the shares of US shocks remain small.

Also consistent with the impulse responses, I find evidence that the transmission of shocks could be operating more strongly in the direction from the US to the Euro Area. As displayed in Table A.2 of Appendix A, the contributions of Euro Area shocks to US macroeconomic volatility is much smaller compared to contributions that US shocks make to Euro Area macroeconomic volatility. This observation can also be made for the efficiency variable, the key variable linking the two economies through technology, as displayed in Panel C of Table 2. The implication here is that US is the principal technology creator in the estimated model. The more critical result, however, is that the higher rate of technology adoption by the Euro Area also opens a wider channel for other US shocks to transmit abroad through their effects on technology creation.

5.5 Strategic decision making

The computational exercises above revealed that technology diffusion flows mostly from the US to the Euro Area. The innovators in the model, the intermediate good producers, however, do not take this into account when determining the optimal amount of R&D activity. Specifically, the higher supply and lower prices caused by the diffusion of technology to competitors requires strategic decision making in a more realistic setup. While incorporating this setup into a two country DSGE model is complicated and goes beyond the scope of this paper, it is necessary to offer some postulations for how strategic decision making would affect technology creation and the degree of international shock transmission.

To aid the discussion, consider a setup with two firms, one in each country, that produce the same good. The firm in country A, firm A, conducts R&D and its production function is given by,

$$y_A = y_{A,0} + \gamma_A \tag{58}$$

where y_A, $y_{A,0}$ and γ_A are the total production, baseline production and the contribution of R&D output to the production process, respectively.

Firm B in country B does not conduct R&D and it just adopts the innovations of firm A. Its production function is given by,

$$y_B = y_{B,0} + \mu \gamma_A \tag{59}$$

where y_B, $y_{B,0}$ have the same interpretation and μ regulates the amount of innovations adopted from firm A.

The price of the common good is determined as follows:

$$p = p_0 - \alpha \left(y_A + y_B\right) \tag{60}$$

where α and p_0 are the slope and the intercept of the demand curve.

Now assume that there are no costs associated with R&D activity and that firm A accounts for the production of firm B when deciding how much R&D to conduct. Firm A's profit maximization problem then yields the following negative relationship between the optimal level of R&D activity and the rate of technology adoption :

$$\gamma_A = \frac{p_0}{2\left(1+\mu\right)} \tag{61}$$

This result implies that if the amount of R&D activity is asymmetric across countries, such that one country is predominantly a technology creator and the other an adopter, there would be a smaller number of innovations. For the central analysis in my paper, this would then constrict a major channel through which shocks are transmitted across countries. Also and as important, the free rider problem alluded to above would put the countries on a flatter balanced growth path by decreasing the steady state growth rate. I should note here that it is possible to enrich the model above by including a trade off between production and R&D labor in each country, by assigning higher costs to R&D activity and by interpreting μ as the cost of adopting firm A's innovations (with lower values of μ indicating higher costs of adoption). In this variation, firm A switches to a less R&D intensive production when firm B's cost of adopting technology decreases so that the inferences remain the same but the solution is much less tractable.

6 Concluding remarks

This paper demonstrated that the diffusion of technology across countries constitutes a strong conduit through which macroeconomic shocks propagate amongst economies. The endogenous technology diffusion mechanism offers an alternative way to account for the high degree of comovement between advanced economies in the data. While a majority of the literature uses frictions that apply to international contracts to match cross-country data moments, the results in my paper imply that the high degree of correlation in a two country model can be generated even in the absence of these frictions. The inferences were drawn from a unique framework that combines an endogenous growth mechanism (i.e., a labor augmenting technology that depends on R&D activity) with a two country DSGE model with nominal and real rigidities. Under a reasonable calibration, technology diffusion accounted for roughly half the correlation between the two countries' output. Estimating the model with US and Euro Area data further revealed that foreign shocks are an important contributor to the macroeconomic volatility in a given country only in the model with a technology diffusion mechanism. If the mechanism is shut-down, foreign shocks' effects on the other economy, consistent with the literature on open economy modelling, is negligible. Post-estimation statistics also demonstrated the importance of shocks that affect the US and Euro Area symmetrically, i.e., common shocks, for macroeconomic volatility.

Due to the complex nature of the two country DSGE framework with endogenous growth, I followed standard assumptions to solve the model and draw inferences. One such assumption was that there is symmetry across firms that engage in R&D activity. This assumption naturally rules out strategic behavior that plays a crucial role in R&D and technology creation. While I made the postulation that strategic behavior would constrict the channel that links the two economies in my model, as a technology creating country/firm would engage in less R&D activity if the firms in the other country adopt these technologies without paying a cost, a more rigorous analysis is necessary to draw quantitative inferences. In particular, incorporating strategic decision making in a simpler two country framework and investigating the role of international policing of copyrights could reveal interesting insights for macroeconomic volatility and integration.

A natural direction for future research is to use richer data sets to more accurately measure the contribution of technology to business cycles. The reporting of R&D activity, however, is very fragmented across the world. Amongst the two economies used in this paper, for example, US has rich data on R&D spending, the Euro Area does not, partially due to the difficulties in data harmonization. Given the importance of technology diffusion for business cycles, generating R&D spending measures that are comparable across countries would have a high value-added. Data construction efforts such as Comin and Hohijn (2004) should be renewed and become routine activities.

