FARAWAY, SO CLOSE! TECHNOLOGY DIFFUSION AND FIRM HETEROGENEITY IN THE MEDIUM TERM CYCLE OF ADVANCED ECONOMIES

2018

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Documentos de Trabajo
N.º 1835

BANCO DE ESPAÑA
Eurosistema

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(*) We appreciate the helpful comments from seminar and conference participants at Universidad Carlos III de Madrid, Banco de España and Simposio de la Asociación Española de Economía 2018. We also thank Javier Perdiguero for assistance with the data. The views expressed in this paper do not necessarily represent those of Banco de España or the Eurosystem. Beatriz de Blas thanks financial support from project ECO2015-69631-P of the Spanish MINECO.
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Documentos de Trabajo. N.º 1835

2018

Updated May 2019

ISSN: 1579-8666 (on line)

Abstract

Large US firms, by diffusing embodied technology through trade in intermediates, appear to drive Europe's output over the medium term. We develop a two-country model of endogenous growth in varieties, cross-country firm heterogeneity and trade to match this evidence. A US TFP slowdown generates a pronounced recession in Europe, while a negative investment-specific shock also imparts a protracted recession in the US since GDP and firm productivity stay below trend beyond a decade. Heterogeneous firms, with endogenously changing productivity cut-offs, and the responses of innovators and adopters determine medium-term adjustment, as import switching processes unfold.

Keywords: medium-term business cycles, international trade, embodied growth, heterogeneous firms.

JEL classification: E32, L11, F44, O33.

Resumen

Las grandes empresas de Estados Unidos, al difundir tecnología a través del comercio de intermedios, parecen ser clave para la producción de Europa en el medio plazo. De cara a explicar esta evidencia, el presente trabajo desarrolla un modelo de dos países con crecimiento endógeno en variedades, heterogeneidad empresarial y comercio. Una desaceleración de la productividad total de los factores en Estados Unidos provoca una marcada recesión en Europa, mientras que un *shock* negativo específico a la inversión también da lugar a una recesión prolongada en Estados Unidos, dado que el PIB y la productividad a nivel de empresa permanecen por debajo de su tendencia más de una década. Las empresas heterogéneas, con cambios endógenos de productividad, y las respuestas de innovadores y adoptadores determinan el ajuste en el medio plazo, a la vez que se despliegan los procesos de sustitución de importaciones.

Palabras clave: ciclo económico a medio plazo, comercio internacional, crecimiento endógeno, empresas heterogéneas.

Códigos JEL: E32, L11, F44, O33.

1 Introduction

Since the end of World War II, advanced economies have experienced long-lasting swings in economic activity (e.g., Crafts and Toniolo, 1996, Blanchard, 1997, Temin, 2002, Comin and Gertler, 2006, Eichengreen, 2008). A closer look at the historical data further reveals that, over the medium term, output and investment fluctuations among European countries have been more volatile and persistent than in the US. In addition, US output and investment show a lead and a strong correlation with European output and investment at the medium frequency.[1] Similarly, a US embodied productivity cycle leads the European one over the medium term. To understand what drives such comovements, we present evidence of international diffusion of US technologies via trade. Furthermore, we find that larger US firms may play a significant role in explaining the observed cross-country aggregate patterns. Standard real business cycle models find it hard to account for the features of international business cycle transmission when calibrated at higher frequencies. Thus, building on the seminal contribution of Comin and Gertler (2006), we develop a quantitative macroeconomic model of two advanced economies in an attempt to match the stylized facts that we observe in the data.

The international medium-term comovement pattern that we identify is suggestive of an important role for persistent US shocks in generating medium term fluctuations across the advanced world. We observe that, at the medium frequency, US R&D spending and patents lead and strongly correlate with the output and investment cycles of Europe. Furthermore, we document strong medium frequency comovements between, on the one hand, the volume of bilateral exports and the number of intermediate varieties exported from the US and, on the other, the output and investment cycles of its main European trading partners. The medium frequency fluctuations in US bilateral trade variables display a small lead over Europe's medium term cycle, which suggests that, once exported, these technologies diffuse rapidly in advanced economies. Importantly, we observe that medium-sized and, especially, large manufacturing firms in the US drive the medium term cycle of US bilateral exports, placing them at the forefront of international technology diffusion. Taken together, this evidence suggests that larger US firms, by diffusing embodied technology through trade in manufacturing intermediates, may determine Europe's output at relatively low frequencies. Previous work has not considered the US firm size distribution as an explanatory force behind medium term comovement. These stylized features reinforce the importance to explore the role of firm heterogeneity, and the channels that it introduces, in the international transmission of shocks via traded intermediates in the capital goods sector, a key driver of embodied growth.

To account for the patterns that we identify in the data, we propose a two-country, asymmetric macroeconomic model in which endogenous growth is driven by embodied technical change in new intermediate varieties for the capital goods sector (e.g., Romer,

[1] We document these features in a sample of European economies, namely France, Germany, Italy, Spain, Sweden and the UK, and in Japan.

1990, Comin and Gertler, 2006, Comin *et al.*, 2014), there is cross-country firm heterogeneity in the production of such intermediates (e.g., Melitz, 2003, Ghironi and Melitz, 2005, Liao and Santacreu, 2015) and trade in varieties (e.g., Comin *et al.*, 2014, Santacreu, 2015). Newly developed intermediates in the capital goods sector are the result of innovation and adoption investments that both countries may undertake. Disembodied technical change in the production of final output is the second source of growth that, for simplicity, is assumed exogenous.[2]

We introduce firm heterogeneity in the production of specialized intermediates adopting the framework pioneered in Melitz (2003), where firms differ in their productivity level and use labor in production. Productivity cut-offs, derived from zero profit conditions, respond to demand (negatively) and costs (positively) variables. Our model adapts Melitz's (2003) framework by abstracting from entry considerations,[3] thus, productivity cut-offs select firms into producing either for the domestic market or for both the domestic and the exporting markets. In turn, the domestic and the exporting productivity cut-offs determine the frequency, or probability, of exporting: holding the other constant, the former increases it while the latter reduces it. The number of varieties produced domestically together with the probability of exporting determine the number of traded intermediates. In a model of endogenous growth in varieties such as ours, productivity cut-offs exhibit long-term dynamics associated to the steady-state growth rate of the economy and short- to medium-term dynamics of adjustment after exogenous disturbances. These are new, desirable features that other macroeconomic models with heterogeneous firms and trade in varieties have not considered yet (e.g., Ghironi and Melitz, 2005, Liao and Santacreu, 2015). As a result, heterogeneity provides a microfoundation for the time-varying speed of international technology diffusion -measured by the inverse of the probability of exporting- that is based on the determinants of firm productivity in the intermediate goods sector. In addition, the use of labor in the production of intermediate varieties introduces the real wage in the cost structure of heterogeneous firms, allowing for a direct and an indirect channel -the latter via productivity cut-offs- through which the real wage affects macroeconomic aggregates and international comovement, as in Ghironi and Melitz (2005) and Liao and Santacreu (2015).

We calibrate the model for two advanced economies, where the US features as the leader, and we examine their macroeconomic response to embodied and disembodied

[2]The setups in Melitz (2003) and Ghironi and Melitz (2005) generate countercyclical productivity proxied by TFP. In our case, it is important to stress that the focus is on the transmission of embodied technical change via trade in varieties of intermediate capital goods while assuming exogenous TFP.

[3]Albeit possibly relevant, we do not explore the propagation mechanisms from entry and exit. Using data covering the universe of French firm-level value added and destination-specific exports and imports, Di Giovanni et al. (2018) show that an overwhelming majority (about 90%) of the aggregate business cycle comovement between France and its main trading partners is accounted for by the intensive margin (that is, by the contribution of firms that exist in both t and t-1) while the extensive margin (that is, the contribution of firms that enter and exit) is much less relevant. These authors also emphasize the importance of heterogeneity among firms in trade to fully understand the impact of the transmission of shocks for aggregate comovement. Following this literature, we focus on our cross-country transmission mechanism when firms are heterogeneous, but currently abstracting from the dynamics of entry and exit.

technological disturbances, often considered the main drivers of short-term fluctuations (e.g., Greenwood *et al.*, 1988, Backus *et al.*, 1992, King and Rebelo, 2000, Greenwood *et al.*, 2000, Fisher, 2006, Comin and Gertler, 2006). Our benchmark calibration implies that 59% of growth in output per working age person in steady state is explained by embodied technical change and 41% by disembodied technical change, which is consistent with the quantitative evidence from steady state US growth decompositions (Greenwood *et al.*, 1997, Cummins and Violante, 2002, Santacreu, 2015). Finally, we provide a quantitative evaluation of the model.

Our microeconomic structure with heterogeneous firms à la Melitz has important implications for medium-term adjustment. We show how the productivity cut-offs vary noticeably across the ten year horizon, countries and shocks. Briefly, consider a negative TFP shock in the US. As the US real wage falls, the number of US varieties exported initially rises since some intermediate manufacturers, facing a domestic recession, become exporters. In other words, the productivity cut-offs behave procyclically, but more so the exporting one, and the probability of exporting and the number of exported varieties by US firms increase.[4] This adjustment turns out to be critical for the follower country. Newly imported varieties from the leader produce efficiency gains in the production of investment in the follower, which staves off the recession in the intermediate goods sector and redirects resources to domestic adoption. The latter, however, makes the recession in the follower economy very pronounced and persistent: the follower reduces investment on innovation substantially, prompting a large fall in the number of new domestic varieties that are, after all, the engine of recovery and growth. Critically, if our model economy did not feature intermediate firms with heterogeneous productivity -i.e. the number of exported varieties would simply amount to a (constant) proportion of the number of domestically produced ones-, the number of US varieties exported in the aftermath of a TFP shock would fall. As a result, the follower country would neither stave off the crisis on impact nor increase adoption spending to the detriment of innovation spending, thus diluting the leading role of country H. In other words, absent heterogeneity the follower's adjustment would resemble the leader's in terms of timing and persistence. However, we show that our model economy with firm heterogeneity reproduces the stylized facts well. In summary, over time, the US recession turns into a protracted foreign downturn, caused mostly by the long-lasting effects of lower embodied technology in the production of intermediates for the capital goods sector. All in all, the model predicts that trade, in quantities and varieties, stays below trend over a significantly long horizon.

On the other hand, the model predicts that a negative investment-specific shock can impart a very prolonged recession in the US since the productivity cut-offs may fall below trend beyond the ten year horizon. On this occasion, the domestic productivity slowdown is highly protracted due to the gradual adjustments of both the relative price of capital

[4] From an entirely domestic perspective, Kehrig (2015) also finds, at business cycle frequencies, a procyclical size distribution of US firms after an aggregate shock.

(persistently above baseline) and, especially, the real wage (persistently below baseline). While the former supports investment activity in real terms, the latter keeps exerting a downward pressure on costs, both allowing low productivity firms in manufacturing. This is suggestive of a protracted procyclical shift in the US firm productivity distribution occurring after a shock that directly impacts the investment sector, which may provide an additional explanation to the sustained productivity slowdown recorded in the US during the recent financial crisis (Reifschneider *et al.*, 2015, Anzoategui *et al.*, 2017).

We simulate the model economy taking into account both embodied and disembodied technological shocks. We find that our framework outperforms standard international business cycle models in reproducing data-like cross-country correlations in most macroeconomic aggregates. In contrast with previous work, the introduction of firm heterogeneity allows us to account for the role of the size distribution of intermediate manufacturing producers in the transmission of technology cycles over the medium term. In the simulations, we find that large firms in the US strongly contribute to the dynamics of the follower's GDP and investment via trade. These findings are consistent with our empirical evidence that ascribes a leading role to the US in international medium-term comovement, with the size of medium and, especially, large US manufacturing firms correlating more strongly with the foreign cycle. At the same time, the model is consistent with recent evidence on the role of R&D in the transmission of shocks, not only domestically (Anzoategui *et al.*, 2017) but internationally as well.

The paper contributes to four strands of research. First, the recent microeconomic evidence shows that large firms directly linked to foreign countries, especially through trade, account for a very significant share of the measured aggregate international business cycle comovement, even after controlling for common shocks (e.g., di Giovanni *et al.*, 2018). Our analysis finds that the behavior of large firms is also key for aggregate fluctuations and the international transmission of shocks at lower frequencies. Second, the stylized features that characterize the international transmission of high-frequency shocks are well documented in the literature and have been extensively addressed in quantitative macroeconomic models (e.g., Backus *et al.*, 1992, 1995, Baxter and Crucini, 1995, Ambler *et al.*, 2004). In comparison, the study of international comovement when supply-side factors endogenously generate persistent output fluctuations is relatively new (e.g., Ghironi and Melitz, 2005, Comin *et al.*, 2014). Third, Greenwood *et al.* (2000) show that, in addition to the more traditional Hicks-neutral technological disturbances, investment-specific technology shocks may be a relevant source of short-run fluctuations. And Fisher (2006) finds that technology disturbances, especially investment-specific ones, are quantitatively important in generating business cycles. Here, we account for their combined relevance to medium frequency dynamics. Finally, the paper addresses the emerging literature on medium term business cycles (e.g., Comin and Gertler, 2006, Schwark, 2014, Comin *et al.*, 2014, Anzoategui *et al.*, 2017).

The rest of the paper is organized as follows. Section 2 briefly describes the macroeconomic data decomposition and explores the main features of the medium term business cycle in our sample of European economies as well as their international comovement with the US. Section 3 presents the model. Section 4 characterizes the balanced growth path and discusses the baseline calibration. Section 5 simulates the model economy in the event of exogenous disturbances. Section 6 evaluates the model quantitatively. Finally, Section 7 concludes.

2 Features of International Medium Term Comovement in Advanced Economies

We use the band-pass filter to extract the medium term business cycle component of annual macroeconomic time series for the US, France, Germany, Italy and Spain in the period 1950-2014, except noted otherwise.[5] Being a frequency domain detrending method, the band-pass filter is able to isolate components according to a predefined frequency range of oscillation (Christiano and Fitzgerald, 1998). The medium term business cycle includes periodicities below 50 years and is defined by the sum of a high frequency component, which isolates frequencies of oscillation between 2 and 8 years, and a medium frequency component, which isolates frequencies of oscillation between 8 and 50 years. The low frequency component includes periodicities of 50 years and above, hence the identified trend is much smoother than the standard decompositions of economic data would allow for. The mapping of the filtered data into the time domain produces medium term business cycles that last, on average, between thirteen (US) and seventeen (Spain) years (Correa-López and de Blas, 2012).

The series are mostly nonstationary and thus are transformed into growth rates by taking log differences. The band pass filter is applied to the data in growth rates. Then, we cumulate the filtered data and demean the resulting series in order to obtain estimates of each frequency component in centered log levels. The variables of interest are divided into two sets. The first set includes "standard" open economy business cycle aggregates such as output, hours, labor productivity, consumption, investment, exports and imports. The second set encompasses "other" variables and intends to capture the medium term oscillations that characterize measures of technology, international relative prices and bilateral trade linkages. Among the latter, the relative price of capital is defined as the investment deflator over the GDP deflator and captures embodied technical change in that its decline reflects positive technological progress (Comin and Gertler, 2006). In addition, patent applications are used as an alternative to R&D spending as they may reflect more accurately the potential pool of available technologies, regardless of whether

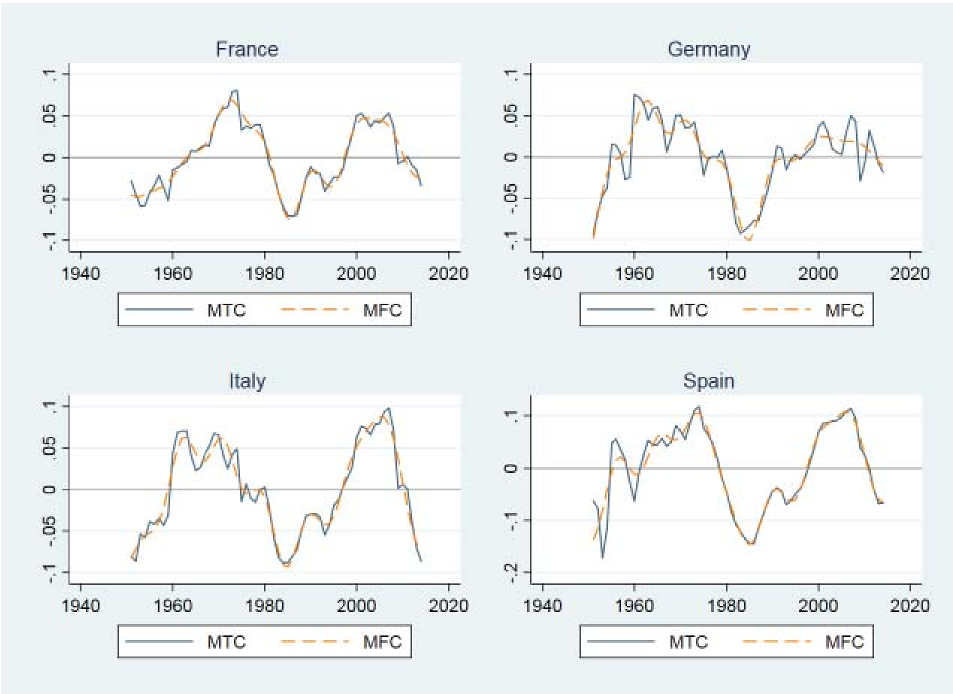
[5]The series are expressed in per working age population (ages 15-64). An extended sample that includes Japan, Sweden and the UK shares qualitatively similar stylized facts, especially for the last two countries. For the interest of brevity, these estimates are available from the authors upon request.

they are home-grown or foreign. A detailed discussion of data definitions, sources and construction is found in Appendix A1.

Figure 1 depicts the medium term cycle of output per capita in our sample of European countries, where the vertical axis measures the percent deviation, in unitary terms, of output per capita from trend. The figure also represents the medium frequency component, hence the standard measure of the business cycle is given by the vertical difference between the medium term cycle and its medium frequency component.

