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ABSTRACT

This paper develops estimates of TFP growth adjusted for movements in unobserved factor utilization for a panel of 29 countries and up to 37 years. When factor utilization changes are unobserved, the commonly used Solow residual mismeasures actual changes in TFP. We use a general equilibrium dynamic multi-country multi-sector model featuring variable factor utilization to derive a production function estimating equation that corrects for unobserved factor usage. We compare the properties of utilization-adjusted TFP series to the standard Solow residual, and discuss the implications for international business cycle comovement generated by technology shocks. Unlike the Solow residual, utilization-adjusted TFP is virtually uncorrelated across countries, and as a result its direct contribution to GDP comovement is negligible. A general equilibrium model calibrated to the observed levels of international trade cannot generate much comovement through propagation of these TFP shocks.

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1 Introduction

It has long been acknowledged in macroeconomics that the intensity of factor utilization varies over the business cycle. When some dimensions of variable factor utilization are not directly observed, conventional ways of inferring TFP changes, such as the Solow residual, can be misleading as measures of technology shocks. Thus, estimation of TFP shocks must account for variations in unobserved factor usage. Following the seminal work of Basu, Fernald, and Kimball (2006, henceforth BFK), it has become standard to use a utilization-adjusted series as a measure of TFP when studying the US economy. Importantly, BFK show that the utilization-adjusted TFP series have substantially different properties than the traditional Solow residual. However, studies of international business cycles have typically employed the Solow residual as the measure of technology shocks, due to the lack of comparable estimates of utilization-adjusted TFP across countries.

This paper develops utilization-adjusted TFP series for a sample of 29 countries, 30 sectors, and up to 37 years. We then use these estimates to study the role of TFP shocks in international GDP comovement. Our main results can be summarized as follows. First, utilization-adjusted TFP is virtually uncorrelated across countries. This is in contrast to the Solow residual, which is modestly positively correlated. Our findings imply that the cross-country correlation in the Solow residual typically found in the literature is in fact due to correlated movements in unobserved factor utilization. Second, TFP shocks alone cannot generate much GDP correlation when fed into a multi-country, multi-sector general equilibrium model of production and trade. In the G7 countries, TFP shocks 10-30% of the observed GDP correlation on average. In the full 29-country sample, they produce zero GDP correlation on average. We thus conclude that the common approach in the international business cycle literature of working with TFP-shock-driven fluctuations is not the most promising way to fully understand international comovement.

We proceed by setting up a theoretical framework in which capital utilization rates, hours per worker, and workers' effort are endogenous, and can vary within a period in response to shocks. The model yields an estimating equation that features a correction for unobserved factor utilization. The key intuition that makes this possible comes from BFK: agents optimize multiple dimensions of factor use intensity simultaneously. Thus, an observed dimension of factor utilization – hours per worker – can serve as a proxy for unobserved dimensions of factor utilization such as worker effort.[1] We

[1]Our framework uses the assumption that production functions are Cobb-Douglas, with variable returns to scale. Additionally, we assume that firms will choose unobservable input margins like effort in proportion to observable margins like hours. The advantage of this assumption is that, as in BFK, it delivers a straightforward estimating equation that can be applied to existing cross-country data. Further, the approach produces TFP estimates that are consistent with the widely used Cobb-Douglas production structure in international business cycle models. These assumptions are not excessively restrictive, however, as our model implies that within-period industry supply curves are isoelastic. This can be viewed as a reasonable approximation to evidence that industry supply curves are upward-sloping or even convex (Shea, 1993; Boehm and Pandalai-Nayar, 2019).

estimate the production function parameters using the theoretically-founded estimating equation, and data on many countries and sectors from the KLEMS database (O'Mahony and Timmer, 2009). Following BFK, to account for the endogeneity of inputs to TFP shocks we use oil shocks and military expenditure as instruments.