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Table 1. Sensitivity summary and the contribution of technology to output correlation

Panel A	Baseline	Low technology spillover	Low trade	Without technology & low trade	Relatively higher R&D adjustment costs	Asymmetric monetary policy	High market power	High wage adjustment costs	High habit persistence	Incomplete Asset Markets
Maximum/minimum amplitude of foreign output										
Consumption shock	1.286	1.365	0.329	0.205	2.074	1.513	1.501	1.237	2.461	0.966
Investment shock	1.428	1.103	1.036	0.122	2.728	1.696	1.838	1.641	1.204	1.068
Government spending shock	0.044	0.043	0.037	0.006	0.118	0.050	0.052	0.039	0.052	0.041
Cost of capital shock	-0.063	-0.047	-0.060	-0.005	-0.133	-0.075	-0.079	-0.073	-0.047	-0.057
Efficiency shock	0.232	0.096	0.237	0.000	0.446	0.246	0.421	0.268	-0.062	0.228
Monetary policy shock	-0.075	-0.046	-0.119	0.006	-0.253	-0.083	-0.086	-0.089	0.077	-0.303
Domestic price shock	-0.845	-0.470	-0.958	0.057	-1.886	-0.922	-0.946	-0.934	0.392	-0.796
Foreign price shock	-0.172	-0.184	-0.028	-0.029	0.199	-0.199	0.379	0.185	0.152	-0.420
Wage shock	-0.615	-0.279	-0.701	0.030	-1.173	-0.664	-0.882	-0.724	0.256	-0.573
Depreciation shock	-0.393	-0.421	-0.058	-0.061	-0.400	-0.464	-0.516	-0.408	-0.342	-0.288

Panel B	Data	Baseline	Without technology	Low trade	Without technology & low trade	Without tech. & perfectly correlated TFP shocks	Without tech. & common shocks	Without tech. & correlated shocks
Correlation of domestic and foreign output	0.860	0.720	0.430	0.518	0.112	0.435	0.752	0.656

Notes: This table reports the sensitivity analysis results obtained from the calibrated form of the model. The specifications with low technology and without technology are obtained by setting the mean values of the standing of shoulders parameter to half its baseline value in each economy and to zero, respectively. For simulations with a low level of trade the share of domestic goods in the consumption and investment CES aggregates are set equal to 0.99. Relatively higher R&D adjustment costs are formulated by setting the R&D adjustment cost parameter to 4 times the value of the investment adjustment cost parameter. Under asymmetric monetary policy, the Taylor rule in the foreign economy only includes inflation. Higher market power corresponds to the calibration with a mark-up rate of 100% in each economy. Results with higher wage adjustment costs are obtained by increasing the wage adjustment cost parameter by 20 percent. For the simulations with higher habit persistence, the habit parameter is set equal to 0.8. Under incomplete asset markets, the exchange rate variable follows an AR(1) process. To obtain the results reported in the last column of Panel B, I set the correlation coefficient for each domestic and foreign shock pair to 0.3.

Table 2. Historical and Forecast Error Variance Decompositions, summary

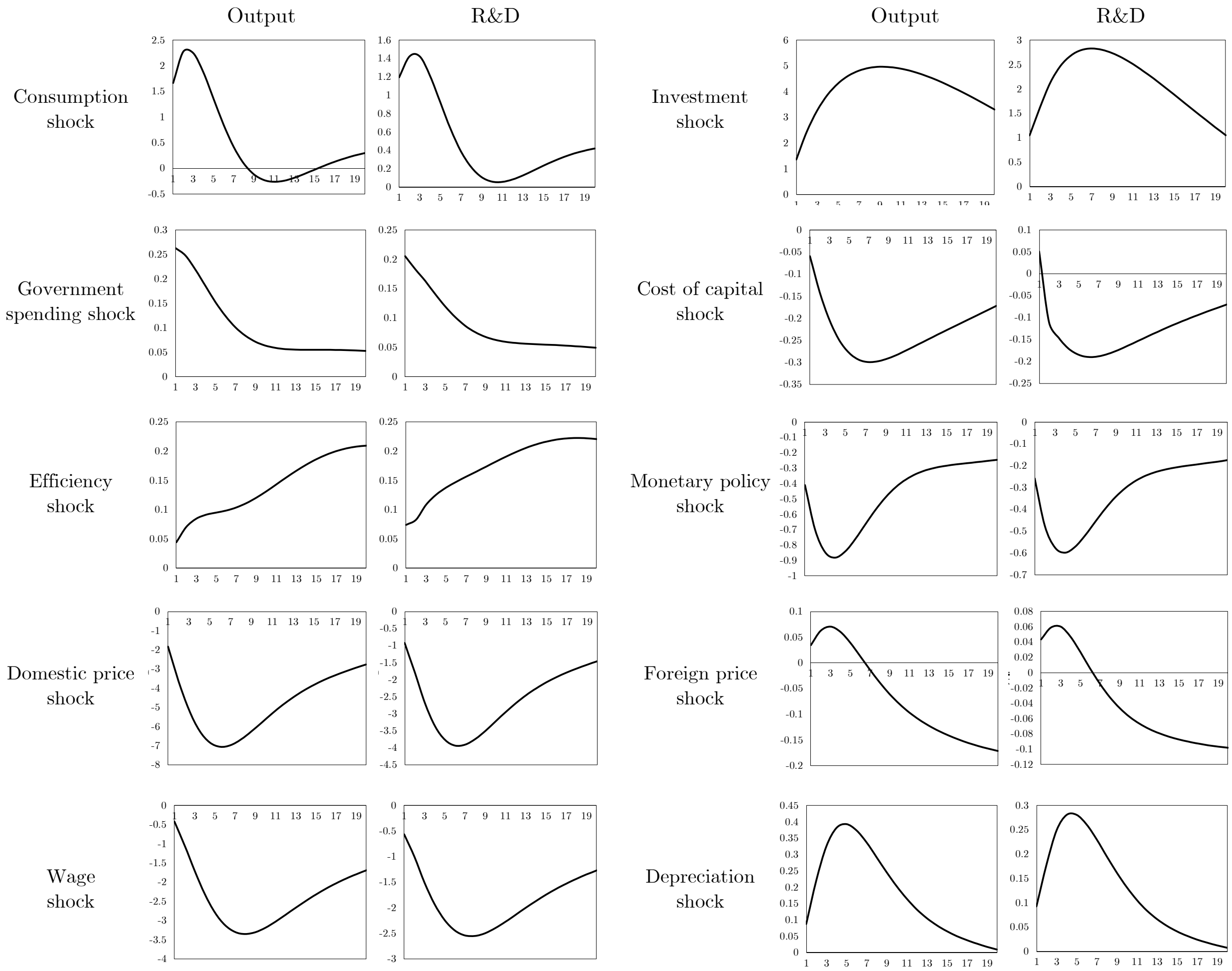
Panel A: Historical variance decomposition	With technology			Without technology		
	U.S. shocks	EA shocks	Common shocks	U.S. shocks	EA shocks	Common shocks
EA endogenous variables						
Output	27.2	24.2	48.6	3.0	89.1	7.9
Consumption	26.3	23.7	50.0	3.9	56.6	39.5
Investment	25.8	24.4	49.8	13.0	54.8	32.2
Production labor	43.2	32.9	23.8	13.4	57.4	29.1
Wage inflation	42.1	25.6	32.3	8.0	63.7	28.2
Interest rates	28.3	27.6	44.1	14.2	59.8	26.1
Inflation	32.0	33.7	34.4	13.5	55.6	30.9
Credit Spreads	30.0	43.7	26.3	0.3	34.2	65.5
Average	**31.9**	**29.5**	**38.7**	**8.7**	**58.9**	**32.4**