As in the US case (Comin and Gertler, 2006), the medium term cycle captures prolonged swings in economic activity in postwar Europe. After the sustained recovery and expansion of the 1950s and 1960s, Europe is hit by a pronounced recession that bottoms out in the first half of the 1980s. Thereafter, we observe, for the most part, a sustained

Figure 1: Medium term cycle (MTC) and medium frequency component (MFC) of GDP



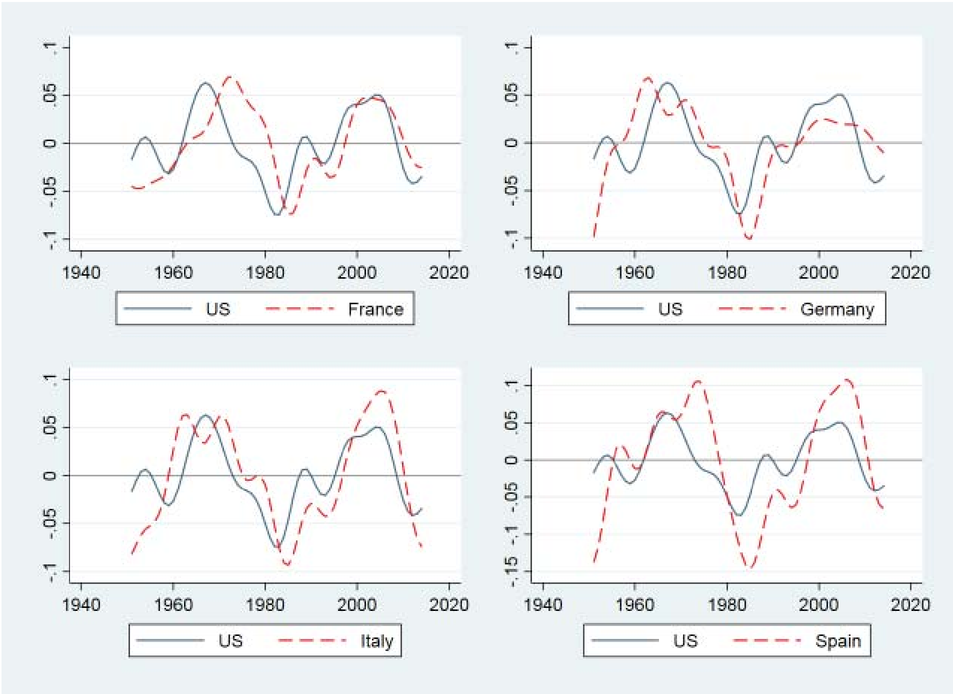
upward movement in output relative to trend that peaks sometime in the second half of the 2000s as the 2008 Financial Crisis finally ensues. As noted in Figure 1, these prolonged movements in economic activity reflect medium frequency variation in the data that is much larger than the high frequency one.[6]

Summary statistics of the medium-term cycle and its high frequency component for each country are reported in Tables A2.1 to A2.3 of Appendix A2. The data are consistent with the analysis of the US in Comin and Gertler (2006). The evidence in Table A2.1 confirms that, within each country, the medium term cycle is more volatile than the high frequency one in our sample of advanced economies. Italy and Spain tend to exhibit the

[6]A similar conclusion follows from the decomposition of consumption, investment, exports and imports.

highest volatility in standard macroeconomic aggregates, while the medium term cycles of output, investment and exports display the lowest volatility in the US. Exports and imports are highly volatile as in Ravn (1997), but still more so at the medium term cycle. Likewise, there is substantially greater variation in "other" variables at the medium frequency if compared to the volatility observed at the high frequency. Furthermore, the medium term fluctuations are very persistent. For the most part, the first-order autocorrelation coefficients reported in Table A2.2 are above 0.8 while the US tends to exhibit the lowest persistence in the medium term cycles of output, investment and exports. In

Figure 2: MFC of GDP per working age population

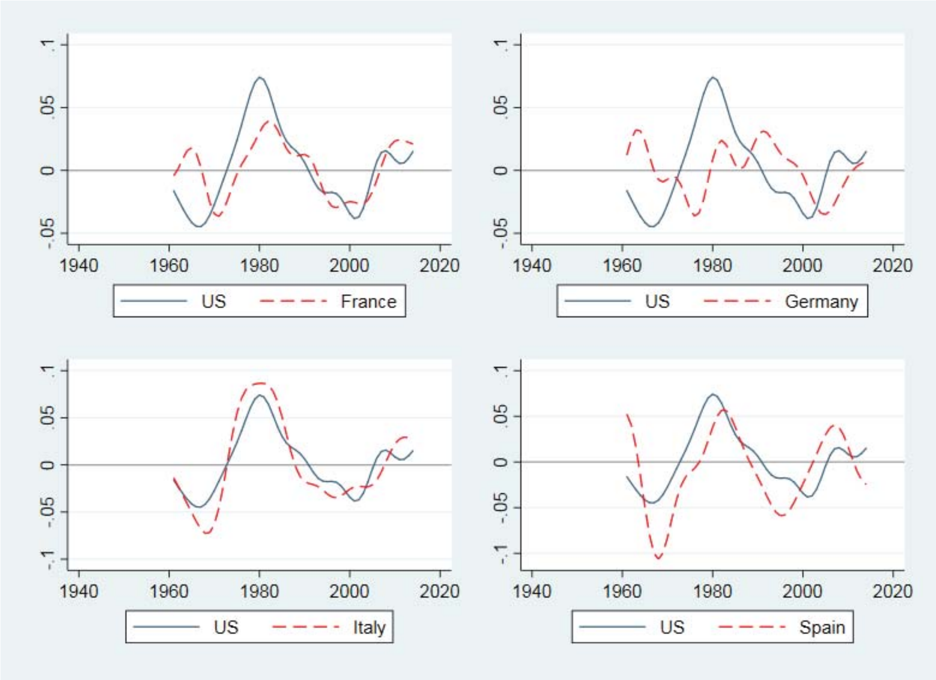


contrast, the first-order autocorrelation coefficient in the high frequency component of the data is not statistically different from zero in most instances.

Table A2.3 reports within-country contemporaneous correlations with GDP. For all countries, the comovement with output is stronger in the medium term for most standard macroeconomic aggregates, again confirming the results in Comin and Gertler (2006). It is worth highlighting that exports are less procyclical than imports, as reported in Ravn (1997), what would imply the countercyclicality of net exports. This difference appears stronger in the medium term for Germany and Spain.

Regarding the "other" set of variables, Table A2.3 shows that, for the US, the relative price of capital is countercyclical, TFP is procyclical and so are R&D and patents, as in Comin and Gertler (2006). For European countries, we can observe a more heterogeneous pattern over the medium term cycle. This may not be surprising, especially if we consider that lead and lag structures become key in understanding the cyclical behavior of

Figure 3: MFC of the relative price of capital



follower economies. This is, for example, the case of R&D data.[7] As for the latter, patent applications display a more procyclical behavior than what is evidenced from R&D. On the other hand, the procyclicality of TFP is present in all European countries as well as the countercyclicality of the relative price of capital, albeit the latter appears on occasion not significant.

Figures 2 and 3 plot, respectively, the medium frequency component of output and the relative price of capital for each European country vis-*à*-vis the US. A visual inspection of the figures suggests that US output and embodied productivity lead and strongly correlate with, respectively, European output and embodied productivity at the medium frequency. A similar conclusion can be reached by visual examination of Figure A2.1 in Appendix A2, where US investment appears to lead European investment over the medium term.

Table 1 explores further these comovement patterns by presenting the cross-country correlations of certain pairs of variables at different lags. All in all, the results are in line with standard international business cycle facts (see, e.g., Backus *et al.*, 1992, Kose and Yi, 2006, among many others). Output is more strongly correlated across countries than investment (Ambler *et al.*, 2004). In particular, we observe a strong and statistically significant positive correlation between the medium frequency component of US output and that of its European counterparts. Furthermore, the US cycle appears to lead the European one by an average of two years, although there is some heterogeneity across European economies. A similar conclusion holds for the case of investment. These figures

[7]With regard to these "other" variables, there is a wide ongoing literature looking into their cyclicality at the high frequency, see, e.g., Wälde and Woitek (2004) and Ouyang (2011) for R&D and Beaudry *et al.* (2015) for the relative price of capital, among others.

are higher than the ones reported by Oviedo and Singh (2013) for a similar set of countries at the high frequency. Notably, a positive medium term cycle of embodied productivity in the US appears to lead a European one, less strongly so in the case of Germany.

Table 1: International comovement in the medium term

	GDP per working age population			
GDP US	France	Germany	Italy	Spain
Lag 0	0.5000*	0.5974*	0.7126*	0.6569*
Lag 1	0.6424*	0.6685*	0.7773*	0.7862*
Lag 2	0.7452*	0.6950*	0.7931*	0.8629*
Lag 3	0.7956*	0.6726*	0.7574*	0.8736*
	Investment per working age population			
Investment US	France	Germany	Italy	Spain
Lag 0	0.3121*	0.3504*	0.3056*	0.5095*
Lag 1	0.5001*	0.4131*	0.4661*	0.6709*
Lag 2	0.6558*	0.4497*	0.5965*	0.7674*
Lag 3	0.7529*	0.4433*	0.6799*	0.7926*
	Relative price of capital			
RPK US	France	Germany	Italy	Spain
Lag 0	0.6583*	-0.0888	0.9405*	0.6459*
Lag 1	0.7439*	0.0944	0.9251*	0.7027*
Lag 2	0.7953*	0.2670*	0.8736*	0.7066*
Lag 3	0.8047*	0.4195*	0.7848*	0.6544*

Notes: Correlation coefficients in the medium frequency component, * denotes significance at the 1 percent level as determined using robust standard errors. The RPK is the investment deflator over the GDP deflator. Period 1951-2014 except for the RPK that starts in 1960.

These summary statistics capture an international medium-term comovement pattern strongly suggestive of a prominent role for persistent US shocks in generating medium term fluctuations in Europe. Even though these economies may be hit by domestic high frequency shocks capable of triggering endogenous persistence mechanisms in technology variables, the evidence indicates that medium term fluctuations originated in the US transmit to highly developed economies.

Tables 2 to 5 question the data to find out what, how and who may matter in driving the observed international comovement over the medium term. The mechanisms that generate comovement may work through the extensive margin of (durable) manufacturing exports embodying new technologies that are incorporated into the importer's production chain (Comin *et al.*, 2014, Liao and Santacreu, 2015). For the US-European country pairs, we find that international technology diffusion via trade matters in explaining the medium term patterns observed in the data. Furthermore, US firms of larger size appear to be behind the transmission of persistent US shocks.

Table 2: US R&D spending and the European MTC

	GDP per working age population			
R&D US	France	Germany	Italy	Spain
Lag 0	-0.2296*	0.3605*	0.3046*	0.0692
Lag 1	-0.0930	0.4691*	0.4210*	0.1708*
Lag 2	0.0492	0.5768*	0.5129*	0.2797*
Lag 3	0.1824*	0.6642*	0.5688*	0.3889*
Lag 4	0.3109*	0.7193*	0.5955*	0.5031*
Lag 5	0.4290*	0.7382*	0.5975*	0.6100*
	Investment per working age population			
R&D US	France	Germany	Italy	Spain
Lag 0	0.0405	0.5146*	0.0541	-0.0548
Lag 1	0.1986*	0.5726*	0.1605*	0.1135*
Lag 2	0.3483*	0.6288*	0.2604*	0.2751*
Lag 3	0.4797*	0.6749*	0.3261*	0.4114*
Lag 4	0.5923*	0.6998*	0.3624*	0.5424*
Lag 5	0.6808*	0.6959*	0.3720*	0.6578*
	Relative price of capital			
R&D US	France	Germany	Italy	Spain
Lag 0	-0.1287*	0.3743*	-0.7085*	-0.1875*
Lag 1	-0.2307*	0.3014*	-0.7908*	-0.2870*
Lag 2	-0.3284*	0.2249*	-0.8425*	-0.3694*
Lag 3	-0.4068*	0.1497*	-0.8661*	-0.4501*
Lag 4	-0.4683*	0.06280	-0.8616*	-0.5287*
Lag 5	-0.5068*	-0.0439	-0.8210*	-0.6042*

Notes: See the notes to Table 1. R&D is the business enterprise R&D expenditure starting in 1953.

More particularly, Table 2 presents evidence on the importance of newly developed US technologies that may end up diffusing internationally. This idea of innovations being transmitted across countries and affecting their productivities is also present in Eaton and Kortum (2001). The authors analyze rich and poor countries, and find that the benefits of R&D undertaken by a few are enjoyed by many others via trade. For the most part, Table 2 shows that there is a strong and significant correlation between, on the one hand, US R&D spending and, on the other, output, investment and the relative price of capital of European countries. A similar conclusion is reached when the pool of US technologies is proxied by the number of patents, as reported in Table A2.4 of Appendix 2. Taken as a whole, the US cycle of technology variables leads the medium term cycles of output, investment and embodied technology in Europe such that, as one might expect, we observe a higher US lead in the R&D spending indicator.

With regard to how transmission may occur, Table 3 shows a strong medium frequency comovement between the volume of bilateral exports from the US and the output, investment and technology cycles of its trading partners. In all cases, there is a strong cor-

Table 3: Bilateral trade linkages and the European MTC

	GDP per working age population			
Bilateral exports US	France	Germany	Italy	Spain
Lag 0	0.6509*	0.7485*	0.7825*	0.7994*
Lag 1	0.7058*	0.7670*	0.7938*	0.7640*
Lag 2	0.7079*	0.7521*	0.7643*	0.6943*
Lag 3	0.6798*	0.7136*	0.7066*	0.6091*
	Investment per working age population			
Bilateral exports US	France	Germany	Italy	Spain
Lag 0	0.6150*	0.7905*	0.4726*	0.7965*
Lag 1	0.6222*	0.7340*	0.4917*	0.7770*
Lag 2	0.5733*	0.6283*	0.4702*	0.7184*
Lag 3	0.5001*	0.5012*	0.4287*	0.6504*
	Relative price of capital			
Bilateral exports US	France	Germany	Italy	Spain
Lag 0	-0.6575*	-0.1974*	-0.7331*	-0.5444*
Lag 1	-0.6416*	-0.2554*	-0.6604*	-0.4967*
Lag 2	-0.6218*	-0.3134*	-0.5667*	-0.4378*
Lag 3	-0.5838*	-0.3694*	-0.4522*	-0.3617*

Notes: See the notes to Table 1. In the construction of the bilateral exports series primacy is given to the trade flows reported by the importer country (see Feenstra *et al.*, 2005).

relation between bilateral exports and both output and investment (Kose and Yi, 2006). The observation that trade may matter in explaining medium term comovement is further confirmed by the evidence presented in Table 4, where the number of varieties exported from the US is significantly correlated with output, investment and the relative price of capital of each trading partner. Although we cannot rule out its relevance in explaining medium term transmission, we find somewhat weaker evidence coming from bilateral FDI flows/stocks, possibly due to data limitations. Yet, using firm-level data covering the universe of French firms, di Giovanni *et al.* (2018) find that bilateral trade linkages appear to matter more than multinational ones in the transmission of high frequency shocks. Overall, the medium frequency fluctuations in US bilateral trade variables display a small lead over Europe's medium term cycle, which suggests that, once they are in the basket of exports, these technologies diffuse relatively fast in advanced economies.

Our final piece of evidence is concerned with characterizing the economic actors that drive international comovement over the medium term. Firm-level manufacturing productivity is strongly associated with firm size and both variables are highly correlated with export propensity (see the review in Bernard *et al.*, 2012). Furthermore, at conventional business cycle frequencies, firms directly linked to foreign countries -which are systematically larger firms- may account for a very significant share of the observed cross-country aggregate comovement, even after controlling for common shocks (e.g., di Giovanni *et*

Table 4: Number of varieties traded and the European MTC

	GDP per working age population			
US varieties exported	France	Germany	Italy	Spain
Lag 0	0.6035*	0.8419*	0.6189*	0.7242*
Lag 1	0.6189*	0.8255*	0.6193*	0.6564*
Lag 2	0.5461*	0.7416*	0.5604*	0.6091*
Lag 3	0.2579	0.4662*	0.4204*	0.5768*
	Investment per working age population			
US varieties exported	France	Germany	Italy	Spain
Lag 0	0.7107*	0.7696*	0.5598*	0.7092*
Lag 1	0.6903*	0.7647*	0.5631*	0.6167*
Lag 2	0.5966*	0.6778*	0.5023*	0.5463*
Lag 3	0.3474*	0.4244*	0.3626*	0.4983*
	Relative price of capital			
US varieties exported	France	Germany	Italy	Spain
Lag 0	-0.4485*	-0.3533*	-0.7024*	-0.4738*
Lag 1	-0.4055*	-0.3044	-0.6203*	-0.4433*
Lag 2	-0.4018*	-0.3067	-0.5712*	-0.4482*
Lag 3	-0.4052*	-0.2920	-0.5680*	-0.4702*

Notes: See the notes to Table 1. Varieties are measured as the nonfiltered number of SITC rev. 2 categories up to the 5-digit disaggregation in manufacturing (excl. consumption goods) with a traded value greater than $1 mn as reported by the importer. Correlation coefficients are computed from 1980 and their significance is reported at the 5 percent level.

al., 2018). Among advanced economies, the US has one of the largest shares of medium to large corporations (OECD, 2017), which may make their behavior more relevant for international comovement via trade.

Here, we postulate that the size distribution of firms in US manufacturing may affect the transmission of US technology cycles over the medium term. The evidence presented in Table 5 appears to confirm this conjecture, where firms are distributed according to the size category they belong to as determined by their number of employees. In Table 5, we specifically report correlation coefficients between the total number of employees by firm size category in US manufacturing and European aggregates over the medium term cycle. At the medium frequency, fluctuations in size of medium and large firms are significantly more correlated with the European output and investment cycles than fluctuations in size of smaller firms.[8] Furthermore, medium-sized and, especially, large US manufacturing firms drive the medium term cycle of bilateral exports from the US to each European trading partner, in that oscillations in firm size correlate more strongly with US bilateral exports when firms are larger. This observation places them at the forefront of international technology diffusion.

[8]Note that these fluctuations encompass two adjustment margins, namely, the extensive and intensive margins. The former relates to the number of firms and the latter to the number of employees per firm.

Table 5: US manufacturing firm size and the European MTC

	GDP per working age population			
US firm size distribution	France	Germany	Italy	Spain
Micro (1-9)	-0.1523*	0.1157*	0.0867	0.0287
Small (10-49)	0.0128	0.1134*	0.1777*	0.0710
Medium (50-249)	0.1510*	0.2793*	0.3033*	0.2135*
Large ($\geq$ 250)	0.4192*	0.3664*	0.4390*	0.3343*
	Investment per working age population			
US firm size distribution	France	Germany	Italy	Spain
Micro (1-9)	-0.1177*	0.3523*	-0.1060	0.1246*
Small (10-49)	-0.0793	0.3270*	-0.0369	0.1442*
Medium (50-249)	0.0877	0.4664*	0.0962	0.2880*
Large ($\geq$ 250)	0.1990*	0.4822*	0.2121*	0.3160*
	Bilateral exports from the US			
US firm size distribution	France	Germany	Italy	Spain
Micro (1-9)	0.2967*	0.3176*	0.3759*	0.1787*
Small (10-49)	0.4861*	0.4333*	0.5039*	0.2030*
Medium (50-249)	0.5427*	0.5208*	0.5791*	0.3674*
Large ($\geq$ 250)	0.7941*	0.7116*	0.7615*	0.4495*

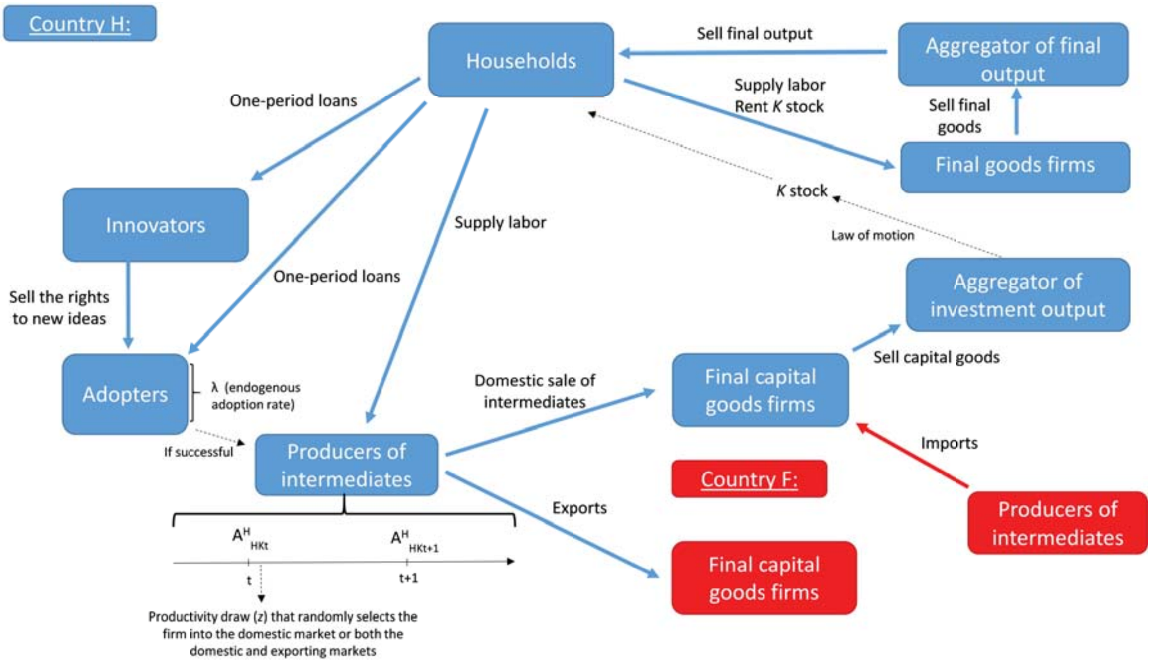
Notes: See the notes to Tables 1 and 3. Size is proxied by the number of employees (e.g. micro firms are those with 1 to 9 employees, and so on) and firm level data starts in 1977. Contemporaneous correlation coefficients, where significance is reported at the 5 percent level.