Having extracted the TFP series as residuals following the production function estimation, we document their cross-country correlations, and simulate GDP fluctuations driven by these shocks in a multi-country, multi-sector model of world production and trade. In the model, there is trade both in intermediate inputs and final goods. We calibrate all the country-sector input and final expenditure shares to data in the World Input-Output Database. We then subject this economy to our estimated TFP shocks, and show that the comovement produced endogenously by the model falls far short of the observed levels of comovement in the data.

Our paper contributes to the empirical and quantitative literature on international business cycle comovement. A number of papers are dedicated to documenting international correlations in productivity shocks and inputs (e.g. Imbs, 1999; Kose, Otrok, and Whiteman, 2003; Ambler, Cardia, and Zimmermann, 2004). Also related is the body of work that identifies technology and demand shocks in a VAR setting and examines their international propagation (e.g. Canova, 2005; Corsetti, Dedola, and Leduc, 2014; Levchenko and Pandalai-Nayar, 2018). Relative to these papers, we use sector-level data to provide novel estimates of utilization-adjusted TFP shocks, and expand the sample of countries. A large research agenda builds models in which fluctuations are driven by productivity shocks, and asks under what conditions those models can generate observed international comovement (see, among many others, Backus, Kehoe, and Kydland, 1992; Heathcote and Perri, 2002). In these analyses, productivity shocks are proxied by the Solow residual, which we show can be misleading. Our quantitative assessment benefits from improved measurement of TFP shocks.

Our estimation belongs to the family of methods of measuring factor utilization. Complementing the more model-based approaches such as BFK and Fernald (2014), other work has considered survey-based direct measures of plant capacity utilization (e.g. Shapiro, 1989; Gorodnichenko and Shapiro, 2011; Boehm and Pandalai-Nayar, 2019), or used other observable proxies such as electricity consumption (e.g. Burnside, Eichenbaum, and Rebelo, 1995). The alternative methods cannot be straightforwardly applied in our setting, as utilization surveys and electricity usage are not available for the large sample of countries, sectors, and years in our analysis. Our indirect measures of utilization are positively correlated with the survey-based measures in the subset of countries and sectors for which those exist. A literature in closed-economy macroeconomics going back to Greenwood, Hercowitz, and Huffman (1988) studies the implications of variable factor utilization for domestic business cycles (see, among many others, Bils and Cho, 1994; Cooley, Hansen, and Prescott, 1995; Gilchrist and Williams, 2000). Closely related to the focus of BFK, Shapiro (1993) finds that variations in capital's workweek explain much of cyclicality of TFP. Our paper builds on this literature by assessing the implications of utilization adjustments to TFP for international GDP comovement.

The rest of the paper is organized as follows. Section 2 sets out a simple decomposition that illustrates the potentially confounding role of unobserved factor utilization in studying international comovement due to TFP shocks. Section 3 presents the framework behind our estimation approach. The results of the estimation are in Section 4. We assess the importance of the utilization-adjusted TFP series for comovement in a general-equilibrium framework in Section 5. Section 6 concludes.

2 Accounting Framework

Let there be J sectors indexed by j and N countries indexed by n. Let gross output in sector j country n be given by:

$$Y_{njt} = Z_{njt}\left[\left(K_{njt}^{\alpha_j}L_{njt}^{1-\alpha_j}\right)^{\eta_j}X_{njt}^{1-\eta_j}\right]^{\gamma_j}, \tag{2.1}$$

where K_{njt}, L_{njt}, and X_{njt} are the capital, labor, and materials inputs, respectively, and Z_{njt} is TFP. Total output is a Cobb-Douglas aggregate of primary factor inputs K_{njt} and L_{njt} and materials inputs X_{njt}, with possibly non-constant returns to scale ($\gamma_j \neq 1$). When it comes to measurement, it will be important that K_{njt} and L_{njt} are true, utilization-adjusted inputs that may not be directly observable to the econometrician.