Panel B: Forecast error variance decomposition	With technology			Without technology		
	U.S. shocks	EA shocks	Common shocks	U.S. shocks	EA shocks	Common shocks
EA endogenous variables						
Output	21.8	15.0	63.2	0.0	99.1	0.8
Consumption	18.7	17.8	63.5	0.2	63.1	36.7
Investment	18.1	18.8	63.1	2.6	71.9	24.7
Labor	56.6	42.2	1.3	0.0	99.3	0.6
Wage inflation	69.4	19.3	11.2	2.7	80.1	15.8
Interest rates	30.3	38.6	31.1	3.6	62.4	32.0
Inflation	21.9	56.7	21.2	8.0	76.6	11.6
Credit Spreads	23.2	69.8	6.9	0.0	23.1	76.9
Average	**32.5**	**34.8**	**32.7**	**2.2**	**72.0**	**24.9**

Panel C: Sources of efficiency growth	US efficiency			EA efficiency		
	U.S. shocks	EA shocks	Common shocks	U.S. shocks	EA shocks	Common shocks
Historical decomposition	51.5	5.3	43.2	29.5	38.3	32.1
Forecast error variance decomposition	58.9	0.3	40.7	9.3	38.1	52.6

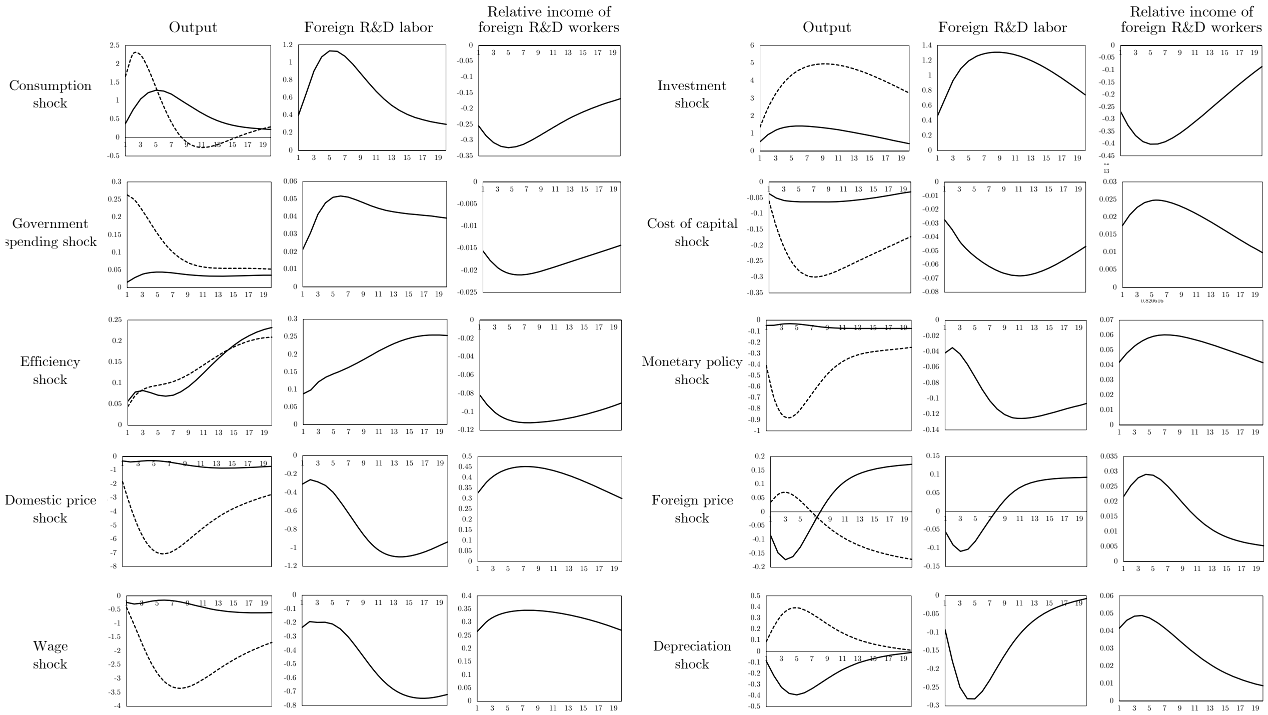
Notes: The table summarizes the contributions of shocks originating in the US, the Euro Area and common shocks to the historical variance decomposition of Euro Area variables. The average contributions are obtained by first measuring the contribution shares for the three types of shock for each time period and then computing the averages of these values across the sample period. The results reported in the last three columns of each panel correspond to the model without technology creation and diffusion.