3 The Model

We explore the observed pattern of international comovement among advanced economies in a two-country model of medium term cycles where the indices $\{H, F\}$ refer to the Home and the Foreign country, respectively. The model is presented in terms of the Home country and the corresponding symmetric specifications would apply to the Foreign one.

The model is a modified real business cycle framework in which endogenous growth is driven by embodied technical change (e.g., Romer, 1990, Comin and Gertler, 2006), firms are heterogeneous in the production of intermediate goods (e.g., Melitz, 2003, Ghironi and Melitz, 2005, Melitz and Redding, 2014) and countries engage in trade of specialized intermediate varieties (e.g., Comin *et al.* 2014, Santacreu, 2015). Newly developed intermediates are the result of investment in innovation and adoption activities. For simplicity, disembodied technical change is assumed exogenous. The set-up of the model is summarized in Figure 4 and described thereafter.

Figure 4: Description of the model



3.1 Households

In country H, there is a representative household that consumes final output, supplies labor and saves. The household has equity claims on all monopolistically competitive firms in the economy. Labor is homogeneous and freely mobile between the production of intermediates and the production of final goods. The household may save either by accumulating new capital stock or by lending. More particularly, it rents capital stock to the producers of final goods in exchange of a rental rate and it lends to innovators and adopters in the form of a one-period risk-free bond. There is no cross-country flow of capital stock and no international borrowing and lending.

Let the household maximize its present discounted utility described in the following problem:

$$\max_{C_{Ht},L_{Ht},K_{Ht+1},B_{Ht+1}} E_t \sum_{i=0}^{\infty} \beta^i \left[\ln C_{Ht+i} - \mu^w_{Ht} \frac{(L_{Ht+i})^{1+\zeta}}{1+\zeta} \right], \tag{1}$$

subject to the budget constraint

$$P_{Ht}C_{Ht} + P_{HKt}(K_{Ht+1} - K_{Ht}) + B_{Ht+1} = W_{Ht}L_{Ht} + \Omega^{tot}_{Ht} + F_{Ht}K_{Ht} + R_{Ht}B_{Ht}, \tag{2}$$

where aggregate labor input is defined as

$$L_{Ht} = L^Y_{Ht} + L^H_{HKt} + L^F_{HKt}. \tag{3}$$

In utility (1), C_{Ht} denotes consumption, L_{Ht} labor, $\beta : 0 < \beta < 1$ is the intertemporal discount factor, μ^w_{Ht} is a shock to the disutility of work and $\zeta : \zeta > 0$ is the inverse of the Frisch elasticity of substitution between labor supply and wages. In the budget constraint

(2), P_{Ht} is the price of final output, P_{HKt} is the price of investment output, B_{Ht+1} are total loans in the form of bonds committed at t and payable to the household at $t+1$, Ω_{Ht}^{tot} denotes the total profits generated in the economy that are dividends to households, F_{Ht} is the rental rate of capital and R_{Ht} is the gross risk-free payoff on the loans. The wage rate W_{Ht} is identical across activities since labor is homogeneously supplied to produce final goods, L_{Ht}^{Y}, and intermediate varieties, both for the domestic market, L_{HKt}^{H}, and the exporting market, L_{HKt}^{F}.

The optimal choice of consumption, labor supply, capital and loans yields the intertemporal Euler equation:

$$E_t \Theta_{Ht,t+1} \left(\frac{F_{Ht+1} + P_{HKt+1}}{P_{HKt}} \right) = 1, \tag{4}$$

and the arbitrage condition between the acquisition of capital stock or the lending to innovators and adopters:

$$E_t \Theta_{Ht,t+1} \left(\frac{F_{Ht+1} + P_{HKt+1}}{P_{HKt}} - R_{Ht+1} \right) = 0, \tag{5}$$

where $\Theta_{Ht,t+1} = \beta(P_{Ht}C_{Ht})/(P_{Ht+1}C_{Ht+1})$ is the intertemporal discount rate. Likewise, the labor supply choice shows that the real wage is a mark-up, μ_{Ht}^{w}, over the household's marginal rate of substitution between consumption and leisure:

$$\frac{W_{Ht}}{P_{Ht}} = \mu_{Ht}^{w} C_{Ht} L_{Ht}^{\zeta}, \tag{6}$$

such that the mark-up shock is assumed to follow a stationary $AR(1)$ process.

The law of motion of capital stock takes the form:

$$K_{Ht+1} = (1 - \delta(U_{Ht}))K_{Ht} + \upsilon_{Ht} Y_{HKt}, \tag{7}$$

where $\delta(U_{Ht}) : 0 < \delta(U_{Ht}) < 1$ is the rate of depreciation of capital which increases in the rate of capital utilization U_{Ht} (Greenwood *et al.*, 1988, Comin and Gertler, 2006). Y_{HKt} denotes investment output and υ_{Ht} is an investment-specific technology shock that affects the efficiency of the economy in turning investment into capital stock, as in Greenwood *et al.* (1997, 2000) and Fisher (2006). We assume that υ_{Ht} follows a stationary $AR(1)$ process.

3.2 Final output

The production of final output, Y_{Ht}, is a CES aggregate of the outputs of $q = 0...N_{Ht}$ symmetric firms, each producing a differentiated final good, such that:

$$Y_{Ht} = \left(\int_0^{N_{Ht}} (Y_{Ht}^{q})^{\frac{1}{\mu_Y}} \, dq \right)^{\mu_Y}, \tag{8}$$

where $\mu_Y : \mu_Y > 1$ is the degree of product differentiation and, under symmetry, the producer's price mark-up over marginal cost. Profit optimization yields the demand for the output of final goods' firm q, as follows:

$$Y_{Ht}^{q} = \left(\frac{P_{Ht}^{q}}{P_{Ht}}\right)^{\frac{\mu_Y}{1-\mu_Y}} Y_{Ht}, \tag{9}$$

and the price level of final output:

$$P_{Ht} = \left(\int_0^{N_{Ht}} (P_{Ht}^{q})^{\frac{1}{1-\mu_Y}} dq\right)^{1-\mu_Y}. \tag{10}$$

The final goods firms have access to the following Cobb-Douglas production function:

$$Y_{Ht}^{q} = \xi_{Ht}(U_{Ht}^{q} K_{Ht}^{q})^{\alpha}(L_{Ht}^{qY})^{1-\alpha}, \tag{11}$$

where U_{Ht}^{q}, K_{Ht}^{q} and L_{Ht}^{qY} denote, respectively, the firm's q capital utilization rate, rented capital and labor input. Parameter α is the capital goods share in the production of final output and ξ_{Ht} is an exogenous trend-stationary TFP shock.

Each of the N_{Ht} differentiated final goods firms solves the following problem:

$$\max_{L_{Ht}^{qY}, K_{Ht}^{q}, U_{Ht}^{q}} \quad P_{Ht}^{q} Y_{Ht}^{q} - W_{Ht} L_{Ht}^{qY} - [F_{Ht} + \delta(U_{Ht}^{q}) P_{HKt}] K_{Ht}^{q} - b_H \Psi_{Ht} \tag{12}$$

subject to (9) and (11). Note that the individual firm incurs in a per-period fixed entry cost to remain productive, $b_H \Psi_{Ht}$, where b_H is a parameter that captures entry barriers in the final goods sector and Ψ_{Ht} represents the time-varying economy-wide operating costs that the firm takes as given (Comin and Gertler, 2006). The first order conditions under symmetry yield, respectively, the labor demand, the capital demand and the utilization rate in the final goods sector:

$$\frac{(1-\alpha)}{\mu_Y} \frac{Y_{Ht}}{L_{Ht}} = \frac{W_{Ht}}{P_{Ht}}, \tag{13}$$

$$\frac{\alpha}{\mu_Y} \frac{P_{Ht} Y_{Ht}}{K_{Ht}} = [F_{Ht} + \delta(U_{Ht}) P_{HKt}], \tag{14}$$

$$\frac{\alpha}{\mu_Y} \frac{P_{Ht} Y_{Ht}}{U_{Ht}} = \delta'(U_{Ht}) P_{HKt} K_{Ht}. \tag{15}$$

Free entry in final goods production determines the number of active firms, N_{Ht}:

$$\frac{(\mu_Y - 1)}{\mu_Y} \frac{P_{Ht} Y_{Ht}}{N_{Ht}} = b_H \Psi_{Ht}, \tag{16}$$

such that firm's profits net of variable costs are exhausted paying the fixed entry cost.

3.3 Investment output

A CES aggregator competitively produces investment output by combining the outputs of $j = 0...N_{HKt}$ symmetric firms, each producing a differentiated final capital good, as described by:

$$Y_{HKt} = \left(\int_0^{N_{HKt}} \left(Y_{HKt}^j \right)^{\frac{1}{\mu_K}} dj \right)^{\mu_K}, \tag{17}$$

where $\mu_K : \mu_K > 1$ is the degree of product differentiation and, in the symmetric solution, the producer's gross mark-up in the final capital goods sector. Profit optimization yields the demand for the output of final capital goods' firm j, given by:

$$Y_{HKt}^j = \left(\frac{P_{HKt}^j}{P_{HKt}} \right)^{\frac{\mu_K}{1-\mu_K}} Y_{HKt}, \tag{18}$$

and the price level of investment output:

$$P_{HKt} = \left(\int_0^{N_{HKt}} \left(P_{HKt}^j \right)^{\frac{1}{1-\mu_K}} dj \right)^{1-\mu_K}. \tag{19}$$

Each of the final capital goods firms bundles up differentiated intermediate goods according to the CES technology:

$$Y_{HKt}^j = \left(\int_0^{A_{HKt}} \left(Q_{HKt}^{j\kappa} \right)^{\frac{1}{\vartheta}} d\kappa \right)^{\vartheta}, \tag{20}$$

where $Q_{HKt}^{j\kappa}$ represents the quantity of an individual intermediate κ used by firm j in production. The number of specialized intermediate goods available in the economy, A_{HKt}, is the sum of the domestically produced and consumed varieties, A_{HKt}^H, and the imported varieties, X_{FKt}^H, with $\vartheta : \vartheta > 1$ being the degree of product differentiation across varieties of intermediates.

In the final capital goods sector, each firm j incurs in a per-period fixed entry cost to remain productive, $b_{HK}\Psi_{Ht}$, where b_{HK} captures entry barriers to activity in the sector. Subject to (18) and (20), profit optimization under symmetry yields the demand for each intermediate good κ from all capital goods firms in country H, as given by:

$$Q_{HKt}^{\kappa} = \left(\frac{P_{HKt}^{\kappa}}{P_{HKt}} \right)^{\frac{\vartheta}{1-\vartheta}} Y_{HKt} N_{HKt}^{\frac{\mu_K - 1}{\vartheta - 1}} \mu_K^{\frac{\vartheta}{1-\vartheta}}, \tag{21}$$

where P_{HKt}^{κ} is the price of the individual intermediate good κ. In (21), note that if κ is a domestically produced intermediate, the quantity demanded and the price charged at Home would be represented by $\left\{ Q_{HKt}^{\kappa,H}, P_{HKt}^{\kappa,H} \right\}$, respectively, while if κ is produced abroad, the quantity demanded and the price charged at Home would be represented by

$\left\{Q^{\kappa,H}_{FKt}, \frac{P^{\kappa,H}_{FKt}}{er_t}\right\}$, respectively, where er_t is the nominal exchange rate defined as country F's currency over country H's currency.

Free entry in the production of final capital goods determines the number of active firms, N_{HKt}:

$$\frac{(\mu_K - 1)}{\mu_K}\frac{P_{HKt}Y_{HKt}}{N_{HKt}} = b_{HK}\Psi_{Ht}, \tag{22}$$

such that firm's profits net of variable costs are exhausted paying the fixed entry cost.

3.3.1 Innovation

Innovators in the economy develop new ideas of intermediate goods, or innovations, and sell the rights to convert these ideas into workable intermediates to adopters. To undertake their research, innovators invest units of final output that they borrow from households. Let J_{HKt} be the value of the right to convert an idea into a workable intermediate. This is the price the adopter is willing to pay for an innovation.

At time t, innovator p solves the following problem:

$$\max_{S^p_{HKt}} \varsigma_H E_t \left\{\Theta_{Ht,t+1} J_{HKt+1}\right\} (Z^p_{HKt+1} - \varsigma_H Z^p_{HKt}) - P_{Ht} S^p_{HKt}, \tag{23}$$

subject to

$$Z^p_{HKt+1} = \varphi_{HKt} S^p_{HKt} + \varsigma_H Z^p_{HKt}, \tag{24}$$

where

$$\varphi_{HKt} = \frac{x_H T_{HKt}}{S^{1-\rho}_{HKt} R \Psi^{\rho}_{Ht}}. \tag{25}$$

In (23), S^p_{HKt} denotes the units of final output that innovator p invests in research and Z^p_{HKt} is the total stock of innovations of innovator p at the beginning of period t. Parameter $\varsigma_H : 0 < \varsigma_H < 1$ is the survival rate of an innovation or, otherwise, $(1 - \varsigma_H)$ is the obsolescence rate of technologies. Innovator p chooses S^p_{HKt} by maximizing the expected (discounted) profits from selling new innovations to adopters subject to the research technology in (24). The productivity of research activity, φ_{HKt}, depends on aggregate conditions and, as such, is taken as given by innovators.

In (25), parameter $x_H : x_H > 0$ captures the set of policies and institutions conducive to innovative activities and T_{HKt} is the total number of innovations available in the economy, defined as the sum of the aggregate stock of domestic innovations, Z_{HKt}, and the number of imported intermediates, X^H_{FKt}. That is, there are domestic and, through trade in varieties, international spillovers in research (Santacreu, 2015). In the denominator, the factor $S^{1-\rho}_{HKt} R \Psi^{\rho}_{Ht}$ represents a congestion externality (Comin and Gertler, 2006) whereby a higher level of aggregate research spending, S_{HKt}, or a more sophisticated real economy,

$R\Psi_{Ht}$, effectively reduces the productivity of research for the individual innovator.[9] In equilibrium, parameter $\rho : 0 < \rho < 1$ is the elasticity of R&D investment with respect to new technology creation.

Free entry of identical innovators yields the arbitrage condition in research:

$$\varsigma_H E_t \left\{ \Theta_{Ht,t+1} J_{HKt+1} \right\} = \frac{P_{Ht}}{\varphi_{HKt}}, \tag{26}$$

where the discounted marginal revenue from developing a new innovation equals the marginal cost, hence innovators break even.

3.3.2 Adoption

A competitive set of identical adopters converts new ideas of intermediate goods into usable form through an adoption process that is costly and takes time (Comin and Gertler, 2006). To undertake their adoption activity, they purchase innovations and invest units of final output that they borrow from households. After successfully adopting an innovation, the adopter becomes the manufacturer of the intermediate good to be sold to producers of final capital goods.

The value or price of an "unadopted" innovation i to the adopter, J_{HKt}, is expressed as:

$$J_{HKt} \equiv \max_{H^i_{HKt}} -P_{Ht} H^i_{HKt} + \varsigma_H E_t \Theta_{Ht,t+1} [\lambda_{HKt} V^i_{HKt+1} + (1 - \lambda_{HKt}) J_{HKt+1}], \tag{27}$$

such that, in period t, the adopter optimally chooses adoption investment, H^i_{HKt}, by maximizing the expected (discounted) flow of net income from such activity. At t, successful adoption occurs randomly with a probability λ_{HKt} and delivers the future stream of profits from manufacturing the intermediate, V^i_{HKt+1}, while unsuccessful adoption arrives at a random rate $(1 - \lambda_{HKt})$ and delivers the continuation value J_{HKt+1} as "unadopted" innovations may be sold for further adoption attempts and thus retain value. In (27), adoption spending H^i_{HKt} affects directly the cost structure of adoption as well as its stochastic arrival rate.

Define V^i_{HKt} as the present value of profits from manufacturing an intermediate good:

$$V^i_{HKt} = \Pi^i_{HKt} + \varsigma_H E_t \Theta_{Ht,t+1} V^i_{HKt+1}, \tag{28}$$

where Π^i_{HKt} denotes profits realized at time t.

[9] A more sophisticated economy is an economy with higher operating costs, here deflated by the price level of final output, or expressed in real terms, as $R\Psi_{Ht}$. To ensure the existence of a balanced growth path, $R\Psi_{Ht}$ is modeled as a deterministic trend, that is $R\Psi_{Ht} = R\Psi_{H0}(1 + g_{Y_H})^t$, where g_{Y_H} is the growth rate of the economy, as in Comin *et al.* (2014).

The adoption rate, λ_{HKt}, increases in the amount of adoption spending committed to by the adopter per individual "unadopted" innovation i, such that:

$$\lambda_{HKt} = \alpha_H^A \frac{A_{HKt}^H}{Z_{HKt}} \left(\frac{H_{HKt}^i}{R\Psi_{Ht}^i} \right)^{\gamma_A}, \tag{29}$$

where parameter $\alpha_H^A : \alpha_H^A > 0$ reflects barriers to domestic adoption in that a higher value of the parameter captures lower adoption barriers. In (29), the aggregate effectiveness of turning innovations into adoptions, (A_{HKt}^H/Z_{HKt}), raises the arrival rate of adoption while the adopter faces a congestion externality per "unadopted" innovation in that the probability of its adoption falls as the economy increases in sophistication. Parameter $\gamma_A : 0 < \gamma_A < 1$ is the elasticity of adoption with respect to adoption investment.