Define real GDP at time t, evaluated at base prices (prices at $t-1$) by:

$$Y_{nt} = \sum_{j=1}^{J}\left(P_{njt-1}Y_{njt} - P_{njt-1}^{X}X_{njt}\right),$$

where P_{njt-1} is the gross output base price, and P_{njt-1}^{X} is the base price of inputs in that sector-country. The change in real GDP between $t-1$ and t is then:

$$\Delta Y_{nt} \quad = \quad \sum_{j=1}^{J}\left(P_{njt-1}\Delta Y_{njt} - P_{njt-1}^{X}\Delta X_{njt}\right),$$

and the proportional change:

$$\begin{aligned}\frac{\Delta Y_{nt}}{Y_{nt-1}} &= \frac{\sum_{j=1}^{J}\left(P_{njt-1}\Delta Y_{njt} - P_{njt-1}^{X}\Delta X_{njt}\right)}{Y_{nt-1}} \\ &= \sum_{j=1}^{J} w_{njt-1}^{D}\left(\frac{\Delta Y_{njt}}{Y_{njt-1}} - \frac{\Delta X_{njt}}{X_{njt-1}}\frac{P_{njt-1}^{X}X_{njt-1}}{P_{njt-1}Y_{njt-1}}\right),\end{aligned}$$

where $w_{njt-1}^{D} \equiv \frac{P_{njt-1}Y_{njt-1}}{Y_{nt-1}}$ is the Domar weight of sector j in country n, that is, the weight of the sector's gross sales in aggregate value added. Approximate the growth rate with log difference:

$$\begin{aligned} d\ln Y_{nt} &\approx \sum_{j=1}^{J} w_{njt-1}^{D}\left(d\ln Y_{njt} - d\ln X_{njt}\frac{P_{njt-1}^{X}X_{njt-1}}{P_{njt-1}Y_{njt-1}}\right) \\ &= \sum_{j=1}^{J} w_{njt-1}^{D}\Big(d\ln Z_{njt} + \gamma_j\alpha_j\eta_j d\ln K_{njt} + \gamma_j(1-\alpha_j)\eta_j d\ln L_{njt} \\ &\quad + \gamma_j\left(1-\eta_j\right)d\ln X_{njt} - d\ln X_{njt}\frac{P_{njt-1}^{X}X_{njt-1}}{P_{njt-1}Y_{njt-1}}\Big). \end{aligned} \tag{2.2}$$

All of the terms in this expression are either observable or will be estimated, except for α_j and η_j. Thus, in order to proceed we need to take a stand on how to measure these. Regardless of the nature of variable returns to scale or market structure, under cost minimization $\alpha_j\eta_j$ is the share of payments to capital in the total costs, while $(1-\alpha_j)\eta_j$ is the share of payments to labor. We do not observe total costs, only total revenues. We will assume that $\alpha_j\eta_j$ also reflects the share of payments to capital in total revenues. This assumption is satisfied if either (i) sector j is competitive and the variable returns to scale are external to the firm; or (ii) profits are distributed among the inputs in proportion to their share in total costs, as in BFK or Hsieh and Klenow (2009). In either of those cases, these can be taken directly from the data as $\alpha_j\eta_j = R_{njt}K_{njt}/P_{njt}Y_{njt}$ and $(1-\alpha_j)\eta_j = W_{njt}L_{njt}/P_{njt}Y_{njt}$, where $P_{njt}Y_{njt}$ is total revenue, R_{njt} is the price of capital, and W_{njt} is the wage rate. The growth in real GDP then can be written as:

$$\begin{aligned} d\ln Y_{nt} &\approx \sum_{j=1}^{J} w_{njt-1}^{D}\Bigg\{\underbrace{d\ln Z_{njt}}_{\text{True TFP}} + \underbrace{(\gamma_j-1)d\ln\left[\left(K_{njt}^{\alpha_j}L_{njt}^{1-\alpha_j}\right)^{\eta_j}X_{njt}^{1-\eta_j}\right]}_{\text{Scale effect}} \\ &\quad + \underbrace{\alpha_j\eta_j d\ln K_{njt} + (1-\alpha_j)\eta_j d\ln L_{njt}}_{\text{Primary inputs}}\Bigg\}. \end{aligned} \tag{2.3}$$