Figure 1. Procyclicality of R&D



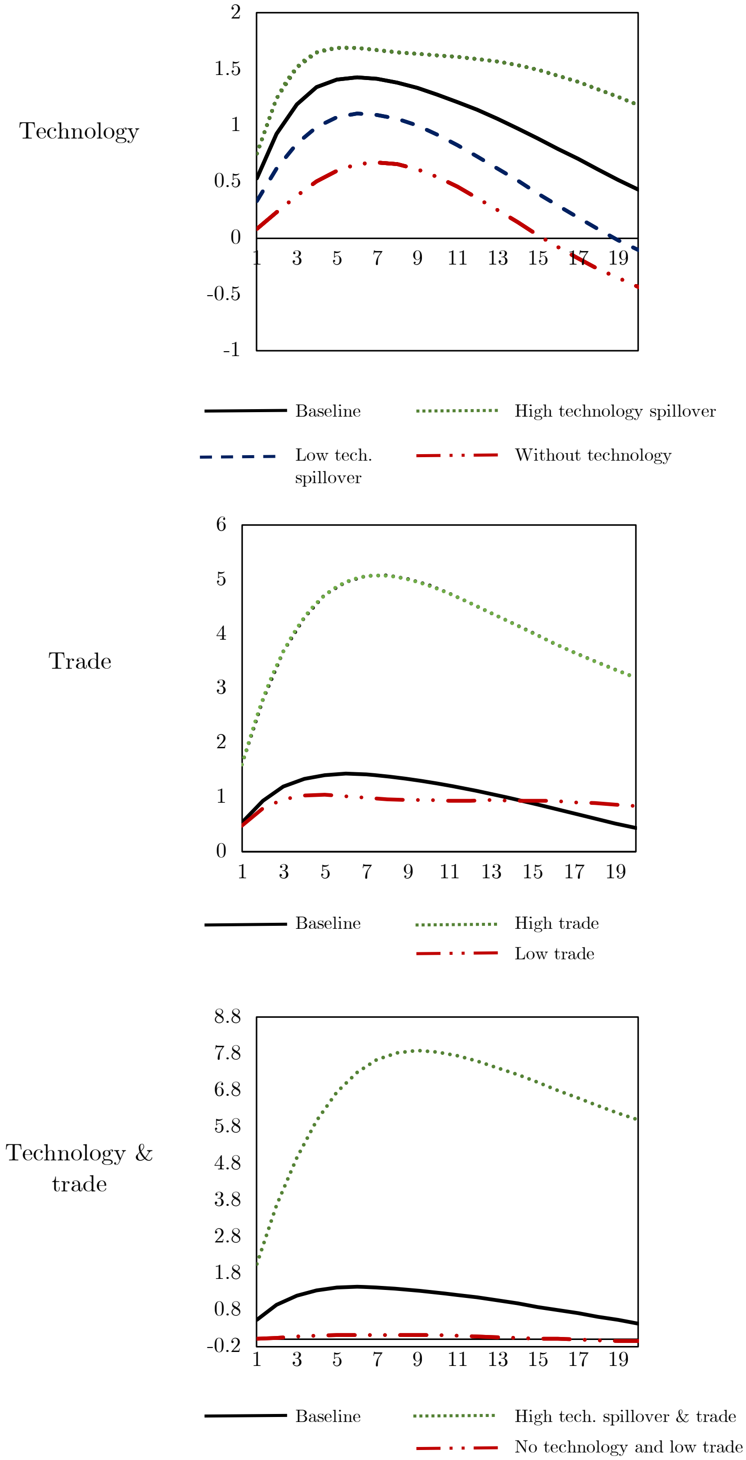
Notes: The figure shows the domestic output and R&D labor responses to one standard deviation domestic shocks.