Free entry of identical adopters yields the arbitrage condition in adoption:

$$\gamma_A \frac{\lambda_{HKt}}{H_{HKt}^i} \varsigma_H E_t \Theta_{Ht,t+1} [V_{HKt+1}^i - J_{HKt+1}] = P_{Ht}. \tag{30}$$

such that, at the margin, each adopter invests up until the discounted marginal revenue from adoption equals the marginal cost, hence adopters break even.

Overall, the adoption technology follows the law of motion:

$$A_{HKt+1}^H = \lambda_{HKt} \varsigma_H (Z_{HKt} - A_{HKt}^H) + \varsigma_H A_{HKt}^H, \tag{31}$$

where $(Z_{HKt} - A_{HKt}^H)$ is the stock of "unadopted" innovations available for adoption at the beginning of period t.

The first order conditions in (26) and (30) show that both, innovation and adoption spending are procyclical in so far as the expected (discounted) marginal revenue from either activity increases in a cyclical expansion, and viceversa.

3.3.3 Production of intermediates by heterogeneous firms

Once an idea has been successfully converted into a workable intermediate, the adopter becomes the manufacturer of that intermediate. In producing intermediates, manufacturers are heterogeneous as indexed by the productivity level z_{Ht} (Melitz, 2003, Melitz and Redding, 2014). At the beginning of the period, manufacturers' technologies are drawn independently from a cumulative distribution function, $G_H(z_{Ht})$, which is assumed Pareto with a shape parameter $\phi_H : \phi_H > 1/(\vartheta - 1)$ for $z_{Ht} \geq z_{HDt} > 0$, where z_{HDt} is the domestic productivity cut-off. That is, once successful in adoption, all adopters sell their intermediates to the domestic market. The productivity draw randomly selects the firm into either the domestic market or both the domestic and the exporting markets.[10] We assume that, in manufacturing intermediates, firms use labor and face fixed per-period

[10]To strive for simplicity and reduce the sources of uncertainty in the model, we abstract from the short-run dynamics of firm entry and exit that are present in Melitz (2003) and Melitz and Redding (2014).

overhead costs in the domestic and the exporting markets, $\{f_{HD}, f_{HX}\}$ respectively, and iceberg variable trade costs, τ_H.

The number of varieties that are exported in period t is given by:

$$X^F_{HKt} = \theta_{HK}[1 - G_H(z_{HXt})]A^H_{HKt}, \tag{32}$$

where z_{HXt} is the productivity cut-off that selects the firm into exporting and $[1 - G_H(z_{HXt})]$ is the time-varying version of Melitz's (2003) frequency of exporting when the lower-bound for the support is z_{HDt}. Parameter $\theta_{HK} : 0 \leq \theta_{HK} \leq 1$ captures the set of policies and institutions that are conducive to international trade, e.g. the absence or presence of non-tariff barriers or the strength of economic diplomacy (e.g., Kee *et al.*, 2009). Equation (32) simply states that the number of exported intermediates at t is a fraction of the domestically produced and consumed varieties. In turn, the probability of exporting a variety can be expressed as $\theta_{HK}(z_{HDt}/z_{HXt})^{\phi_H}$. Hence, given the stock of available domestic adoptions, an increase (decrease) in the exporting (domestic) productivity cut-off reduces the probability of exporting, and therefore the number of varieties exported.

The profit optimization problem from manufacturing an intermediate good κ of productivity z_{Ht} for the domestic market H is described as:

$$\max_{P^{\kappa,H}_{HKt}} \Pi^{\kappa,H}_{HKt}(z_{Ht}) = P^{\kappa,H}_{HKt}Q^{\kappa,H}_{HKt} - W_{HKt}L^{\kappa,H}_{HKt}, \tag{33}$$

subject to the production technology

$$Q^{\kappa,H}_{HKt} = z_{Ht}\left(L^{\kappa,H}_{HKt} - \frac{f_{HD}}{\chi_{Ht}}\right), \tag{34}$$

and, from the demand structure in (21), the demand function

$$Q^{\kappa,H}_{HKt} = \left(\frac{P^{\kappa,H}_{HKt}}{P_{HKt}}\right)^{\frac{\vartheta}{1-\vartheta}} Y_{HKt}N_{HKt}^{\frac{\mu_K-1}{\vartheta-1}}\mu_K^{\frac{\vartheta}{1-\vartheta}}, \tag{35}$$

where $W_{HKt} = W_{Ht}$. In (34), the per-period fixed costs are measured in units of labor and χ_{Ht} is an index of technology in the investment good sector relative to the final output sector. The latter reflects that having a relatively more advanced investment good sector shows up in lower production costs, as defined in Appendix A3.

The first order condition of profit optimization yields the price set by the individual manufacturer in market H:

$$P^{\kappa,H}_{HKt} = \vartheta\frac{W_{HKt}}{z_{Ht}}, \tag{36}$$

such that the optimal price is a mark-up ϑ over the marginal cost. A constant mark-up implies that higher intermediate firm's productivity is passed on to final capital goods firms in the form of a lower intermediate good's price (Melitz and Redding, 2014).

The profit optimization problem from manufacturing an intermediate good κ of productivity z_{Ht} for the exporting market F is as follows:

$$\max_{P^{\kappa,F}_{HKt}} \Pi^{\kappa,F}_{HKt}(z_{Ht}) = P^{\kappa,F}_{HKt} Q^{\kappa,F}_{HKt} - W_{HKt} L^{\kappa,F}_{HKt}, \tag{37}$$

subject to the production technology

$$Q^{\kappa,F}_{HKt} = \frac{z_{Ht}}{\tau_H}\left(L^{\kappa,F}_{HKt} - \frac{f_{HX}}{\chi_{Ht}} \right), \tag{38}$$

and, from the country F's demand structure, the demand function

$$Q^{\kappa,F}_{HKt} = \left(\frac{P^{\kappa,F}_{HKt} er_t}{P_{FKt}} \right)^{\frac{\vartheta}{1-\vartheta}} Y_{FKt} N_{FKt}^{\frac{\mu_K - 1}{\vartheta - 1}} \mu_K^{\frac{\vartheta}{1-\vartheta}}, \tag{39}$$

where the parameter $\tau_H : \tau_H > 1$ represents iceberg variable trade costs.

The first order condition of profit optimization yields the export price set by the individual manufacturer:

$$P^{\kappa,F}_{HKt} = \vartheta \frac{W_{HKt}\tau_H}{z_{Ht}}. \tag{40}$$

Productivity thresholds. Firms are monopolistically competitive and earn positive profits every period in which their respective productivity level, z_{Ht}, is greater than the domestic cut-off level, z_{HDt}. Marginal firms, drawing a productivity level of z_{HDt}, would still operate at zero profits. Thus, the domestic productivity cut-off is derived from the zero profit condition:

$$\Pi^{\kappa,H*}_{HKt}(z_{Ht}) = 0 \Rightarrow z_{HDt} = \left(\frac{f_{HD}}{\chi_{Ht} B^H_{HKt}} \right)^{\vartheta - 1} W^{\vartheta}_{HKt}, \tag{41}$$

where $\Pi^{\kappa,H*}_{HKt}$ is the equilibrium level of profits in the domestic market H and B^H_{HKt} is a demand index for domestic investment output as defined in Appendix A3.

Likewise, the productivity threshold that selects firms into exporting is derived from the zero profit condition:

$$\Pi^{\kappa,F*}_{HKt}(z_{Ht}) = 0 \Rightarrow z_{HXt} = \left(\frac{f_{HX}}{\chi_{Ht} B^H_{FKt}} \right)^{\vartheta - 1} W^{\vartheta}_{HKt}\tau_H, \tag{42}$$

where $\Pi^{\kappa,F*}_{HKt}$ is the equilibrium level of profits in the exporting market F and B^H_{FKt} is a demand index for foreign investment output, expressed in Home's currency, as defined in Appendix A3.

Note that all adopters face the same uncertainty on whether they will be able to export or not in a period, hence, on average, the expected profits from manufacturing an intermediate in period t can be written as:

$$\Pi^{\kappa,H}_{HKt}(z_{Ht}) + \theta_{HK} \left(\frac{z_{HDt}}{z_{HXt}} \right)^{\phi_H} \Pi^{\kappa,F}_{HKt}(z_{Ht}), \tag{43}$$

where the term $\theta_{HK}(z_{HDt}/z_{HXt})^{\phi_H}$ is the exporting probability that depends on the time-varying behavior of the productivity cut-offs.

Finally, we define the average productivity levels that summarize the information on the productivity distributions that are relevant to the macroeconomic variables (Melitz, 2003, Ghironi and Melitz, 2005), as:

$$\widetilde{z}_{HDt} = \left[\frac{\phi_H(\vartheta-1)}{\phi_H(\vartheta-1)-1}\right]^{\vartheta-1} z_{HDt}, \tag{44}$$

$$\widetilde{z}_{HXt} = \left[\frac{\phi_H(\vartheta-1)}{\phi_H(\vartheta-1)-1}\right]^{\vartheta-1} z_{HXt}, \tag{45}$$

where the average productivity of domestic producers, (44), and exporters, (45), is a constant factor of the respective productivity thresholds.

3.4 Aggregation and macroeconomic consistency

The underlying assumptions of the model, based on within-country symmetry, CES formulations and Pareto productivity distributions, facilitate aggregation. Macroeconomic aggregates thus depend on the number of varieties, both domestic and imported, and the average productivity of firms in manufacturing intermediates, both domestic and foreign.

As an illustration of how mechanisms work, we analyze the expression for the price level of investment output relative to the price level of final output, or the relative price of capital, given by:

$$RP_{HKt} = \frac{\mu_K}{N_{HKt}^{\mu_K-1}}\left(A_{HKt}^{H}(\vartheta RW_{HKt})^{\frac{1}{1-\vartheta}}\widetilde{z}_{HDt}^{\frac{1}{\vartheta-1}} + X_{FKt}^{H}\left(\frac{\vartheta RW_{FKt}\tau_F}{rer_t}\right)^{\frac{1}{1-\vartheta}}\widetilde{z}_{FXt}^{\frac{1}{\vartheta-1}}\right)^{1-\vartheta}, \tag{46}$$

where $\{RW_{HKt}, RW_{FKt}\}$ represent real wages and rer_t is the real exchange rate defined as $(P_{Ht}er_t/P_{Ft})$. In (46), the relative price of capital varies: (i) negatively with the number of final capital goods firms, (ii) negatively with the number of domestic varieties and imported varieties used in the production of final capital goods, (iii) negatively with the average productivity of domestic producers and foreign exporters of intermediates, and (iv) with the cost structure in each country, as summarized by the real wage (positively) and the real exchange rate (negatively). However, note that, in equilibrium, all these variables display further interdependencies among them.

In a model economy as the one depicted in Figure 4, the value of output produced in country H equals the sum of final output, investment output and net exports:

$$GO_{Ht} \equiv P_{Ht}Y_{Ht} + P_{HKt}Y_{HKt} + NEX_{HKt}. \tag{47}$$

The uses of output are, in turn, divided between consumption, investment, innovation spending, adoption spending and operating costs:

$$GO_{Ht} \equiv P_{Ht}C_{Ht} + P_{HKt}Y_{HKt} + P_{Ht}S_{HKt} + P_{Ht}H_{HKt} + N_{Ht}b_H\Psi_{Ht} + N_{HKt}b_{HK}\Psi_{Ht}. \quad (48)$$

Since there is financial autarky, trade is balanced every period, hence, the resource constraint is written as:

$$P_{Ht}Y_{Ht} = P_{Ht}C_{Ht} + P_{Ht}S_{HKt} + P_{Ht}H_{HKt} + N_{Ht}b_H\Psi_{Ht} + N_{HKt}b_{HK}\Psi_{Ht}. \quad (49)$$

3.5 Symmetric equilibrium

A complete system of equations determines the symmetric equilibrium in which all firms within a country behave symmetrically. Countries, however, are asymmetric as characterized by the parameter set $\{b_H, b_{HK}, \varsigma_H, x_H, \alpha_H^A, \phi_H, \theta_{HK}, f_{HD}, f_{HX}, \tau_H\}$ in country H, and likewise in country F. In the system, the endogenous state variables are the capital stock, K_{Ht}, the stock of innovations, Z_{HKt}, and the stock of domestic adoptions, A_{HKt}^H. In a general symmetric equilibrium, the state variables satisfy the laws of motion, the endogenous variables solve the households' and the firms' optimization problems, prices and wages are such that all markets clear, and the resource constraint and aggregate production are satisfied. The system of equations that describes the symmetric equilibrium in the Home country figures in Appendix A3.

4 The balanced growth path and the calibration

4.1 Balanced growth

International technology diffusion through trade guarantees that countries grow at the same rate along the balanced growth path. However, countries differ in their income per capita levels due to asymmetries in the parameter space. In steady state, the endogenous variables grow at a constant rate, such that:

$$g_{Z_{HK}} = g_{A_{HK}} = g_{A_{HK}^H} = g_{X_{FK}^H} = g_{T_{HK}} = g_{\chi_H}; \quad (50)$$

$$g_{K_H} = g_{Y_{HK}}; \quad (51)$$

$$g_{S_{HK}} = g_{H_{HK}} = g_{R\Psi_H} = g_{RW_H} = g_{Q_{HKt}} = g_{C_H} = g_{z_{HD}} = g_{z_{HX}} = g_{Y_H}. \quad (52)$$

The growth rate of final output along the balanced growth path depends upon the growth rate of disembodied technology, which is exogenous, and the growth rate of embodied technology, which is endogenous, as described by:

$$g_{Y_H} = \frac{(1 + g_{\xi_H})^{\frac{1}{1-\alpha}}}{(1 + g_{RP_{HK}})^{\frac{\alpha}{1-\alpha}}} - 1, \quad (53)$$

where the growth rate of the relative price of capital varies inversely with the growth rate of new intermediate varieties:

$$g_{RP_{HK}} = \frac{1}{\left(1 + g_{A^H_{HK}}\right)^{\vartheta - 1}} - 1. \tag{54}$$

4.2 Calibration

We present a benchmark calibration. Whenever possible, we inform the conditions at the balanced growth path with empirical regularities in order to back out the unknown parameters. In addition, we borrow parameter values from previous studies, drawing as often as possible from the microeconomic evidence, and we propose estimates for the remaining ones while checking that the within- and cross-country restrictions along the model's balanced growth path always hold. We calibrate country H (leader economy) with data for the US and country F (follower economy) with data for a representative advanced economy that shares features with a sample of European economies.[11] A period in the model is set to a year and data is collected for, as often as possible, the whole post 1950 period. A detailed account of the calibration exercise figures next.

Following the literature (Comin and Gertler, 2006, Comin *et al.*, 2014), we set the discount factor β equal to 0.95, the gross markup for specialized intermediate goods ϑ equal to 1.5 and the share of capital in output equal to 0.33.[12] The latter, together with an estimate (0.07) of the share of US output that accrues to labor in the manufacturing of intermediates, yields a baseline value of parameter α equal to 0.4.[13] By using the balanced growth path conditions and matching the average growth rate of output per working age person (0.0195) and the average growth rate of disembodied technical change (0.0045), we back out the steady state growth rate of the relative price of capital (-0.0176) and the steady state growth rate of new intermediates (0.0361).[14] These benchmark results

[11] Generally, we use information from the four largest EMU countries (Germany, France, Italy and Spain) that, occasionally, is extended to other advanced economies if we consider that their experience might add value.

[12] The literature typically ascribes a high estimate of the markup to the production of intermediate goods that embody new technology (Comin and Gertler, 2006). We find that our results are robust to alternative values around this number.

[13] From 1950 up until 2015, we obtain an average estimate of the manufacturing labor share of 13% while, over the last twenty years or so, the share of compensation of employees that goes to the production of durables amounts to 65% of the US manufacturing total (Bureau of Economic Analysis). In light of these two observations, we cautiously choose a baseline value of 0.07.

[14] Our values conform well with the related literature on postwar US growth. Greenwood *et al.* (1997, 2000) estimate an average annual growth rate of neutral productivity in the range of 0.3-0.4% in a model that explicitly accounts for investment-specific technical change in the accumulation of capital equipment. Their estimate of the average annual rate of decline of the price of quality-adjusted equipment -as measured by Gordon's equipment price index- relative to the price of consumer nondurables and nonhousing services stands at 1.032%. Cummins and Violante (2002) estimate a growth rate of disembodied technical change slightly above 0.5% and an average annual growth rate of decline of the quality-adjusted relative price of equipment and structures of 2.6%. The calibration of the model in Comin *et al.* (2014) delivers an estimate of disembodied productivity growth of 0.7%. On the other hand, the evidence presented in Santacreu (2015) suggests that our calibration of the steady state growth rate of new intermediates falls within the plausible estimates for the leader economy during the postwar period.

imply that 59% of growth in output per working age person in steady state is explained by embodied technical change and 41% by disembodied technical change, which is consistent with the quantitative evidence from steady state growth decompositions that exist in the literature (Greenwood *et al.*, 1997, Cummins and Violante, 2002, Santacreu, 2015).

We choose a value for the Frisch elasticity of labor supply equal to 0.2, that is $\zeta = 5$, which is consistent with the estimates from micro data studies of the US economy, see the discussion in Chetty *et al.*, 2012, and Reichling and Whalen, 2015. We set the steady state gross value added mark-up in the final output sector μ_Y equal to 1.1 (Basu and Fernald, 1997) and the steady state investment to final output ratio to 0.25, which yields, from the households' arbitrage condition, an estimate of the depreciation rate δ of 0.082, in line with the value in Comin and Gertler (2006). We normalize the steady state number of final goods firms in country H to 1 (Comin *et al.*, 2014) and we target a steady state gross value added mark-up in the final capital goods sector μ_K of 1.15 (Basu and Fernald, 1997) to obtain an estimate close to 10% of the total operating costs from entering both final goods markets as a share of gross output in each country (Comin *et al.*, 2014).

We set the overhead, or entry costs, parameters b_H and b_{HK} equal to 0.035 and 0.015, respectively, values that are in line with the ones considered in Comin *et al.* (2014). For the follower country, we use an indicator that conveys information on the administrative burdens on start-ups and on the legal barriers to entry (Product Market Regulation database, OECD) to back out the relative position of Europe with respect to the US in terms of entry barriers. As a result of this exercise, we set the entry costs parameters b_F and b_{FK} equal to 0.044 and 0.019, respectively, suggesting that firm entry is, on average, 26% more burdensome in Europe than in the US.[15]

The parameters calibrated so far let us obtain the steady state number of final capital goods firms (0.83) in country H such that there is a lower number of firms in the sector with the higher mark-up. From the law of motion of capital stock, the condition on sectoral utilization and a steady state utilization rate $\overline{U}$ of 0.8 (US Board of Governors), we obtain an estimate of the elasticity of the change in the depreciation rate with respect to the utilization rate, $(\delta''/\delta')U$, of 0.15 in steady state, which lies within the range of values found in the literature (King and Rebelo, 2000, Baxter and Farr, 2005).

We target an average obsolescence rate of 3% (Comin and Gertler, 2006), accordingly, we set ς_H equal to 0.96 and ς_F equal to 0.98 to reflect that product survival is harder in more innovative countries. The elasticity of adoption with respect to adoption investment γ_A equals 0.9, as in Comin *et al.* (2009). The probability of domestic adoption per unit of time is given by the stochastic rate of adoption in steady state, $\overline{\lambda}_{HK}$, or adoption frequency. Its inverse, $1/\overline{\lambda}_{HK}$, reflects the average time that it takes to adopt an innovation, which we calibrate using the information on technology diffusion lags available in the literature.