Write real GDP growth as a sum of two components:

$$d\ln Y_{nt} \approx d\ln Z_{nt} + d\ln \mathcal{I}_{nt}, \tag{2.4}$$

where aggregate TFP is denoted by:

$$d\ln Z_{nt} = \sum_{j=1}^{J} w_{njt-1}^{D} d\ln Z_{njt}, \tag{2.5}$$

and the input-driven component of GDP growth is defined as:

$$d\ln \mathcal{I}_{nt} \equiv \sum_{j=1}^{J} w^D_{njt-1} \left\{ \underbrace{(\gamma_j - 1) d\ln \left[\left(K^{\alpha_j}_{njt} L^{1-\alpha_j}_{njt} \right)^{\eta_j} X^{1-\eta_j}_{njt} \right]}_{\text{Scale effect}} + \underbrace{\alpha_j \eta_j d\ln K_{njt} + (1-\alpha_j)\eta_j d\ln L_{njt}}_{\text{Primary inputs}} \right\}. \quad (2.6)$$

2.1 Unobserved Factor Utilization

Let the true factor inputs be comprised of:

$$K_{njt} \equiv U_{njt} M_{njt} \quad (2.7)$$

and

$$L_{njt} \equiv E_{njt} H_{njt} N_{njt}. \quad (2.8)$$

The true capital input is the product of the quantity of capital input ("machines") M_{njt} that can be measured in the data, and capital utilization U_{njt} that is not directly observable. Similarly, the true labor input is the product of the number of workers N_{njt}, hours per worker H_{njt}, and labor effort E_{njt}. While N_{njt} and H_{njt} can be obtained from existing datasets, E_{njt} is unobservable.

Relationship to Solow residual The Solow residual S_{njt} takes factor shares and nets out the observable factor uses. It has the following relationship to gross output and observed inputs:

$$d\ln Y_{njt} = d\ln S_{njt} + \alpha_j \eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln H_{njt} + (1-\alpha_j)\eta_j d\ln N_{njt} + (1-\eta_j)\, d\ln X_{njt}.$$

Plugging this way of writing output growth into the real GDP growth equation (2.2), we get the following expression:

$$\begin{aligned} d\ln Y_{nt} &\approx \sum_{j=1}^{J} w^D_{njt-1} \left(d\ln S_{njt} + \alpha_j \eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln H_{njt} + (1-\alpha_j)\eta_j d\ln N_{njt} \right. \\ &\quad \left. + (1-\eta_j)\, d\ln X_{njt} - d\ln X_{njt} \frac{p^X_{njt-1} X_{njt-1}}{p_{njt-1} Y_{njt-1}} \right) \\ &= \sum_{j=1}^{J} w^D_{njt-1} \left(d\ln S_{njt} + \alpha_j \eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln H_{njt} + (1-\alpha_j)\eta_j d\ln N_{njt} \right) \quad (2.9) \end{aligned}$$

Comparing (2.3) to (2.9), the Solow residual contains the following components:

$$\begin{aligned} d\ln S_{njt} &= \underbrace{d\ln Z_{njt}}_{\text{True TFP}} + \underbrace{(\gamma_j - 1) d\ln\left[\left(K_{njt}^{\alpha_j} L_{njt}^{1-\alpha_j}\right)^{\eta_j} X_{njt}^{1-\eta_j}\right]}_{\text{Scale effect}} \\ &\quad + \underbrace{\alpha_j \eta_j d\ln U_{njt} + (1-\alpha_j)\eta_j d\ln E_{njt}}_{\text{Unobserved utilization}}. \end{aligned}$$

This expression makes it transparent that in this setting, the Solow residual can diverge from the true TFP shock for two reasons: departures from constant returns to scale at the industry level, and unobserved utilization of inputs.