Figure 2. Cross country shock transmission



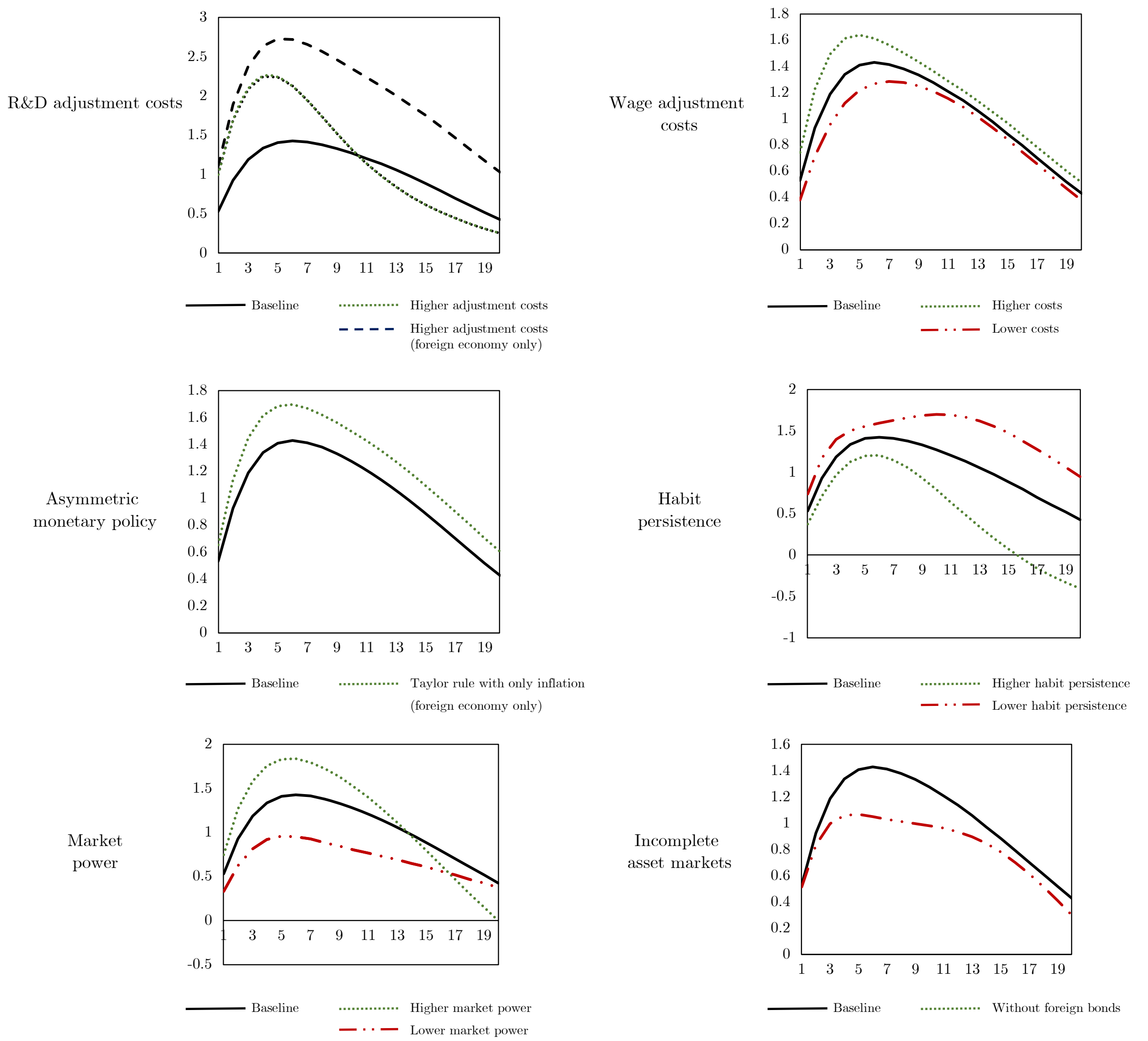
Notes: The figure shows the responses of output (both domestic and foreign), foreign R&D labor and the relative income of foreign labor to one standard deviation domestic shocks. Dashed and solid lines represent the domestic and foreign variable responses, respectively.

Figure 3. Technology and trade



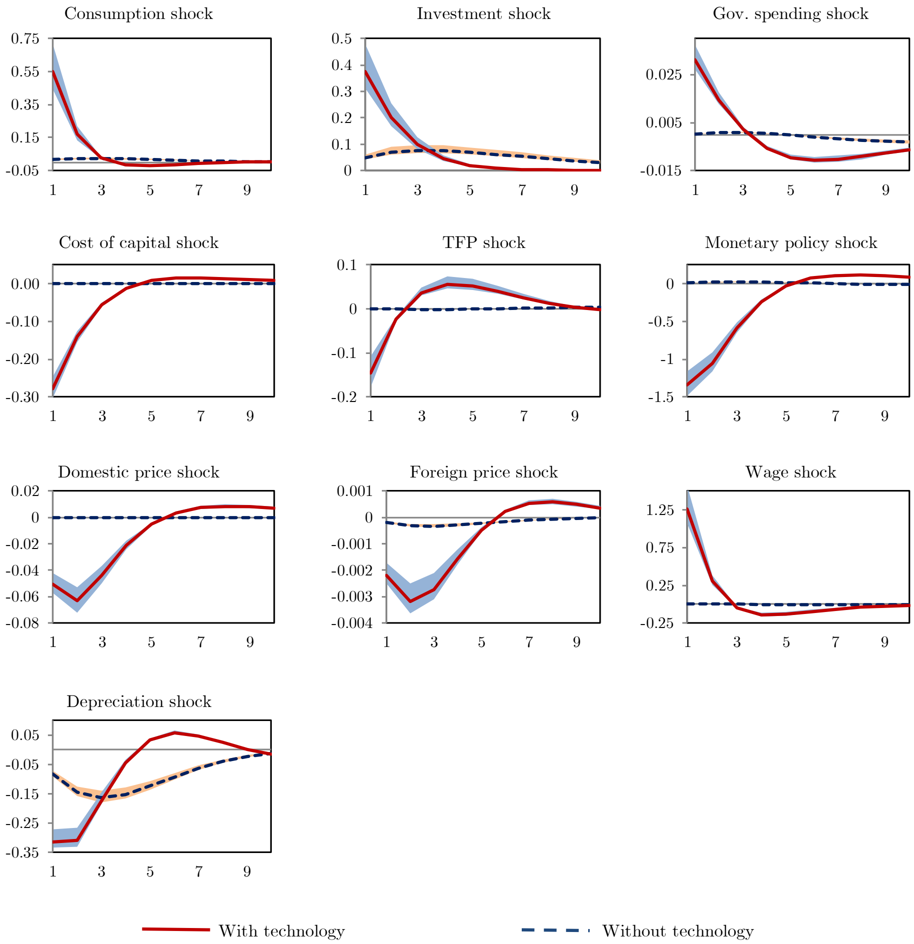
Notes: The figure shows the responses of foreign output to a one standard deviation domestic investment shock. For the high and low spillover scenarios in the first plot, the source of efficiency growth is 100% local and foreign R&D, respectively. I shut-down R&D activity in both economies to obtain the responses without technology. High trade and low trade in the second plot correspond to 70% and 1% share of imports for both consumption and investment goods (in both economies), respectively. I make the assumption that consumers do not hold foreign bonds to obtain the responses, without foreign bonds, in the third plot.