[15]Traditionally, the US has scored as one of the advanced economies with the least restrictions to doing business. The evidence presented in Coe *et al.* (2009) suggests that countries where it is relatively easy to engage in business activities benefit more, in terms of productivity performance, from their own R&D effort and from international R&D spillovers.

From Comin and Hobijn (2010), we compute a postwar US average adoption lag for domestic innovations of 7 years, implying a value of $\overline{\lambda}_{HK}$ equal to 0.1429. For the follower country, we assume an adoption lag for postwar innovations of 8.7 years ($\overline{\lambda}_{FK} = 0.1145$), which mimics the average international adoption lag among OECD countries in Comin and Hobijn (2010). These estimates are consistent with the average time to domestic adoption considered in the literature (Mansfield, 1989, Comin and Gertler, 2006) and suggest that the country leader is faster in the adoption of newly discovered domestic innovations. Finally, we combine the balanced growth results obtained so far with data on adoption expenditures to back out an estimate of the barriers to adoption parameter for each country. Given the structure of the model, we assume that innovation expenditures include the funds for basic research and about half of the funds for applied research while adoption expenditures include the funds for development and the remaining funds for applied research.[16] Our estimates of the barriers to adoption, α_H^A and α_F^A, round up to 19.

The elasticity of new innovations with respect to R&D investment ρ is set to 0.65 (Comin *et al.*, 2014), which is consistent with the estimates derived from patent data in Griliches (1990). From the steady state growth of innovations and matching the imports' share of total intermediates in manufacturing (0.15 for country H and 0.27 for country F) [17], we calibrate the parameter that captures how conducive the institutional environment is to innovative activity, x_H and x_F, to 5.3 and 4.6, respectively.

The iceberg transport cost parameter is set at 1.2 for the leader country and 1.4 for the follower country, which lie within the range of values estimated in Santacreu (2015). Fixed exporting costs, f_{HX} and f_{FX}, are assumed equal to 0.14 and 0.33 and, from the balanced growth conditions, we calibrate the fixed overhead costs for domestic production, f_{HD} and f_{FD}, to 0.25 and 0.36, respectively. Hence, our benchmark calibration assumes that country H has a cost advantage in producing and trading intermediates. Combining the information in Bernard *et al.* (2012) for the US and in Eaton *et al.* (2011) for France, we assume that exporters are 11% more productive than nonexporters in country H and 9.3% in country F. From the latter and the balanced growth results and conditions, we back out a value of the shape parameter ϕ_H equal to 3.70 and of ϕ_F equal to 4.57, which fall in line with the values considered in the literature (Ghironi and Melitz, 2005). Note, therefore, that the productivity distribution of country H shows greater dispersion. Finally, we calibrate the parameter that encapsulates the policies and institutions affecting the international trade of varieties and obtain a value of θ_{HK} equal to 0.41 and of θ_{FK} equal to 0.35. With the above information, we can compute the frequency of exporting a domestic intermediate, or exporting probability, for the leader country (28%) and for the

[16]For the US, this breakdown of R&D data is provided by the National Science Foundation. For the follower country, we compute the average of total business R&D spending in a selected group of advanced economies and apply the US weights for each type of fund during the postwar period.

[17]Admittedly, this is a rough approximation based on values rather than number of varieties. The estimate for the US is taken from Eldridge and Harper (2010) and a conservative figure is informed by the World Input Output Table for the European counterpart.

follower country (23%).[18] This baseline calibration implies an average time to exporting an adopted variety of 3.6 years for country H and 4.3 years for country F. Our parameterization is in line with Santacreu's (2015) who estimates that, on average, it takes between 3 and 5 years to start importing an intermediate variety that has been developed elsewhere.

Table 6 provides a summary of the calibration as well as some of the steady state results that further characterize our two country benchmark exercise. Notice that, in terms of quantities, the follower country's dependence on imported intermediates (21.1%) nearly doubles that of the leader economy (11.5%); likewise in terms of varieties, such that the number exported by F is 60% of the number exported by H. Overall, under the assumption that the steady state TFP level at Home is 5% above that of Foreign, we find a cross-country difference in income per working age person of 15% in steady state and an appreciated real exchange rate for the richer economy (Harrod-Balassa-Samuelson effect), while the size of both countries in terms of labor input is practically identical.

Finally, we need to calibrate the parameters regarding shock processes in the model. Table 7 displays the results. We follow a similar approach to Comin and Gertler (2006) in the calibration of disembodied and embodied technology shocks. In particular, we set the

Table 6: Calibration summary

Standard			Innovation and adoption			Trade		
β	0.95						$n=$H	$n=$F
ζ	5		ϑ	1.5		θ_{nK}	0.41	0.35
δ	0.08		ρ	0.65		τ_n	1.2	1.4
U	0.8		γ_A	0.9		f_{nD}	0.25	0.36
$\frac{\delta'' U}{\delta'}$	0.15			$n=$H	$n=$F	f_{nX}	0.14	0.33
α	0.4		ς_n	0.96	0.98	Miscellaneous		
μ_Y	1.1		x_H	5.31	4.56	$\overline{Z}_{HK}/\overline{Z}_{FK}$	1.397	
μ_K	1.15		α_n^A	19.00	18.96	$\overline{N}_H/\overline{N}_F$	1.186	
Market entry			$\overline{\lambda}_{nK}$	0.143	0.114	$\overline{T}_{HK}/\overline{T}_{FK}$	1.239	
	$n=$H	$n=$F	Firm heterogeneity			$\overline{Q}^H_{FK}/\overline{Q}^H_{HK}$	0.115	
b_n	0.035	0.044		$n=$H	$n=$F	$\overline{Q}^F_{HK}/\overline{Q}^F_{FK}$	0.211	
b_{nK}	0.015	0.019	ϕ_n	3.70	4.57	$\overline{X}^H_{FK}/\overline{X}^F_{HK}$	0.611	

autocorrelations of TFP shocks in both countries equal to 0.65 annually, which is close to the values employed by the standard RBC literature at a quarterly frequency. Similarly, the autocorrelations of the embodied technology processes are set equal to 0.64 for both countries. We then calibrate the standard deviations of disembodied technology shocks to match the standard deviations of TFP in the data, for the US and for a representative

[18] These values seem to conform well with evidence from the literature. Comin *et al.* (2014) target a share of intermediate goods exported of 33%, above the estimate of Bernard *et al.* (2007) according to which about 20% of US durable manufacturing plants export. In the same spirit, Eaton *et al.* (2011) reported a figure of 15% of French manufacturers selling outside France.

advanced economy, in the medium term cycle.[19] This is done over 1000 simulations of a 1064-year horizon each, later adjusted to match the sample size in the data.

The process for embodied technological change is calibrated as follows. Given time series for capital depreciation, capital stock and investment, we generate time series for what many authors[20] consider investment-specific technology, Υ_{it} where $i = H, F$, as follows:

$$\Upsilon_{it} Y_{iKt} = K_{it+1} - (1 - \delta(U_{it})) K_{it}, \tag{55}$$

using data for the US and for a representative advanced economy. Once the medium term cycle is obtained from Υ_{Ht} and Υ_{Ft}, we calibrate the standard deviations of υ_{Ht} and υ_{Ft} in the model to match the standard deviations found in the data. The calibration procedure follows the one previously described for TFP shocks.

We set the autocorrelations of the wage markup shocks equal to 0.65 at Home and 0.7 at Foreign, in line with the autocorrelation parameters provided in Galí *et al.* (2007). Regarding the standard deviations, we take the value provided by these authors for the US and, for the Foreign country, we assume a volatility similar to the one reported in the literature for European countries (see Andrés *et al.*, 2009).

Table 7: Shocks description

		Persistence		S.D.	
		n =H	n =F	n =H	n =F
TFP shock	ξ_{nt}	0.65	0.65	0.0219	0.0349
Investment-specific shock	υ_{nt}	0.64	0.64	0.077	0.0749
Wage mark-up shock	μ^w_{nt}	0.65	0.7	0.054	0.091

5 Impulse response functions

The model is first expressed in real terms and then solved using Dynare once the set of equations is log-linearized around the deterministic balanced growth path.[21] We consider three sources of economic fluctuations that may affect country H and country F: a total factor productivity shock, an investment-specific technology shock and a wage markup shock. These shocks have been extensively analyzed in the literature (e.g., Greenwood *et al.*, 1988, Backus *et al.*, 1992, King and Rebelo, 2000, Greenwood *et al.*, 2000, Fisher, 2006, Comin and Gertler, 2006, Comin *et al.*, 2014). Given the structure of our model economy, we focus on the impulse responses to embodied and disembodied technological disturbances, often assumed to be the main drivers of short-run fluctuations. It is worth

[19] The representative advanced economy captures the stylized fact that other countries have a more volatile TFP than the US in the medium term cycle. We also calibrated the volatilities of the TFP processes to the individual European countries analyzed in the stylized facts section, and the results are qualitatively the same.

[20] Among others Greenwood *et al.* (1988), Fisher (2006) and Justiniano *et al.* (2010, 2011).

[21] The system of log-linearized equations is available from the authors upon request.

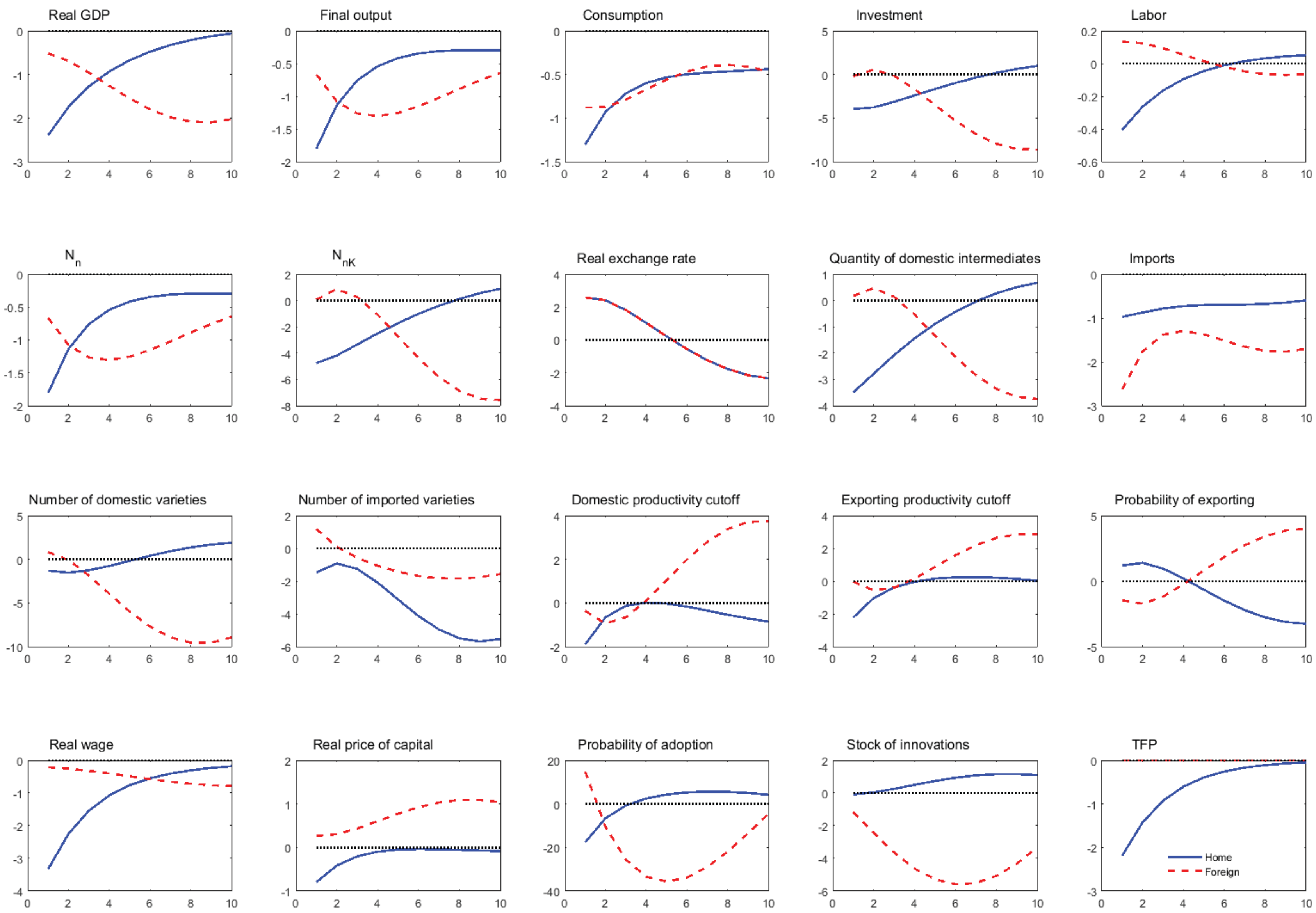
noting that, while the real business cycle literature has emphasized disembodied technical change as the underlying force driving the business cycle, other authors have looked into technology disturbances broadly understood. More particularly, Fisher (2006) argues that technology shocks, especially investment-specific ones, are quantitatively important in generating business cycle fluctuations. Here, we further investigate their relevance for medium frequency adjustment and we leave the analysis of a wage mark-up shock to the robustness section. In the graphs, the solid (blue) line refers to the Home country and the dashed (red) line to the Foreign country. The magnitude of the responses is reported in percentage point deviations from the balanced growth path over a ten year horizon. Finally, recall that the shocks are not correlated across countries, therefore, all the transmission reflects the internal mechanisms at work.

5.1 A negative TFP shock at Home

Figure 5 illustrates the dynamics of the model to a one standard deviation negative shock to TFP at Home at time 1. In country H, the fall in TFP reduces both marginal products of labor and capital. Labor demand and capital utilization decline, leading to a recession at Home that causes an overall fall in employment, the real wage and consumption. The decline in the demand for capital stock drives the reduction in investment output which, in turn, prompts a decline in the demand for intermediate goods that are domestically produced and imported. The fall in profits from producing both final output and investment output induces firms' exit and, hence, a real exchange rate appreciation. Likewise, the stream of profits from manufacturing an intermediate declines, which contracts adoption spending and the probability of adoption, leading to a reduction in the number of intermediate varieties produced domestically. Critically, the number of varieties exported initially rises since some intermediate manufacturers in H, facing a domestic recession, become exporters. Or, in other words, as the real wage falls, there is a procyclical movement in the productivity cut-offs -more so in the exporting one- and an increase in the probability of exporting by Home firms. On the other hand, the recession prompts an initial decline in the price of an innovation followed by a rapid recovery and subsequent expansion since domestic innovators anticipate a medium-term compositional change in the basket of intermediates away from imported varieties and quantities (import switching process), which supports innovation spending.[22] Hence, the TFP shock has an initial contractionary effect on the number of varieties imported by the Home country that becomes very pronounced and persistent over the medium term, as panel 12 in Figure 5 shows.

[22]The literature that separately identifies the mechanisms that induce import switching at the product level is just emerging. Using supermarket scanner-level data, Bems and di Giovanni (2016) find that the income effect, rather than the change in relative prices, drove the expenditure switching from (more expensive, high-quality) imports to (cheaper, low-quality) domestic products observed in Latvia during the 2008–2009 financial and balance of payment crisis.

Figure 5: Impulse response functions to a negative TFP shock in country H



In the case of our two advanced economies, the response of country F to the TFP shock at Home differs from the ten-year hump-shaped response described in Comin *et al.* (2014) for a developing country. In particular, the magnitude of the initial response to the shock is much smaller at Foreign than at Home, while the recession turns deeper and highly persistent in the Foreign country within approximately five years and beyond the ten-year horizon. As panel 1 of Figure 5 shows, the effect of the shock in F's real GDP after ten years is much larger than the initial impact, while the Home country has experienced a complete recovery. Why is country F's recession milder at the beginning? And why does a TFP shock in the leader economy ends up imparting such a prolonged decline in the follower country? It turns out that the adjustment profile and the strength of the effects are shaped by the reaction of heterogeneous intermediate producers in both countries. On impact, country F's exporting market shrinks. The fall in labor demand for export production drives the initial decline in F's real wage, consumption and, hence, the production of final output and the number of final goods firms. Country F's probability of exporting declines -both productivity cut-offs are procyclical but more so the domestic one-, which shows up in a decline in the number and the quantity of varieties exported. The cross-country fall in average firm productivity caused by the shock drives the initial rise in country F's relative price of capital. In addition, imported quantities significantly fall as the real cost of imports rises, except for the newly imported varieties that produce efficiency gains in the production of investment. Hence, aided by the fall in the real wage and, critically, by newly imported varieties, country F's intermediate good sector temporarily staves off the crisis, prompting a reallocation of labor input to support domestic activity. The rise in the stream of profits from manufacturing an intermediate for the domestic market increases adoption spending and the probability of adoption, both on impact. That is, country F responds to the shock by substituting quantity of imports with both domestic production and new adoptions (domestic and imported). Thus, there is an import switching process occurring early on in country F. As a result, investment output increases slightly and firms enter the sector. This is how the investment sector, at first, makes the recession at Foreign milder than at Home.

However, country F initial response to the shock also involves a significant reallocation of scarcer resources away from innovation. The marked decline in innovation spending translates into a gradual but persistent fall in the flow of new domestic innovations and, consequently, domestic varieties. As a result, the relative price of capital rises further over the medium term and investment drops in a protracted manner, inducing exit of final capital goods firms and the contraction of the quantity of intermediate goods, both domestic and imported. The recession becomes very pronounced and persistent. At Home, the decline in the relative price of capital is caused by the downward response of wages to the shock, an effect initially compounded by the real exchange rate appreciation. This cost-driven effect dominates the impact of the initial fall in the number of final capital goods firms, in the number of domestic and imported varieties, and in the average productivity of domestic producers and foreign exporters, which would all tend to increase the relative price of capital.[23] As the TFP shock wears off, the dynamics of the recovery in H are shaped by the flow of newly created domestic innovations that are gradually adopted and incorporated into the production of domestic intermediates. The recovery arrives to country H's investment sector. Noticeably, the exporting probability of F's producers eventually rises, however, this is not sufficient to offset the effect of the fall in the number of domestic varieties caused by the recession, hence country F's quantity and varieties exported decline. Overall, the recession at Foreign becomes more pronounced and persistent than at Home and the TFP shock to the leader economy reduces trade, in quantity and varieties traded, over a protracted period.

Critically, if our model economy did not have intermediate firms with heterogeneous productivity -hence $z_{Ht} = z = 1$ and $X^F_{HKt} = \theta_{HK} A^H_{HKt}$ compared to (32), and likewise for country F-, the number of varieties exported by country H in the aftermath of the shock would fall in line with the decline in the number of intermediate varieties produced domestically. As a result, country F would not stave off the crisis on impact and would not increase adoption spending to the detriment of innovation spending, diluting the leading role of country H. The latter implies that country F would not experience such a persistent fall in domestic varieties, which is the adjustment margin that makes the downturn so pronounced and, especially, protracted. In other words, absent heterogeneity country F's response would resemble country H's, in terms of timing and persistence. As it will be shown in a later section, our model economy with firm heterogeneity reproduces the stylized facts well.