Let aggregate Solow residual be denoted by:

$$d\ln S_{nt} = \sum_{j=1}^{J} w_{njt-1}^{D} d\ln S_{njt} = d\ln Z_{nt} + d\ln \mathcal{U}_{nt},$$

where in the second equality, $d\ln \mathcal{U}_{nt}$ is the aggregate utilization adjustment:

$$\begin{aligned} d\ln \mathcal{U}_{nt} &\equiv \sum_{j=1}^{J} w_{njt-1}^{D} \left\{ (\gamma_j - 1) d\ln\left[\left(K_{njt}^{\alpha_j} L_{njt}^{1-\alpha_j}\right)^{\eta_j} X_{njt}^{1-\eta_j}\right] \right. \\ &\quad \left. + \alpha_j \eta_j d\ln U_{njt} + (1-\alpha_j)\eta_j d\ln E_{njt} \right\}. \end{aligned}$$

2.2 Implications for International Comovement

We now use this accounting decomposition to study the role of TFP shocks and utilization for international comovement. The covariance of real GDP between countries n and m is:

$$\begin{aligned} Cov(d\ln Y_{nt}, d\ln Y_{mt}) &= Cov(d\ln Z_{nt}, d\ln Z_{mt}) + Cov(d\ln \mathcal{I}_{nt}, d\ln \mathcal{I}_{mt}) \\ &\quad + Cov(d\ln Z_{nt}, d\ln \mathcal{I}_{mt}) + Cov(d\ln \mathcal{I}_{nt}, d\ln Z_{mt}). \end{aligned} \tag{2.10}$$

This expression can be converted into correlations, as those have a more natural scale and are most commonly found in business cycle analyses:

$$\begin{aligned} \varrho(d\ln Y_{nt}, d\ln Y_{mt}) &= \frac{\sigma_{Z_n}\sigma_{Z_m}}{\sigma_n \sigma_m} \varrho(d\ln Z_{nt}, d\ln Z_{mt}) + \frac{\sigma_{\mathcal{I}_n}\sigma_{\mathcal{I}_m}}{\sigma_n \sigma_m} \varrho(d\ln \mathcal{I}_{nt}, d\ln \mathcal{I}_{mt}) \\ &\quad + \frac{\sigma_{Z_n}\sigma_{\mathcal{I}_m}}{\sigma_n \sigma_m} \varrho(d\ln Z_{nt}, d\ln \mathcal{I}_{mt}) + \frac{\sigma_{\mathcal{I}_n}\sigma_{Z_m}}{\sigma_n \sigma_m} \varrho(d\ln \mathcal{I}_{nt}, d\ln Z_{mt}), \end{aligned} \tag{2.11}$$

where $\varrho(.,.)$ denotes correlation, σ_n is the standard deviation of $d\ln Y_{nt}$, and σ_{Z_n} and $\sigma_{\mathcal{I}_n}$ are standard deviations of $d\ln Z_{nt}$ and $d\ln \mathcal{I}_{nt}$, respectively. Equations (2.10)-(2.11) convey that in the proximate sense, comovement in real GDP between two countries can be driven by correlated TFP shocks

$\varrho(d\ln Z_{nt}, d\ln Z_{mt})$, correlated inputs $\varrho(d\ln \mathcal{I}_{nt}, d\ln \mathcal{I}_{mt})$, or the cross-correlations between them.