Figure 4. Other features



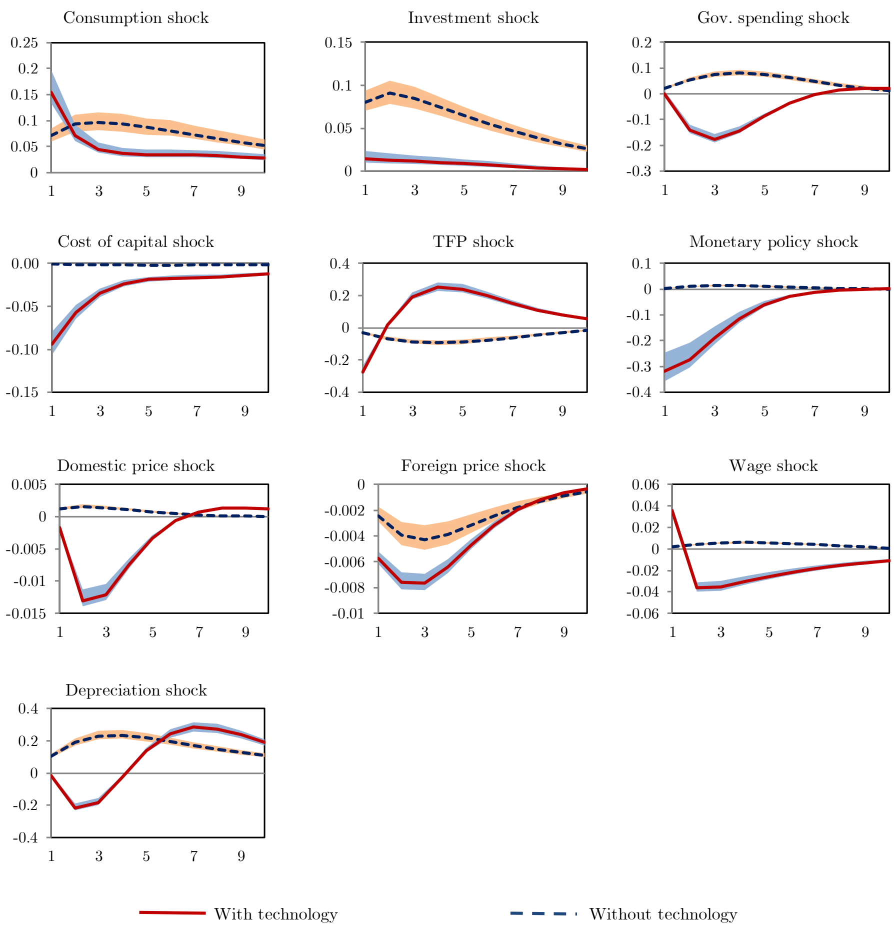
Notes: Relatively higher R&D adjustment costs are formulated by setting the R&D adjustment cost parameter to 4 times the value of the investment adjustment cost parameter. Under asymmetric monetary policy, the Taylor rule in the foreign economy only includes inflation. Higher market power corresponds to the calibration with a mark-up rate of 100% in each economy. Results with higher wage adjustment costs are obtained by increasing the wage adjustment cost parameter by 20 percent. For the simulations with higher habit persistence, the habit parameter is set equal to 0.8. Under incomplete asset markets, the exchange rate variable follows an AR(1) process.

Figure 5. Euro Area output response to US shocks, estimated model



Notes: The figure displays the mean values and the 5 percent confidence band of the Euro Area output responses to 1 standard deviation US shocks from the estimated models with and without technology creation and diffusion.

Figure 6. US output response to EA shocks, estimated model



Notes: The figure displays the mean values and the 5 percent confidence band of the US output responses to 1 standard deviation Euro Area shocks from the estimated models with and without technology creation and diffusion.

Figure 7. Historical decomposition of Euro Area output

Notes: US and Euro Area shocks are the 10 shocks that originate in these economies. Common shocks correspond to the component of each type of shock that symmetrically affects the two economies and the common depreciation shock.

Online Appendix A. Alternative tests and results

Table A.1. Data versus model moments

	Data	Model
Correlations with output		
Investment	0.65	0.79
Consumption	0.89	0.89
Labor	0.86	0.88
Inflation	0.08	0.11
Standard deviation relative to output		
investment	2.73	3.28
consumption	0.98	0.98
labor	1.35	0.67
inflation	0.73	0.83