The short- and medium-term dynamics just described have relevant implications for our calibrated leader. In the aftermath of a domestic TFP shock, US innovation would be either acyclical or mildly procyclical while adoption would be strongly procyclical. Thereafter, GDP recovery would be sustained by the recovery and expansion of, first, innovation and, later on, adoption. These observations appear to be supported by the data, as it will be explored further below.

5.2 A negative investment-specific shock at Home

Figure 6 presents the impulse response functions to a one standard deviation negative investment-specific shock in country H. This shock reduces the productivity of investment in the dynamics of capital stock accumulation, thus representing a contractionary embodied technology shock. At Home, capital stock becomes more expensive to buy and

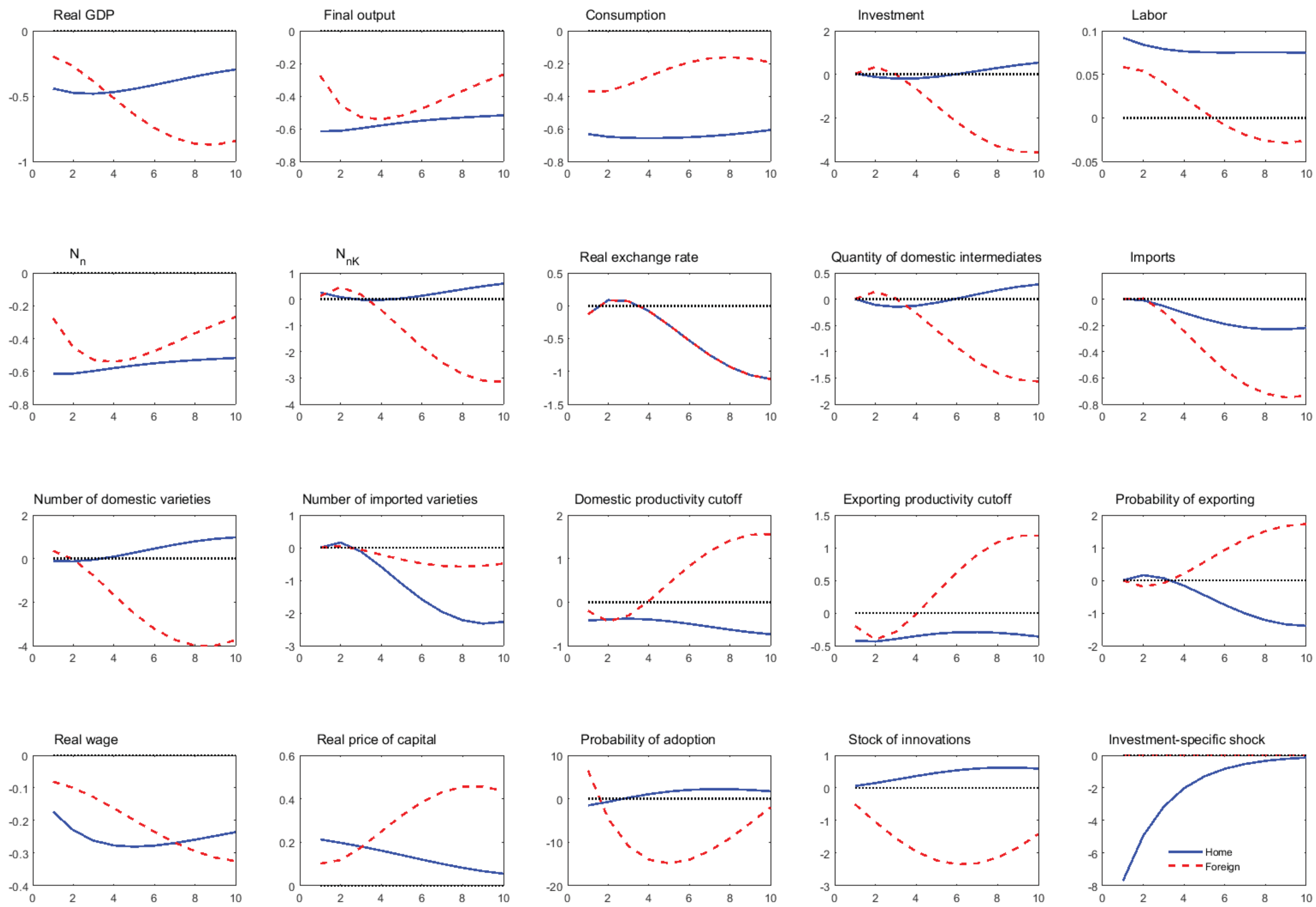
[23]Note that the adjustment of country H's relative price of capital to the TFP shock is different from that in Comin and Gertler (2006) and Comin *et al.* (2014). Unlike our framework, these models do not feature heterogeneity or include labor in the production of intermediate goods, hence they do not account for neither the direct channel through which real wages affect the real price of capital nor the indirect one through the productivity cut-offs. In an extended version of his model with sectoral adjustment costs, Fisher (2006) also finds a positive comovement between a disembodied technology shock and the real price of investment.

to rent and, as a result, the demand for capital stock falls and final output declines leading to a recession where the real wage and consumption decrease. Profits from producing final goods fall and final goods firms exit the market. Households at Home respond by increasing their labor supply, which further reduces the real wage but allows final goods producers to substitute capital stock for labor, hence employment expands slightly. The decline in the demand for capital stock drives the gradual fall in investment output, however, final capital goods firms still enter the sector as the negative effect of lower investment output on profits is more than offset by the increase in the relative price of capital.

The contraction of investment output reduces the demand for intermediate goods at Home, both domestically produced and imported. Profits from manufacturing an intermediate fall and thus the probability of adoption, which leads to an initial decline in the number of varieties produced domestically. Yet, similarly to the TFP shock, the price of an innovation increases during the recession as innovators anticipate that final capital goods firms will substitute imported varieties and quantities for domestic ones (import switching process) over the medium term. The latter drives the increase in innovation spending and the expansion in the stock of innovations that underpins the eventual recovery. Importantly, as in the case of a TFP disturbance, the investment-specific shock reduces the average productivity of intermediate goods manufacturers at Home. However, the productivity slowdown is highly persistent on this occasion due to the gradual adjustments of the relative price of capital and, especially, the real wage, while the former supports investment activity in real terms the latter keeps exerting a downward pressure on costs, both allowing low productivity firms in manufacturing. For the Home country, the investment-specific technology shock imparts a very protracted recession, as real GDP and average firm productivity stay below trend in excess of ten years. In addition, notice that the substitution of capital stock for labor induced by the shock takes a long time to unwind.

On the other hand, panel 1 in Figure 6 shows that the dynamic response of country F to the investment-specific shock in H is very similar to the one featured after a TFP shock. To begin with, the recession at Foreign is milder than at Home but turns more pronounced and persistent within the first five years. The mechanisms behind country F's adjustment to the shock are the same, saving the noticeable decrease in exports, both in quantity and varieties, that occurs later on, since country H's final capital goods producers initially compensate the reduction in domestic varieties with imported ones. The latter further encourages adoption spending in country F, adding to the detriment of innovation spending. Once again, trade decreases significantly beyond the ten year horizon and the short- and medium-term dynamics of adjustment of innovation and adoption are distinctive in both, the country leader and the follower.

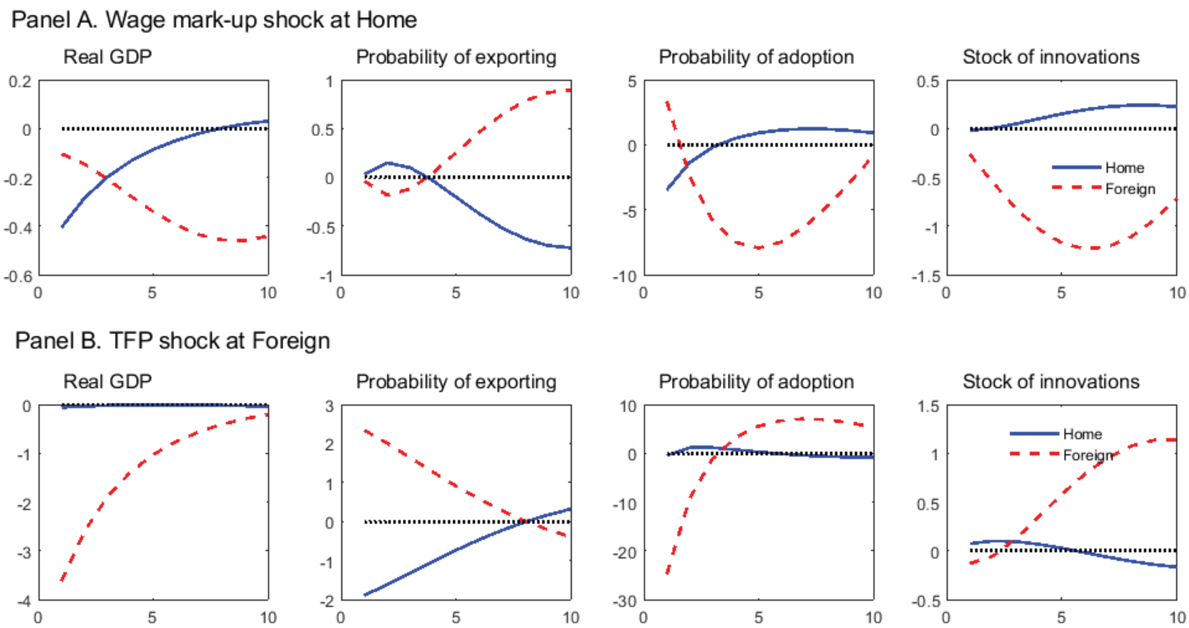
Figure 6: Impulse response functions to a negative investment-specific technology shock in country H



5.3 Robustness to other shocks

Above, we have illustrated that the medium term adjustment of our advanced economies is sensitive to the source of technology shocks at Home. Next, we draw lessons from the introduction of a (positive) wage mark-up shock in country H and a (negative) TFP shock in country F. Panel A of Figure 7 encapsulates the main adjustment features to the wage mark-up shock. Qualitatively, the dynamic response of both economies is very close to the one that was described after a TFP shock at Home. Mainly, a negative wage mark-up shock originating at Home has strong and lasting effects for the Foreign economy. Panel B of Figure 7 shows that a TFP disturbance at Foreign has very limited effects on the macroeconomic aggregates at Home. Both, the lower technological dependence of the leader on the follower and the response of the leader through increased innovation and adoption, largely explain the small effects that the TFP shock imparts on country H. Hence, the recession in F does not induce such protracted negative effects on either trade or real GDP. Still, several features of medium term adjustment are worth mentioning. On

Figure 7: Dynamic response to other shocks



the one hand, Panel B shows that, in country F, the probability of exporting a variety increases as a result of the fall in the real wage while, in country H, this probability decreases as the recession at Foreign reduces the demand for investment output and intermediates. The total quantity imported by country H temporarily falls since the real cost of imports increases at the back of a real depreciation. In addition, country F's initial response to the shock involves a significant reduction of the resources that fund innovation and, most noticeably, adoption activities. As the TFP shock wears off, we first observe a recovery in the price of an innovation and innovation spending, followed by an increase in adoption investment, the probability of adoption and the production of new varieties.

6 Quantitative evaluation

Given the calibration strategy explained above, in this section we assess the ability of the model to replicate the dynamics observed in the data as reported in Section 2. We do so in terms of volatility, persistence, and comovement across variables within and across countries.

Volatility and persistence. Tables 8 and 9 report, respectively, the standard deviations and the autocorrelations of a selection of macroeconomic aggregates at Home and at Foreign, both at the high frequency and in the medium term cycle.

Table 8 shows that the model economy tends to perform better in terms of volatilities along the medium term cycle compared to the high frequency. As expected, the volatilities implied by the model are higher in the medium term. The model reports volatilities of output and investment close to those in the data for both countries. This is so despite the low autocorrelations of shocks imposed in the calibration, hence the model has strong propagation mechanisms for fluctuations across countries. In general, the model performs relatively well along most of the variables. In particular, volatilities in the foreign country are higher than at home, in line with the data. Exports and imports are much more volatile than output. However, the model predicts consumption and labor series which appear too smoothed relative to output, and also in contrast with the data at both frequencies. This may be due to the lack of financial interactions across countries that may distort risk sharing. As in Comin *et al.* (2014)[24], the volatility of the relative price of capital

Table 8: Standard deviations, Home and Foreign countries - unconditional moments

	US (Home country)				Foreign country			
	HFC		MTC		HFC		MTC	
Variable	Data	Model	Data	Model	Data	Model	Data	Model
Output	1.34*	1.55	3.77*	3.24	2.33*	2.49	7.71*	8.02
Labor	1.29*	0.29	3.48*	0.49	0.90*	0.45	7.36*	1.12
Consumption	1.12*	0.88	3.50*	1.68	1.21*	1.58	8.19*	2.64
Investment	3.47*	2.44	8.86*	8.94	2.96*	4.55	18.80*	35.88
Exports	4.09*	2.06	8.25*	6.59	6.26*	2.79	17.15*	5.20
Imports	4.20*	2.79	10.27*	5.20	5.78*	2.06	23.41*	6.59
Relative price of capital	0.57*	0.61	3.91*	0.95	0.97*	0.99	4.35*	3.40
TFP	0.85*	1.47	2.58*	2.31	2.37*	2.42	3.95*	3.86
Patents	3.23*	0.26	6.98*	4.43	5.30*	1.38	25.15*	22.88

Notes: The model statistics are simulated moments of 1000 replicae over 1064 periods each, and then adjusted to keep the same sample length as in the data of Section 2. Data are filtered using the band-pass filter over the medium term (2 to 50 years). Values reported are in percentage terms, * denotes significance at the 1 percent level as determined using robust standard errors. To illustrate, data for the Foreign country correspond to Spain, as reported in the Appendix.

[24]Note that this is the case in spite of the fact that our calibration approach of shocks differs. Comin *et al.* (2014) calibrate standard deviations to match volatilities at the high frequency whereas we follow Comin and Gertler's (2006) procedure of matching volatilities in the medium term cycle.

is underestimated in the model compared to the data. This guarantees that we are not overemphasizing its role in the dynamics or in the response to shocks.

Table 9 confirms that the internal mechanisms at work in our medium term model are substantial, allowing for the propagation and the persistence of shocks. Most of the variables considered propagate over time close to the data. Still, the model falls somewhat short regarding the persistence of variables such as TFP, labor or consumption in the medium term cycle. Regarding persistence at high frequencies, notice that most of the correlations are negative or close to zero. This is consistent with previous research and our numbers lie within most of the confidence intervals of the autocorrelations found in the data, as reported in Table A2.2.

Table 9: Autocorrelations, Home and Foreign countries - unconditional moments

	US (Home country)				Foreign country			
	HFC		MTC		HFC		MTC	
Variable	Data	Model	Data	Model	Data	Model	Data	Model
Output	0.06	-0.2749	0.84*	0.6601	0.23	0.0161	0.90*	0.8359
Labor	0.19	-0.3125	0.85*	0.4806	0.31	0.0171	0.96*	0.7565
Consumption	0.23	-0.1515	0.88*	0.6600	-0.16	-0.0195	0.94*	0.5474
Investment	0.27*	-0.2206	0.84*	0.8452	0.16	0.1662	0.94*	0.9181
Exports	0.12	-0.2641	0.73*	0.8103	0.05	-0.0157	0.78*	0.6130
Imports	0.17	-0.0157	0.82*	0.6130	-0.31*	-0.2641	0.89*	0.8103
Relative price of capital	0.12	-0.3199	0.96*	0.4129	0.30	0.0373	0.92*	0.8554
TFP	0.06	-0.3260	0.87*	0.4007	0.26	0.0093	0.71*	0.5034
Patents	0.22	0.8032	0.80*	0.9370	-0.01	0.8274	0.91*	0.9567

Notes: See the notes to Table 8.

Within- and cross-country comovement. Next, we evaluate whether the model has the ability to generate medium-term comovement patterns that resemble those identified in the data. The results are displayed in Tables 10 through 14. When lags are reported these correspond to the lag for which the correlation is largest in absolute terms.

Table 10 shows that the model generates the strong medium-term GDP comovement observed in the data, with the Home country (US) leading the fluctuations. Furthermore, the model is able to match certain correlations that are hard to replicate using standard international business cycle models (Backus *et al.*, 1992). In particular, we find that the cross-country correlation of consumption is positive and lower than that of output. This is evidence of the strength of the international transmission mechanisms that are present in our model. The model also reproduces successfully the positive cross-country comovements of investment and the relative price of capital. Notice that the international comovement of output, investment and the relative price of capital reaches its highest value over time, after five years, reflecting the leading role of the Home country and the lower-frequency character of the transmission of shocks across countries. These predictions are consistent with the evidence reported in Section 2 for the US versus a set of European economies.

Table 10: Cross-country comovement of main macroeconomic aggregates MTC, $\rho(x_{Ht-k}, x_{Ft})$

Real GDP	0.6790 ($k = 5$)
Consumption	0.2911 ($k = 0$)
Investment	0.6832 ($k = 5$)
Relative price of capital	0.3322 ($k = 5$)
Labor	-0.4569 ($k = 0$)
Labor in the exporting sector	0.9293 ($k = 0$)

Notes: See the notes to Table 8. In the correlations reported, k is number of lags, the first term corresponds to the lagged Home variable and the second to the current period Foreign variable.

Regarding labor, the model generates a negative comovement of employment across countries (-0.4569 at $k = 0$), as it is often the case in standard international business cycle models. This is at odds with the data (Kehoe and Perri, 2002). However, this correlation becomes strong and positive (0.9293 at $k = 0$) when we measure it in terms of labor in the exporting sector, which is precisely the link across countries that is featured in the model.

As for the endogenous productivity mechanism, the model fares well with the stylized facts reported in Comin and Gertler (2006) and it seems to shed further light on the distinctive role of innovation and adoption expenditures for medium-term adjustment. As Table 11 shows, innovation and adoption are procyclical over the medium term, but innovation leads adoption while adoption is more strongly correlated with GDP. The lead-lag correlation structure also suggests that, say, a positive cycle of innovation and adoption spending translates to more varieties adopted and, subsequently, a lower relative price of capital. Using a different measure, Anzoategui *et al.* (2017) also find that the strong procyclicality of adoption spending may have been the critical driver of the US productivity slowdown during and after the Great Recession. Thus, our model is able to account for this mechanism present in the data.

Table 11: Within-country transmission MTC, $\rho(x_{Ht-k}, y_{Ht})$

	Home country
Relative price of capital, real GDP	-0.0914 ($k = 1$)
Innovation expenditure, real GDP	0.4839 ($k = 5$)
Adoption expenditure, real GDP	0.5965 ($k = 4$)
Adopted varieties, relative price of capital	-0.5422 ($k = 3$)

Notes: See the notes to Tables 8 and 10.