It is immediate that the observed Solow residual can be correlated across countries both due to correlated shocks to true TFP, and due to correlated unobserved input adjustments:

$$\begin{aligned}\varrho(d\ln S_{nt}, d\ln S_{mt}) &= \frac{\sigma_{Z_n}\sigma_{Z_m}}{\sigma_{S_n}\sigma_{S_m}}\varrho(d\ln Z_{nt}, d\ln Z_{mt}) + \frac{\sigma_{\mathcal{U}_n}\sigma_{\mathcal{U}_m}}{\sigma_{S_n}\sigma_{S_m}}\varrho(d\ln \mathcal{U}_{nt}, d\ln \mathcal{U}_{mt}) \\ &+ \frac{\sigma_{Z_n}\sigma_{\mathcal{U}_m}}{\sigma_{S_n}\sigma_{S_m}}\varrho(d\ln Z_{nt}, d\ln \mathcal{U}_{mt}) + \frac{\sigma_{\mathcal{U}_n}\sigma_{Z_m}}{\sigma_{S_n}\sigma_{S_{n'}}}\varrho(d\ln \mathcal{U}_{nt}, d\ln Z_{mt}),\end{aligned}$$

where σ_{S_n} and $\sigma_{\mathcal{U}_n}$ are standard deviations of $d\ln S_{nt}$ and $d\ln \mathcal{U}_{nt}$, respectively. Thus, it is an empirical question to what degree correlations in the Solow residual reflect true technology shock correlation as opposed to endogenous input adjustments. It is clear, however, that using the Solow residual as a measure of technology shocks can lead to incorrect assessments of the importance of correlations in TFP shocks vs their transmission (through the input adjustments) for comovement.

To compute TFP and input cross-country correlations, we need to overcome the measurement challenge of estimating the TFP processes when utilization-adjusted factor usage is unobserved.

3 Estimation

Note that $d\ln K_{njt}$ and $d\ln L_{njt}$ are true, utilization-adjusted primary input growth rates. Log-differencing (2.1), and writing input usage breaking up the observed and the unobserved components yields:

$$\begin{aligned}d\ln Y_{njt} &= \gamma_j \underbrace{\left(\alpha_j\eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln\left(H_{njt}N_{njt}\right) + (1-\eta_j)d\ln X_{njt}\right)}_{\text{Observed Inputs}} \\ &+ \gamma_j \underbrace{\left(\alpha_j\eta_j d\ln U_{njt} + (1-\alpha_j)\eta_j d\ln E_{njt}\right) + d\ln Z_{njt}}_{\text{Unobserved Inputs}}.\end{aligned} \tag{3.1}$$

This equation makes it plain that measuring TFP innovations is difficult because the intensity with which factors are used in production varies over the business cycle, and cannot be directly observed by the econometrician. As unobserved factor utilization will respond to TFP innovations, it is especially important to account for it in estimation, otherwise factor usage will appear in estimated TFP.

We now set up a multi-country, multi-sector framework with variable factor utilization to derive the BFK estimating equation. The key insight of BFK is that the agents' static optimization implies that the intensity of usage of observed and unobserved inputs are related. While the framework below is useful to build intuition, it is only intended as motivation and is not necessary for the estimation. Indeed, BFK derive the same estimating equation in a partial-equilibrium setting without specifying the details of household choices or dynamics. While the BFK intuition is more general than the model below, fully articulating a model as we do here has two benefits. First, it shows that the BFK structural equation applies in a fairly general open economy setting. And second, after estimating the TFP series, we return to this theoretical framework and simulate the worldwide business cycle fluctuations that result from these measured TFP shocks.

3.1 Framework

Households Each country n is populated by a representative household. The household consumes the final good available in country n and supplies labor and capital to firms. There is a continuum of workers in the household who share the same consumption. The problem of the household is

$$\max_{\substack{\{M_{njt}\},\{N_{njt}\},\\ \{H_{njt}\},\{E_{njt}\},\{U_{njt}\}}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \ \Psi \left(C_{nt} - \sum_j \xi_{nj} N_{njt} G(H_{njt}, E_{njt}, U_{njt}) - \sum_j \Xi\left(N_{njt}\right) \right) \tag{3.2}$$

subject to

$$P_{nt} \left(C_{nt} + \sum_j I_{njt} \right) = \sum_j W_{njt} N_{njt} H_{njt} E_{njt} + \sum_j R_{njt} U_{njt} M_{njt}$$

$$M_{njt+1} = (1-\delta_j) M_{njt} + I_{njt}$$

where C_{nt} is consumption and I_{njt} is investment. The effective total efficiency units of labor supplied in a sector is $E_{njt}H_{njt}N_{njt}$, and the effective total efficiency units of capital supplied is $U_{njt}M_{njt}$. Labor collects a sector-specific wage W_{njt}, and capital is rented for the price R_{njt}.