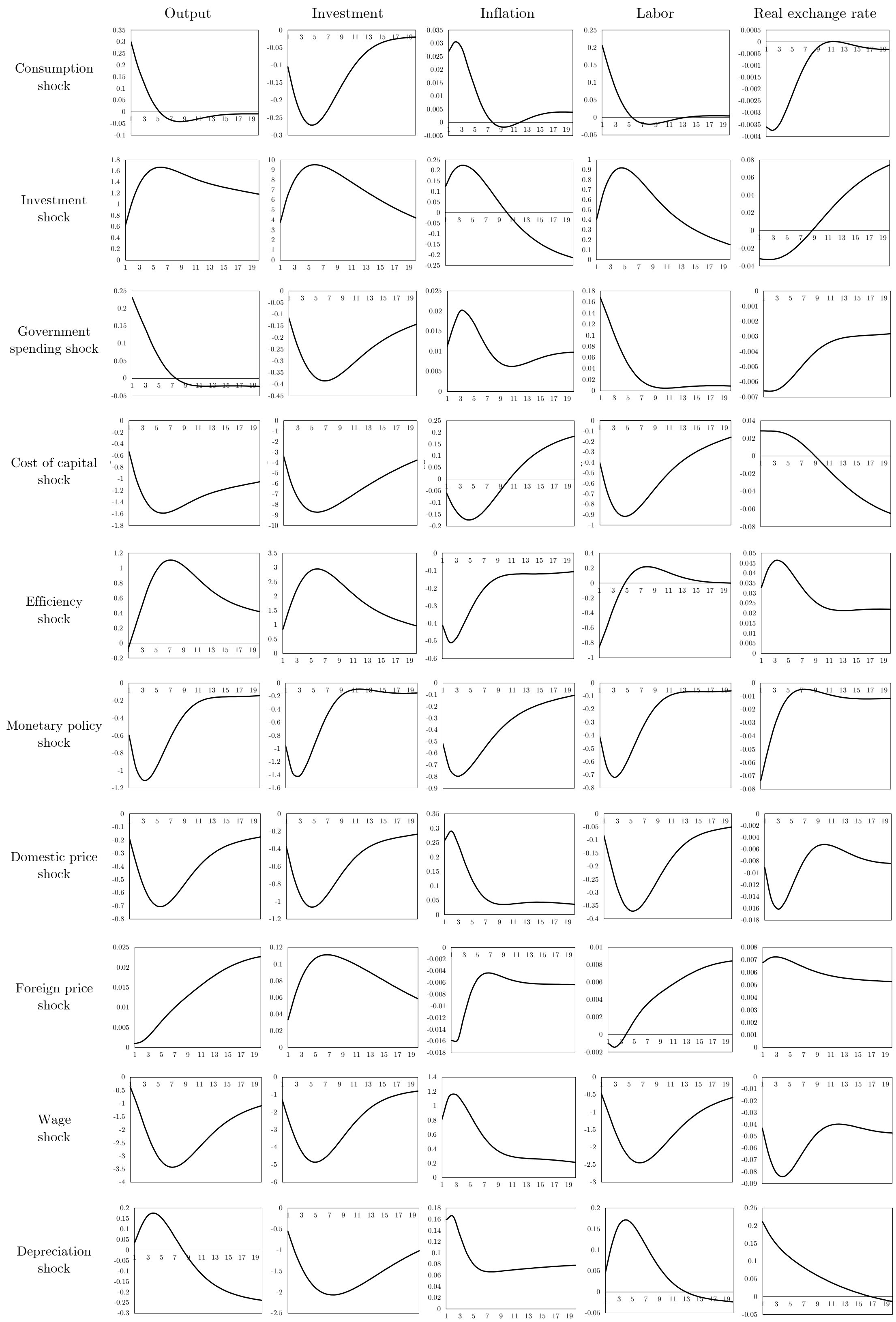
Notes: The data series are measured as year-over-year growth rates. Data definitions and sources are listed in Table B.1 of Appendix B.

Table A.2. Historical decomposition of US variables

Panel A: Historical variance decomposition	With technology			Without technology		
	U.S. shocks	EA shocks	Common shocks	U.S. shocks	EA shocks	Common shocks
US endogenous variables						
Output	58.0	14.7	27.3	51.5	24.0	24.5
Consumption	66.8	4.8	28.4	51.4	5.0	43.5
Investment	65.9	5.0	29.1	61.5	6.7	31.8
Production labor	43.3	39.2	17.6	59.3	22.1	18.6
Wage inflation	36.6	28.4	35.0	47.7	13.3	39.0
Interest rates	64.9	10.8	24.3	30.9	7.6	61.5
Inflation	49.3	7.2	43.5	38.2	17.6	44.2
Credit Spreads	43.9	10.2	45.9	23.4	2.1	74.5
Average	**53.6**	**15.0**	**31.4**	**45.5**	**12.3**	**42.2**

Notes: The table summarizes the contributions of shocks originating in the Euro Area and common shocks to the historical variance decomposition of US variables. The average contributions are obtained by first measuring the contribution shares for the three types of shock for each time period and then computing the averages of these values across the sample period. The results reported in the last three columns correspond to the model without technology creation and diffusion.

Figure A.1. Domestic variable responses to domestic shocks



Notes: The figure shows the domestic variable responses to one standard deviation domestic shocks in the calibrated model.

Online Appendix B. Estimation data, prior distributions and posterior means

Table B.1. Data definitions and sources

Variable	Description	Data Source
US		
Output	Real Gross Domestic Product	Federal Reserve Economic Data
Consumption	Real Personal Consumption Expenditures	Federal Reserve Economic Data
Investment	Real Private Fixed Investment	Federal Reserve Economic Data
Government Expenditures	Real Government Consumption Expenditures and Gross Investment	Federal Reserve Economic Data
Hours	Nonfarm Business Sector: Hours Worked for All Workers	Federal Reserve Economic Data
GDP Deflator	Gross Domestic Product: Implicit Price Deflator, Index, Seasonally adjusted	Federal Reserve Economic Data
Import prices	Import Price Index by Origin (NAICS): All Industries for European Union	Federal Reserve Economic Data
Interest rate	Immediate Rates: Less than 24 Hours: Call Money/Interbank Rate	Federal Reserve Economic Data
Cost of capital	ICE BofA US High Yield Index Effective Yield	Federal Reserve Economic Data
Wages	Hourly Earnings: Private Sector	Federal Reserve Economic Data
R&D labor	Scientific research and development services, all employee	Bureau of Labor Statistics
Exchange rate	US Dollar to Euro Spot Exchange Rate	Federal Reserve Economic Data
Euro Area		
Output	Euro area 19 (fixed composition) - Real gross domestic product at market price, reference year 2000.	European Central Bank
Consumption	Euro area 19 (fixed composition) - Real final consumption of households and NPISH s (private consumption), reference year 2000	European Central Bank
Investment	Euro area 19 (fixed composition) - Real gross fixed capital formation, reference year 2000	European Central Bank
Government Expenditures	Government Final Consumption Expenditure for the Euro Area, constant prices, (19 Countries)	Federal Reserve Economic Data
Hours	Euro area 19 (fixed composition), Hours worked, all activities.	European Central Bank
GDP Deflator	Gross Domestic Product: GDP Deflator for the Euro Area (19 Countries)	Federal Reserve Economic Data
Import prices	Deflator, Imports of goods and services - Euro area 19 (fixed composition)	European Central Bank
Interest rate	Immediate Rates (< 24 Hrs): Call Money/Interbank Rate: Total for the Euro Area (19 Countries)	Federal Reserve Economic Data
Cost of capital	CE BofA Euro High Yield Index Effective Yield	Federal Reserve Economic Data
Wages	Labour Compensation: Earnings: Private Sector: Hourly for the Euro Area (19 Countries)	Federal Reserve Economic Data
R&D labor	Euro area 19 (fixed composition), Professional, scientific and technical activities; administrative and support service activities, Persons.	European Central Bank