Table 12 shows that GDP fluctuations at Home lead Foreign investment positively. This is accompanied by a negative comovement of the relative price of capital at Home, that leads a positive reaction of exports to the Foreign economy, first, in terms of varieties and, then, in total quantity exported. Intuitively, a boom generated at Home leads to a boom in the Foreign country, mainly transmitted via trade and the relative price of capital. This mechanism is consistent with the one in Comin *et al.* (2014) between the US and Mexico, which reinforces the leading character of the Home country. In our model, more trade from Home to Foreign leads the cycle at Foreign. In turn, trade comoves across countries, as noted in the strong positive correlation between exports and imports at Home, what feeds back into the dynamics overtime. In summary, the predictions of the model conform well with the evidence presented in Section 2 with regard to the role of trade in driving the international comovement over the medium term.

Table 12: Cross-country transmission (I) MTC, $\rho(x_{t-k}, y_t)$

Home exports, Home imports	0.7124 ($k = 0$)
Home exports, Foreign real GDP	0.8881 ($k = 0$)
Home exports, Foreign investment	0.8955 ($k = 0$)
Home real GDP, Home exports	0.5712 ($k = 5$)
Home relative price of capital, Home exports	-0.3911 ($k = 5$)
Home relative price of capital, Home varieties exported	-0.3342 ($k = 3$)

Notes: See the notes to Tables 8 and 10.

Given the relevance of trade for international transmission, our model permits the analysis of the role played by intermediate varieties. To this end, Table 13 reports some correlations. We can observe how trade in varieties comoves with an ample set of variables across countries. A boom at Home leads an export cycle in varieties that translates into a boom at Foreign, where investment is higher and the relative price of capital is lower. It is worth noticing that the largest correlation between Home varieties exported and Foreign GDP occurs contemporaneously, which indicates that, once in the basket of exports, technologies diffuse rapidly among advanced economies, as documented in the stylized features. Notice that the transmission to investment and the relative price of capital occurs with a lead from the Home country.

Table 13: Cross-country transmission (II) MTC, $\rho(x_{t-k}, y_t)$

Home real GDP, Home varieties exported	0.7428 ($k = 5$)
Home varieties exported, Foreign real GDP	0.9601 ($k = 0$)
Home varieties exported, Foreign investment	0.9431 ($k = 1$)
Home varieties exported, Foreign relative price of capital	-0.8255 ($k = 1$)
Home varieties exported, Foreign exports	0.7637 ($k = 0$)
Home varieties adopted, Home varieties exported	0.7433 ($k = 5$)

Notes: See the notes to Tables 8 and 10.

What does the model predict with regard to the role of large firms in medium-term international transmission? Table 14 explores the correlations between the size of large firms, captured by employment among Home exporters, and a variety of macroeconomic aggregates at Foreign. We observe that larger exporting firms at Home comove positively and strongly with Foreign output, investment and exports (both in varieties and total quantity). Furthermore, they strongly lead the cycle of the relative price of capital in the Foreign country. All in all, these predictions are consistent with the evidence presented in Section 2, showing that larger US firms are key as drivers of international technology diffusion over the medium term, usually leading the process.

Table 14: Cross-country transmission (III) MTC, $\rho(x_{t-k}, y_t)$

$\rho(L^F_{HK}, RGDP_F)$	0.9612 ($k = 0$)
$\rho(L^F_{HK}, Y_{FK})$	0.9488 ($k = 1$)
$\rho(L^F_{HK}, RP_{FK})$	-0.8545 ($k = 1$)
$\rho(L^F_{HK}, Q^H_{FK})$	0.7584 ($k = 0$)
$\rho(L^F_{HK}, X^H_{FK})$	0.9430 ($k = 1$)

Notes: See the notes to Tables 8 and 10.

7 Conclusion

We present evidence suggesting that larger US firms, by diffusing embodied technology through trade in varieties of intermediates, may be one of the key drivers of European countries' output at relatively low frequencies. In an attempt to quantitatively account for the persistence and the international comovement observed in the medium term, we propose a two-country, asymmetric model in which endogenous growth is driven by embodied technical change in new intermediate varieties for the capital goods sector (Romer, 1990, Comin and Gertler, 2006), there is cross-country firm heterogeneity (Melitz, 2003, Ghironi and Melitz, 2005, Melitz and Redding, 2014) and trade in intermediates (Comin *et al.*, 2014, Santacreu, 2015).

Firms with heterogeneous productivity introduce relevant channels for medium-term adjustment and comovement. Through changing productivity cut-offs, firms respond to short- and medium-term fluctuations in costs variables and demand conditions. Moreover, since the microfounded probability of exporting depends on productivity thresholds, they influence the investment decisions of innovators and adopters, hence the path of recovery after exogeneous disturbances and long-term growth.

Once we calibrate the model for two advanced economies, with the US featuring as the leader, we examine their macroeconomic response to embodied and disembodied technological disturbances. Consider a negative TFP shock in the US. With heterogeneous productivity, some US firms, facing a domestic recession, become exporters. On impact, newly imported varieties from the US help stave off the recession in the follower's intermediate goods sector. But the latter is accompanied by a redirection of the follower's resources away from innovation and into adoption. This is very costly in terms of medium-term growth: the recession in the follower country turns very pronounced and persistent as the number of new domestic varieties falls. Absent heterogeneity, this transmission mechanism would disappear and the follower's adjustment would resemble the leader's in terms of timing and persistence. Furthermore, the model predicts that an adverse investment-specific shock can impart a prolonged recession in the US, as real GDP and firm productivity stay below trend in excess of ten years, which may help explain the sustained productivity slowdown observed after a major financial crisis. In this framework, disembodied and embodied technology shocks have long-lasting consequences for trade, both in quantities and in varieties.

Quantitatively, our framework outperforms standard international business cycle models in reproducing data-like cross-country correlations in most macroeconomic aggregates. As a novelty, the introduction of firm heterogeneity allows us to account for the role of the size distribution of intermediate manufacturers in the transmission of technology cycles over the medium term. As in the data, the simulations show that large US exporters contribute strongly to the dynamics of the follower's GDP and investment over the medium term. Given our modelization of trade in new intermediate varieties produced by heterogeneous firms as the link across countries, a policy lesson calls for reconsidering the medium-term effects of an excessive reduction in innovation spending after a slowdown.

Appendix

A1. Data definitions and sources

The database contains information of 5 OECD countries and, for most of the variables, spans from 1950 until 2014. The countries in the sample include: France, Germany, Italy, Spain and the United States. Unless otherwise indicated, variables are expressed in US, constant prices, constant PPPs and OECD base year 2010.

GDP is the gross domestic product based on the expenditure approach taken from the OECD Economic Outlook, various volumes, and the US Bureau of Economic Analysis. For the period 1950-1959, the data are extrapolated using the International Financial Statistics of the IMF and the National Income Statistics of the United Nations, except for France and the US.

Working-age population 15-64 is taken from the OECD Economic Outlook and the OECD Annual Labour Force Statistics, various volumes.

Hours is defined as the average hours worked per employee multiplied by the total number of employees. The data are from the OECD Economic Outlook (national accounts basis whenever available), various volumes, backdated with the OECD Annual Labour Force Statistics and B.R. Mitchell (2007) "International Historical Statistics 1750-2005" Palgrave Macmillan.

Labor productivity is the ratio of GDP to total hours worked in the economy.

Consumption is the private final consumption expenditure of households and non-profit financial institutions serving households from the OECD Economic Outlook, various volumes. For the period 1950-1959, the data are extrapolated using the International Financial Statistics of the IMF and the National Income Statistics of the United Nations. Data for Spain starts in 1955.

Investment is the private non-residential gross fixed capital formation from the OECD Economic Outlook, various volumes. For the period 1950-1959, the data are extrapolated using the International Financial Statistics of the IMF and the National Income Statistics of the United Nations. Data for Spain starts in 1955.

Exports, Imports, Export and Import price deflators are from the OECD Economic Outlook, various volumes, the AMECO database of the European Commission, the International Financial Statistics of the IMF and the US Bureau of Economic Analysis. Whenever necessary, the data for extrapolating the sample back to 1950 are taken from the OECD Statistics of National Accounts, various issues, the United Nations Historical Data 1900-1960, the United Nations Yearbook of International Trade Statistics, various issues, and Estadísticas Históricas de España, siglos XIX y XX, Fundación BBVA. The deflators are index numbers.

Bilateral exports are obtained by multiplying total exports by the corresponding bilateral exports shares. Bilateral exports shares are constructed from Feenstra *et al.* (2005) "World Trade Flows: 1962-2000" NBER Working Paper No. 11040, giving primacy to trade flows reported by the importer country, and extended with the OECD International Trade by Commodity Statistics, B.R. Mitchell (2007) "International Historical Statistics 1750-2005" Palgrave Macmillan, the United Nations Yearbook of International Trade Statistics, various issues, and Estadísticas Históricas de España, siglos XIX y XX, Fundación BBVA. A similar method and data sources are used for the construction of the bilateral imports series.

GDP deflator is an index taken from the OECD Economic Outlook, various volumes, with the exception of pre-1960 values that are from the AMECO database of the European Commission and the Yearbook of National Accounts Statistics of the United Nations, various issues.

Investment deflator is the price deflator of gross fixed capital formation taken from the AMECO database and available since 1960.

Total factor productivity is calculated as the residual of a standard Cobb-Douglas production function on capital stock and labor use. The estimated capital stock series are based on investment series from the OECD Economic Outlook and the OECD Statistics of National Accounts, various issues.

R&D spending is the Business Enterprise Research and Development Expenditure from the OECD ANBERD Database. The data start in 1973 with the exception of the US that start in 1953 and data are from the National Science Foundation.

Patent applications are taken from the World Intellectual Property Organization Statistics Database and the European Patent Office Annual Report, Statistical Tables, various issues.

US varieties traded are the number of SITC revision 2 categories up to the 5-digit disaggregation in manufacturing (excluding consumption goods) with a traded value greater than $1 mn as reported by the importer, extracted from the OECD International Trade by Commodity Statistics and available since 1961.

Firm size refers to the number of employees by size category in US manufacturing firms. Size categories correspond to firms with: a) 1-9, b) 10-49, c) 50-249 or d) ≥ 250 employees. The data are from the Longitudinal Business Database 1977-2013, US Census Bureau.

A2. Stylized features

Figure A2.1: Medium frequency component of investment per working age population

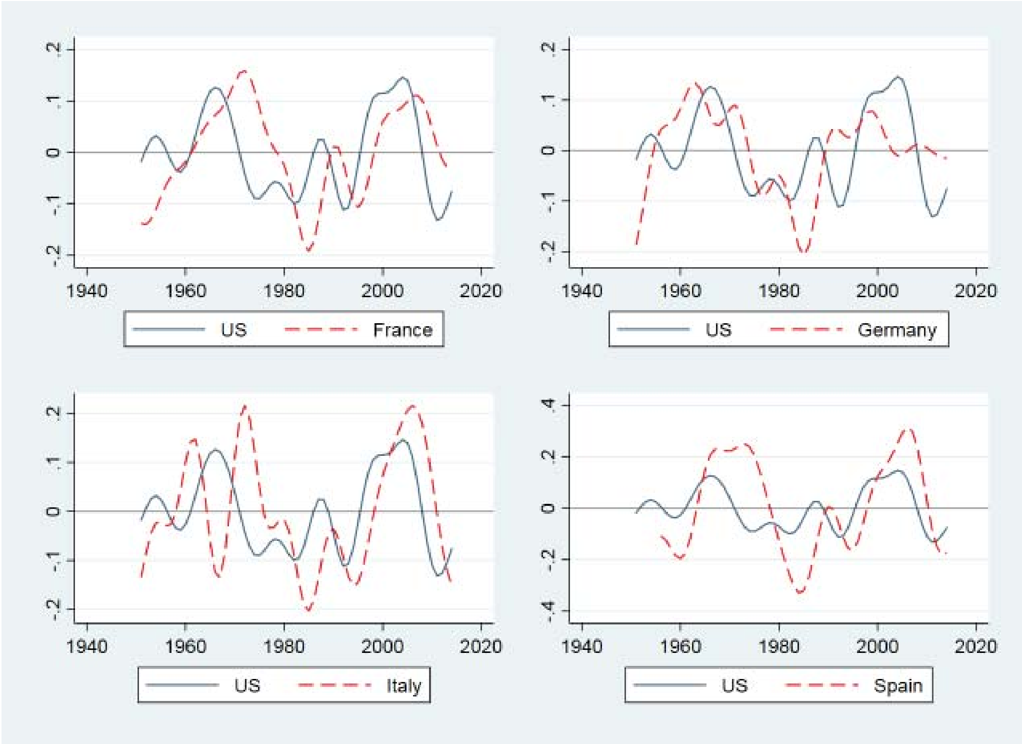


Table A2.1: Standard deviations: Annual frequencies, 1951-2014

	France		Germany		Italy		Spain		US	
	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8
Standard variables										
GDP	3.96*	0.89*	4.32*	1.65*	5.46*	1.32*	7.71*	2.33*	3.77*	1.34*
	(3.54,4.59)	(0.70,1.14)	(3.70,5.06)	(1.36,2.03)	(4.87,6.08)	(1.12,1.60)	(6.84,8.65)	(1.71,3.30)	(3.23,4.54)	(1.13,1.68)
Hours	2.42*	0.62*	2.67*	0.96*	2.93*	0.87*	7.36*	0.9*	3.48*	1.29*
	(1.97,2.70)	(0.56,0.68)	(2.36,3.02)	(0.82,1.16)	(2.57,3.52)	(0.75,1.01)	(6.45,8.43)	(0.73,1.11)	(2.99,4.07)	(1.11,1.51)
LP	2.58*	0.72*	3.49*	1.09*	4.94*	1.08*	3.53*	2.32*	2.89*	0.69*
	(2.40,2.95)	(0.68,0.83)	(3.12,3.91)	(0.84,1.65)	(4.46,5.43)	(0.93,1.31)	(2.91,4.96)	(1.70,3.48)	(2.63,3.21)	(0.59,0.84)
Consumption	3.03*	0.78*	3.76*	1.06*	4.62*	1.32*	8.19*	1.21*	3.5*	1.12*
	(2.70,3.26)	(0.60,0.91)	(3.16,4.51)	(0.92,1.23)	(4.14,5.29)	(1.11,1.61)	(7.37,9.24)	(0.91,1.93)	(3.07,4.11)	(0.97,1.32)
Investment	9.23*	1.79*	8.97*	3.25*	12.29*	3.01*	18.8*	2.96*	8.86*	3.47*
	(8.68,10.37)	(1.49,1.99)	(7.83,10.34)	(2.91,3.77)	(10.74,13.72)	(2.50,3.93)	(16.90,21.73)	(2.43,3.82)	(7.74,10.17)	(2.97,4.09)
Exports	10.34*	2.86*	9.56*	3.57*	11.53*	3.52*	17.15*	6.26*	8.25*	4.09*
	(9.65,11.69)	(2.47,3.36)	(8.04,11.18)	(2.89,5.14)	(10.42,13.00)	(2.92,4.87)	(14.87,20.39)	(5.00,8.40)	(6.94,10.02)	(3.46,5.26)
Imports	9.91*	3.52*	10.79*	3.58*	13.98*	4.08*	23.41*	5.78*	10.27*	4.2*
	(9.16,10.22)	(2.88,4.19)	(9.23,12.83)	(3.13,4.48)	(12.61,15.53)	(3.50,4.95)	(20.89,26.78)	(4.48,7.99)	(8.93,12.13)	(3.40,5.54)
Other variables										
RPK	2.35*	0.45*	2.93*	1.34*	4.11*	1.21*	4.35*	0.97*	3.91*	0.57*
	(2.20,2.43)	(0.40,0.48)	(2.53,3.55)	(1.10,1.77)	(3.55,5.02)	(0.91,1.82)	(3.77,5.08)	(0.81,1.22)	(3.40,4.51)	(0.48,0.78)
TFP	2.34*	0.77*	2.65*	1.3*	3.87*	1.14*	3.95*	2.37*	2.58*	0.85*
	(1.68,2.50)	(0.57,0.86)	(2.32,3.02)	(1.06,1.77)	(3.54,4.28)	(0.99,1.40)	(3.37,4.78)	(1.70,3.38)	(2.26,3.03)	(0.72,1.00)
R&D	5.56*	1.05*	7.95*	2.2*	12.87*	2.55*	14.46*	3.74*	13.57*	2.5*
	(4.61,5.89)	(0.79,1.17)	(6.90,9.31)	(1.80,2.83)	(10.67,15.35)	(2.16,3.05)	(12.28,17.45)	(3.14,4.42)	(11.82,15.55)	(2.10,3.24)
Patents	12.24*	2.65*	12.35*	3.86*	14.39*	2.81*	25.15*	5.3*	6.98*	3.23*
	(12.03,12.77)	(2.39,2.88)	(10.55,14.19)	(2.56,6.14)	(12.93,16.20)	(2.36,3.38)	(21.36,29.25)	(4.32,6.72)	(5.93,8.15)	(2.72,4.10)

Notes: LP is labor productivity, RPK is the relative price of capital, MTC refers to the medium term cycle and HFC to the high frequency component. The sample period is 1951-2014 unless otherwise indicated in Appendix A1, where a detailed description of the variables can be found. In parenthesis is the 95-percent bootstrap confidence interval (1,000 random samples with replacement) of the corresponding statistic, where * denotes its significance.

Table A2.2: First-order autocorrelations: Annual frequencies, 1951-2014

	France		Germany		Italy		Spain		US	
	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8
Standard variables										
GDP	0.92*	0.08*	0.83*	0.15	0.91*	0.12	0.9*	0.23	0.84*	0.06
	(0.89,0.95)	(0.01,0.16)	(0.68,0.91)	(-0.25,0.46)	(0.84,0.95)	(-0.15,0.39)	(0.75,0.95)	(-0.38,0.75)	(0.75,0.90)	(-0.20,0.25)
Hours	0.87*	-0.14	0.84*	0.18	0.88*	0.23	0.96*	0.31	0.85*	0.19
	(0.81,0.93)	(-0.19,0.00)	(0.74,0.90)	(-0.10,0.45)	(0.82,0.93)	(-0.04,0.43)	(0.93,0.97)	(-0.15,0.58)	(0.75,0.91)	(-0.07,0.43)
LP	0.89*	-0.01	0.88*	0.17	0.93*	0.01	0.67*	0.27	0.91*	0.01
	(0.87,0.92)	(-0.17,0.12)	(0.63,0.95)	(-0.51,0.55)	(0.86,0.96)	(-0.28,0.27)	(0.20,0.85)	(-0.33,0.78)	(0.87,0.94)	(-0.29,0.25)
Consumption	0.9*	0.19	0.9*	0.37*	0.88*	0.12	0.94*	-0.16	0.88*	0.23
	(0.88,0.94)	(-0.26,0.41)	(0.82,0.94)	(0.16,0.54)	(0.82,0.92)	(-0.12,0.34)	(0.91,0.96)	(-0.58,0.18)	(0.80,0.93)	(-0.07,0.47)
Investment	0.93*	0.14	0.86*	0.31*	0.87*	0.01	0.94*	0.16	0.84*	0.27*
	(0.93,0.93)	(-0.09,0.45)	(0.76,0.92)	(0.01,0.52)	(0.75,0.92)	(-0.25,0.24)	(0.90,0.95)	(-0.10,0.43)	(0.71,0.89)	(0.01,0.49)
Exports	0.9*	0.06	0.83*	0.09	0.88*	-0.01	0.78*	0.05	0.73*	0.12
	(0.86,0.91)	(0.00,0.22)	(0.69,0.89)	(-0.22,0.33)	(0.75,0.93)	(-0.33,0.24)	(0.54,0.90)	(-0.30,0.35)	(0.54,0.84)	(-0.24,0.44)
Imports	0.85*	0.04	0.86*	0.24*	0.86*	-0.14	0.89*	-0.31*	0.82*	0.17
	(0.81,0.90)	(-0.16,0.34)	(0.78,0.92)	(0.01,0.44)	(0.76,0.92)	(-0.37,0.10)	(0.83,0.93)	(-0.64,-0.05)	(0.69,0.89)	(-0.02,0.38)
Other variables										
RPK	0.91*	-0.12	0.8*	0.44	0.9*	0.17	0.92*	0.3	0.96*	0.12
	(0.86,0.92)	(-0.29,0.08)	(0.49,0.90)	(-0.15,0.68)	(0.82,0.94)	(-0.23,0.49)	(0.87,0.95)	(-0.03,0.54)	(0.93,0.97)	(-0.14,0.31)
TFP	0.86*	0.1	0.74*	0.17	0.88*	0.06	0.71*	0.26	0.87*	0.06
	(0.75,0.91)	(-0.06,0.22)	(0.34,0.88)	(-0.39,0.50)	(0.78,0.94)	(-0.24,0.32)	(0.36,0.87)	(-0.37,0.77)	(0.79,0.91)	(-0.21,0.32)
R&D	0.92*	-0.18	0.87*	0.11	0.93*	0.05	0.83*	-0.28	0.92*	0.11
	(0.82,0.94)	(-0.32,-0.04)	(0.75,0.93)	(-0.19,0.37)	(0.86,0.96)	(-0.22,0.34)	(0.76,0.89)	(-0.55,0.06)	(0.79,0.96)	(-0.41,0.40)
Patents	0.91*	-0.19	0.93*	0.35	0.9*	-0.32	0.91*	-0.01	0.8*	0.22
	(0.87,0.94)	(-0.38,0.06)	(0.87,0.96)	(-0.12,0.84)	(0.83,0.93)	(-0.52,-0.09)	(0.80,0.95)	(-0.28,0.27)	(0.66,0.87)	(-0.07,0.48)

Note: See the notes to Table A2.1.

Table A2.3: Within-country contemporaneous correlations with domestic GDP: Annual frequencies, 1951-2014

	France		Germany		Italy		Spain		US	
	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8	MTC 0-50	HFC 0-8
Standard variables										
Hours	0.78*	0.60*	0.63*	0.77*	0.44*	0.58*	0.89*	0.15	0.69*	0.86*
	(0.72,0.82)	(0.37,0.75)	(0.46,0.75)	(0.57,0.86)	(0.23,0.60)	(0.40,0.73)	(0.82,0.94)	(-0.01,0.28)	(0.57,0.77)	(0.78,0.92)
LP	0.81*	0.74*	0.80*	0.83*	0.85*	0.75*	0.26*	0.94*	0.48*	0.33*
	(0.77,0.85)	(0.70,0.84)	(0.72,0.85)	(0.74,0.89)	(0.78,0.89)	(0.64,0.84)	(0.02,0.51)	(0.87,0.98)	(0.24,0.65)	(0.17,0.51)
Consumption	0.91*	0.64*	0.79*	0.54*	0.94*	0.70*	0.84*	0.58	0.92*	0.85*
	(0.87,0.94)	(0.55,0.72)	(0.65,0.87)	(0.34,0.68)	(0.91,0.96)	(0.56,0.78)	(0.72,0.91)	(-0.01,0.83)	(0.87,0.95)	(0.71,0.91)
Investment	0.91*	0.80*	0.90*	0.80*	0.82*	0.66*	0.91*	0.60*	0.88*	0.91*
	(0.88,0.93)	(0.78,0.88)	(0.84,0.94)	(0.67,0.88)	(0.69,0.90)	(0.45,0.78)	(0.84,0.94)	(0.38,0.73)	(0.82,0.91)	(0.85,0.95)
Exports	0.81*	0.72*	0.47*	0.51*	0.84*	0.37*	0.28*	0.25	0.38*	0.39*
	(0.78,0.82)	(0.55,0.77)	(0.28,0.63)	(0.19,0.74)	(0.76,0.89)	(0.08,0.66)	(0.07,0.48)	(-0.03,0.47)	(0.17,0.56)	(0.13,0.60)
Imports	0.87*	0.80*	0.78*	0.55*	0.95*	0.78*	0.83*	0.22	0.85*	0.85*
	(0.79,0.89)	(0.74,0.85)	(0.64,0.85)	(0.26,0.74)	(0.92,0.96)	(0.68,0.87)	(0.72,0.91)	(-0.13,0.55)	(0.77,0.91)	(0.74,0.90)
Other variables										
RPK	-0.48*	0.28*	-0.07	0.51*	-0.47*	0.49*	-0.20	0.52*	-0.77*	-0.33
	(-0.65,-0.28)	(0.12,0.52)	(-0.29,0.14)	(0.24,0.69)	(-0.59,-0.29)	(0.24,0.69)	(-0.44,0.02)	(0.19,0.74)	(-0.87,-0.64)	(-0.64,0.02)
TFP	0.77*	0.88*	0.73*	0.94*	0.91*	0.91*	0.54*	0.97*	0.84*	0.84*
	(0.68,0.81)	(0.81,0.91)	(0.59,0.82)	(0.90,0.96)	(0.87,0.94)	(0.86,0.94)	(0.38,0.68)	(0.93,0.99)	(0.75,0.90)	(0.74,0.91)
R&D	-0.47*	0.31*	-0.47*	0.61*	-0.58*	0.26	0.40*	0.08	0.42*	0.41*
	(-0.53,-0.38)	(0.17,0.39)	(-0.65,-0.24)	(0.36,0.75)	(-0.71,-0.39)	(-0.12,0.55)	(0.16,0.61)	(-0.24,0.35)	(0.19,0.59)	(0.00,0.62)
Patents	0.40*	0.09	0.16	0.03	0.68*	0.17	0.66*	0.15*	0.60*	-0.01
	(0.26,0.56)	(-0.12,0.33)	(-0.09,0.41)	(-0.18,0.27)	(0.56,0.77)	(-0.08,0.43)	(0.53,0.77)	(0.00,0.32)	(0.46,0.72)	(-0.24,0.19)

Notes: See the notes to Table A2.1.

Table A2.4: US patents and the European MTC

	GDP per working age population			
US patents	France	Germany	Italy	Spain
Lag 0	0.6801*	0.8095*	0.7522*	0.8187*
Lag 1	0.7346*	0.8097*	0.7244*	0.8606*
Lag 2	0.7419*	0.7506*	0.6640*	0.8489*
Lag 3	0.7137*	0.6563*	0.5870*	0.7865*
	Investment per working age population			
US patents	France	Germany	Italy	Spain
Lag 0	0.8487*	0.7206*	0.6944*	0.8196*
Lag 1	0.8681*	0.6767*	0.6859*	0.8176*
Lag 2	0.8281*	0.5705*	0.6286*	0.7659*
Lag 3	0.7424*	0.4298*	0.5494*	0.6761*
	Relative price of capital			
US patents	France	Germany	Italy	Spain
Lag 0	-0.6214*	-0.3373*	-0.6846*	-0.4540*
Lag 1	-0.5521*	-0.4037*	-0.5371*	-0.4055*
Lag 2	-0.4693*	-0.4830*	-0.3702*	-0.3479*
Lag 3	-0.3816*	-0.5609*	-0.1982*	-0.2785*

Notes: See the notes to Table 1. Patents refer to the number of patent applications.

A3. Model equations

This appendix describes the system of equations that characterizes equilibrium. For simplicity, only those equations corresponding to the Home country are enumerated, except when both versions are required. Equations are expressed in real terms and the deflator used is the price level of final output.

Households' labor-leisure choice

$$RW_{Ht} = \mu_{Ht}^{w} L_{Ht}^{\zeta} C_{Ht} \tag{A3.1}$$

Labor demand in the production of final output

$$(1-\alpha) Y_{Ht} = \mu_Y RW_{Ht} L_{Ht}^{Y} \tag{A3.2}$$

Capital demand in the production of final output

$$\alpha Y_{Ht} = \mu_Y \left[RF_{Ht} + \delta(U_{Ht}) RP_{HKt} \right] K_{Ht} \tag{A3.3}$$

Sectoral utilization rate

$$\alpha Y_{Ht} = \mu_Y \delta'(U_{Ht}) RP_{HKt} K_{Ht} U_{Ht} \tag{A3.4}$$

Production function of final output

$$Y_{Ht} = N_{Ht}^{\mu_Y - 1} \xi_{Ht} \left(U_{Ht} K_{Ht} \right)^{\alpha} \left(L_{Ht}^{Y} \right)^{1-\alpha} \tag{A3.5}$$

Free entry condition in the final output sector

$$\left(\frac{\mu_Y - 1}{\mu_Y} \right) Y_{Ht} = N_{Ht} b_H R\Psi_{Ht} \tag{A3.6}$$

Free entry condition in the investment good sector

$$\left(\frac{\mu_K - 1}{\mu_K} \right) RP_{HKt} Y_{HKt} = N_{HKt} b_{HK} R\Psi_{Ht} \tag{A3.7}$$

Law of motion of capital stock

$$K_{Ht+1} = (1 - \delta(U_{Ht})) K_{Ht} + \upsilon_{Ht} Y_{HKt} \tag{A3.8}$$

Law of motion of innovations

$$Z_{HKt+1} = \varphi_{HKt} S_{HKt} + \varsigma_H Z_{HKt} \tag{A3.9}$$

Research productivity

$$\varphi_{HKt} S_{HKt}^{1-\rho} R\Psi_{Ht}^{\rho} = x_H T_{HKt} \tag{A3.10}$$

Number of innovations available

$$T_{HKt} = Z_{HKt} + X_{FKt}^{H} \tag{A3.11}$$

Law of motion of adoptions

$$A_{HKt+1}^{H} = \lambda_{HKt}\varsigma_{H}\left(Z_{HKt} - A_{HKt}^{H}\right) + \varsigma_{H}A_{HKt}^{H} \tag{A3.12}$$

Probability of adoption

$$\lambda_{HKt} = \alpha_{H}^{A}\frac{A_{HKt}^{H}}{Z_{HKt}}\left(\frac{H_{HKt}}{R\Psi_{Ht}}\right)^{\gamma_{A}} \tag{A3.13}$$

Number of intermediate goods available

$$A_{HKt} = A_{HKt}^{H} + X_{FKt}^{H} \tag{A3.14}$$

Number of exported intermediates

$$X_{HKt}^{F} = \theta_{HK}\left[1 - G_{H}\left(z_{HXt}\right)\right]A_{HKt}^{H} \tag{A3.15}$$

$$G_{H}\left(z_{HXt}\right) = 1 - \left(\frac{z_{HDt}}{z_{HXt}}\right)^{\phi_{H}} \tag{A3.16}$$

Average productivity of H's domestic producers

$$\widetilde{z}_{HDt} = \left[\frac{\phi_{H}(\vartheta-1)}{\phi_{H}(\vartheta-1)-1}\right]^{\vartheta-1} z_{HDt}, \tag{A3.17}$$

Average productivity of H's exporters

$$\widetilde{z}_{HXt} = \left[\frac{\phi_{H}(\vartheta-1)}{\phi_{H}(\vartheta-1)-1}\right]^{\vartheta-1} z_{HXt}, \tag{A3.18}$$

Productivity threshold for H's domestic production

$$z_{HDt} = \left(\frac{f_{HD}}{\chi_{Ht}B_{HKt}^{H}}\right)^{\vartheta-1} W_{HKt}^{\vartheta}, \tag{A3.19}$$

$$B_{HKt}^{H} = \left(\frac{\vartheta-1}{\vartheta}\right)\vartheta^{\frac{1}{1-\vartheta}}Y_{HKt}P_{HKt}^{\frac{\vartheta}{\vartheta-1}}N_{HKt}^{\frac{\mu_{K}-1}{\vartheta-1}}\mu_{K}^{\frac{\vartheta}{1-\vartheta}} \tag{A3.20}$$

Productivity threshold for H's exports

$$z_{HXt} = \left(\frac{f_{HX}}{\chi_{Ht}B_{FKt}^{H}}\right)^{\vartheta-1} W_{HKt}^{\vartheta}\tau_{H}, \tag{A3.21}$$

$$B_{FKt}^{H} = \left(\frac{\vartheta-1}{\vartheta}\right)\vartheta^{\frac{1}{1-\vartheta}}Y_{FKt}P_{FKt}^{\frac{\vartheta}{\vartheta-1}}er_{t}^{\frac{\vartheta}{1-\vartheta}}N_{FKt}^{\frac{\mu_{K}-1}{\vartheta-1}}\mu_{K}^{\frac{\vartheta}{1-\vartheta}} \tag{A3.22}$$

Index of relative technology

$$\chi_{Ht} = \left(\frac{1}{RP_{HKt}}\right)^{\frac{1}{\vartheta-1}} \tag{A3.23}$$

Average productivity of F's domestic producers

$$\widetilde{z}_{FDt} = \left[\frac{\phi_F(\vartheta-1)}{\phi_F(\vartheta-1)-1}\right]^{\vartheta-1} z_{FDt} \tag{A3.24}$$

Average productivity of F's exporters

$$\widetilde{z}_{FXt} = \left[\frac{\phi_F(\vartheta-1)}{\phi_F(\vartheta-1)-1}\right]^{\vartheta-1} z_{FXt} \tag{A3.25}$$

Productivity threshold for F's domestic production

$$z_{FDt} = \left(\frac{f_{FD}}{\chi_{Ft}B^F_{FKt}}\right)^{\vartheta-1} W^{\vartheta}_{FKt} \tag{A3.26}$$

$$B^F_{FKt} = \left(\frac{\vartheta-1}{\vartheta}\right)\vartheta^{\frac{1}{1-\vartheta}} Y_{FKt} P_{FKt}^{\frac{\vartheta}{\vartheta-1}} N_{FKt}^{\frac{\mu_K-1}{\vartheta-1}} \mu_K^{\frac{\vartheta}{1-\vartheta}} \tag{A3.27}$$

Productivity threshold for F's exports

$$z_{FXt} = \left(\frac{f_{FX}}{\chi_{Ft}B^F_{HKt}}\right)^{\vartheta-1} W^{\vartheta}_{FKt}\tau_F \tag{A3.28}$$

$$B^F_{HKt} = \left(\frac{\vartheta-1}{\vartheta}\right)\vartheta^{\frac{1}{1-\vartheta}} Y_{HKt} P_{HKt}^{\frac{\vartheta}{\vartheta-1}} e_t^{\frac{\vartheta}{\vartheta-1}} N_{HKt}^{\frac{\mu_K-1}{\vartheta-1}} \mu_K^{\frac{\vartheta}{1-\vartheta}} \tag{A3.29}$$

Relative (real) price of capital

$$RP_{HKt} = \frac{\mu_K}{N_{HKt}^{\mu_K-1}}\left(A^H_{HKt}(\vartheta RW_{HKt})^{\frac{1}{1-\vartheta}}\widetilde{z}_{HDt}^{\frac{1}{\vartheta-1}} + X^H_{FKt}\left(\frac{\vartheta RW_{FKt}\tau_F}{rer_t}\right)^{\frac{1}{1-\vartheta}}\widetilde{z}_{FXt}^{\frac{1}{\vartheta-1}}\right)^{1-\vartheta} \tag{A3.30}$$

Euler equation for capital stock

$$RP_{HKt} = E_t\left\{\Lambda_{Ht,t+1}\left[RP_{HKt+1} + RF_{Ht+1}\right]\right\} \tag{A3.31}$$

Euler equation for bonds

$$1 = E_t\left[\Lambda_{Ht,t+1}RR_{Ht+1}\right] \tag{A3.32}$$

Discount rate in real terms

$$\Lambda_{Ht,t+1} = \beta\frac{C_{Ht}}{C_{Ht+1}} \tag{A3.33}$$

FOC innovators

$$\varsigma_H E_t \Lambda_{Ht,t+1} RJ_{HKt+1} \varphi_{HKt} = 1 \tag{A3.34}$$

FOC adopters

$$1 = \gamma_A \frac{\lambda_{HKt}}{H_{HKt}} \varsigma_H \left[Z_{HKt} - A^H_{HKt} \right] E_t \Lambda_{Ht,t+1} \left[RV^i_{HKt+1} - RJ_{HKt+1} \right] \tag{A3.35}$$

Market value of an unadopted innovation

$$RJ_{HKt} = -\frac{H_{HKt}}{[Z_{HKt} - A^H_{HKt}]} + \varsigma_H E_t \Lambda_{Ht,t+1} \left[\lambda_{HKt} RV^i_{HKt+1} + (1 - \lambda_{HKt}) RJ_{HKt+1} \right] \tag{A3.36}$$

Stream of profits from a successful adoption

$$RV^i_{HKt} = R\Pi^i_{HKt} + \varsigma_H E_t \Lambda_{Ht,t+1} RV^i_{HKt+1} \tag{A3.37}$$

Profits from manufacturing an intermediate

$$R\Pi^i_{HKt} \equiv R\Pi^{\kappa,H}_{HKt} + \theta_{HK} \left[1 - G_H \left(z_{HXt} \right) \right] R\Pi^{\kappa,F}_{HKt} \tag{A3.38}$$

Profits from selling an intermediate domestically

$$R\Pi^{\kappa,H}_{HKt} = RW_{HKt} \frac{f_{HD}}{\chi_{Ht}} \left(\frac{1}{\phi_H(\vartheta - 1) - 1} \right) \tag{A3.39}$$

Profits from exporting an intermediate

$$R\Pi^{\kappa,F}_{HKt} = RW_{HKt} \frac{f_{HX}}{\chi_{Ht}} \left(\frac{1}{\phi_H(\vartheta - 1) - 1} \right) \tag{A3.40}$$

Trade balance

$$\frac{rer_t RW_{HKt}}{RW_{FKt}} = \frac{X^H_{FKt}}{X^F_{HKt}} \frac{\phi_F}{\phi_H} \frac{[\phi_H(\vartheta - 1) - 1]}{[\phi_F(\vartheta - 1) - 1]} \frac{f_{FX}}{f_{HX}} \left(\frac{RP_{FKt}}{RP_{HKt}} \right)^{\frac{1}{\vartheta - 1}} \tag{A3.41}$$

Labor market clearing

$$L_{Ht} = L^Y_{Ht} + L^H_{HKt} + L^F_{HKt} \tag{A3.42}$$

$$L^H_{HKt} + L^F_{HKt} = A^H_{HKt} \frac{f_{HD}}{\chi_{Ht}} \left[\frac{\phi_H}{\phi_H(\vartheta - 1) - 1} + 1 \right] + X^F_{HKt} \frac{f_{HX}}{\chi_{Ht}} \left[\frac{\phi_H}{\phi_H(\vartheta - 1) - 1} + 1 \right] \tag{A3.43}$$

Resource constraint

$$Y_{Ht} = C_{Ht} + S_{HKt} + H_{HKt} + N_{Ht} b_H R\Psi_{Ht} + N_{HKt} b_{HK} R\Psi_{Ht} \tag{A3.44}$$

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