Notes: The table displays the definitions and sources of the data that are used to estimate the models with and without technology.

Table B.2. Prior distributions and posterior mean values, estimated structural parameters

		Posterior Means			
		With technology		Without technology	
	Prior Densities	US	Euro Area	US	Euro Area
Innovation hazard rate	B (0.5, 0.2)	0.20	0.02		
Habit persistence	B (0.7, 0.2)	0.96	0.98	0.96	0.98
Elasticity of labor supply	G (2, 0.7)	1.66	1.63	1.73	1.77
Elasticity of capital utilization costs	B (0.5, 0.2)	0.07	0.24	0.12	0.25
Investment adjustment costs elasticity	G (4, 1.5)	4.68	5.51	4.05	5.75
Price indexation, home goods	B (0.5, 0.1)	0.45	0.26	0.46	0.34
Price indexation, foreign goods	B (0.5, 0.1)	0.50	0.44	0.50	0.45
Wage indexation	B (0.5, 0.1)	0.11	0.27	0.07	0.36
Price adjustment probability, home goods	B (0.5, 0.1)	0.83	0.72	0.85	0.78
Price adjustment probability, foreign goods	B (0.5, 0.1)	0.39	0.59	0.39	0.58
Wage adjustment probability	B (0.5, 0.1)	0.88	0.85	0.86	0.82
Elasticity of sub., home & foreign consumption goods	G (1, 0.5)	0.39	2.09	0.23	2.06
Elasticity of sub., home & foreign investment goods	G (0.25, 0.1)	0.38	1.10	0.38	1.11
Taylor rule, interest rate smoothing	B (0.75, 0.1)	0.84	0.83	0.83	0.82
Taylor rule, inflation	G (1.5, 0.25)	1.45	1.42	1.42	1.43
Taylor rule, output	G (0.25, 0.12)	0.04	0.05	0.01	0.06

Notes: The table displays the prior distributions and the posterior mean estimates for the structural parameters in the models with and without technology. B and G in the second column denote beta and gamma distributions, respectively.

Table B.3. Prior distributions and posterior mean values, shock process parameters

		Posterior Means					
		With technology			Without technology		
	Prior Densities	US	Euro Area	Common	US	Euro Area	Common
Persistence parameters							
Consumption shock	B (0.5, 0.2)	0.45	0.25	0.53	0.47	0.33	0.49
Investment shock	B (0.5, 0.2)	0.631	0.204	0.506	0.598	0.239	0.426
Government spending shock	B (0.5, 0.2)	0.91	0.90	0.49	0.89	0.90	0.42
TFP shock	B (0.5, 0.2)	0.78	0.84	0.46	0.75	0.85	0.49
Monetary policy shock	B (0.5, 0.2)	0.48	0.41	0.46	0.34	0.40	0.46
Domestic price shock	B (0.5, 0.2)	0.08	0.15	0.50	0.11	0.19	0.43
Foreign price shock	B (0.5, 0.2)	0.71	0.57	0.45	0.70	0.52	0.42
Wage shock	B (0.5, 0.2)	0.50	0.08	0.47	0.46	0.08	0.45
Cost of capital shock	B (0.5, 0.2)	0.88	0.88	0.47	0.86	0.81	0.54
Efficiency shock	B (0.5, 0.2)	0.50	0.21	0.46			
Depreciation shock	B (0.5, 0.2)	0.72			0.70		
Standard deviations							
Consumption shock	IG (0.5%, inf)	0.0015	0.0016	0.0014	0.0009	0.0016	0.0009
Investment shock	IG (0.5%, inf)	0.0034	0.0016	0.0038	0.0062	0.0061	0.0020
Government spending shock	IG (0.5%, inf)	0.0273	0.2093	0.0024	0.0257	0.2108	0.0032
TFP shock	IG (0.5%, inf)	0.0072	0.0342	0.0015	0.0087	0.0333	0.0021
Monetary policy shock	IG (0.5%, inf)	0.0039	0.0025	0.0024	0.0038	0.0026	0.0020
Domestic price shock	IG (0.5%, inf)	0.0188	0.0212	0.0103	0.0011	0.0038	0.0010
Foreign price shock	IG (0.5%, inf)	0.0065	0.0063	0.0041	0.0077	0.0055	0.0042
Wage shock	IG (0.5%, inf)	0.0009	0.0028	0.0008	0.0010	0.0028	0.0010
Cost of capital shock	IG (0.5%, inf)	0.0230	0.0231	0.0171	0.0023	0.0055	0.0143
Efficiency shock	IG (0.5%, inf)	0.0054	0.0053	0.0051			
Depreciation shock	IG (0.5%, inf)	0.0124			0.0095		

Notes: The table displays the prior distributions and the posterior mean estimates for the shock process parameters in the models with and without technology. B and IG in the second column denote beta and inverse gamma distributions, respectively.