We assume the following functional form for $G\left(.\right)$:

$$G\left(H,E,U\right) = \left(\frac{H}{\psi_h}\right)^{\psi_h} + \left(\frac{E}{\psi_e}\right)^{\psi_e} + \left(\frac{U}{\psi_u}\right)^{\psi_u}. \tag{3.3}$$

We highlight three features of the household problem. First, labor and capital are differentiated by sector, as the household supplies factors to, and accumulates capital in, each sector separately. In this formulation, labor and capital are neither fixed to each sector nor fully flexible. As $\psi_\iota \to 1$, $\iota = h, e, u$, factor supply across sectors becomes more sensitive to factor price differentials, in the limit households supplying variable factors only to the sector offering the highest factor price. At the opposite extreme, as $\psi_\iota \to \infty$, the supply of hours, effort, and capital utilization is fixed in each sector by the preference parameters.

Second, we assume that the number of employed workers N_{njt} and machines M_{njt} in a sector is predetermined. This is required in order to have a well-defined notion of variable utilization. While this approach is standard for machines, it is less common for employment, where it is usually assumed that hours and employment move in parallel. Specifically, in our model the number of workers in a particular sector has to be chosen before observing the current shocks as in Burnside, Eichenbaum, and Rebelo (1993), reflecting the fact that it takes time to adjust the labor force.[2] On the other hand, within a period households can choose the hours H_{njt} and effort E_{njt} that change the effective amount of labor supply, and utilization rates U_{njt} that change the effective amount of capital supply. These margins capture the idea that utilization rates of factor inputs typically vary over the business cycle. Our framework thus implies that within a period, labor and capital supply to each sector are upward-sloping (e.g. Christiano, Motto, and Rostagno, 2014).

Third, our formulation of the disutility of the variable factor supply (3.3) is based on the Greenwood, Hercowitz, and Huffman (1988) preferences for labor and a similar isoelastic formulation of the utilization cost of capital. The GHH preferences mute the interest rate effects and income effects on the choice of hours, effort, and utilization rates, which helps to study the properties of the static equilibrium where the number of machines and employees are treated as exogenous variables.

Firms A representative firm in sector j in country n operates a CRS production function

$$Y_{njt} = Z_{njt}\Theta_{njt}\left(K_{njt}^{\alpha_j}L_{njt}^{1-\alpha_j}\right)^{\eta_j}X_{njt}^{1-\eta_j}, \tag{3.4}$$

where K_{njt} and L_{njt} are the true capital and labor inputs as in (2.7)-(2.8), and the total factor productivity $Z_{njt}\Theta_{njt}$ is taken as given. The intermediate input usage X_{njt} is an aggregate of inputs from potentially all countries and sectors:

$$X_{njt} \equiv \left(\sum_{m,i}\mu_{mi,nj}^{\frac{1}{\varepsilon}}X_{mi,njt}^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}},$$

where $X_{mi,njt}$ is the usage of inputs coming from sector i in country m in production of sector j in country n, and $\mu_{mi,nj}$ is the input coefficient.

The total factor productivity consists of two parts: the exogenous shocks Z_{njt} and the endogenous component:

$$\Theta_{njt} = \left(\left(K_{njt}^{\alpha_j}L_{njt}^{1-\alpha_j}\right)^{\eta_j}X_{njt}^{1-\eta_j}\right)^{\gamma_j-1}, \tag{3.5}$$

where γ_j controls possible congestion or agglomeration effects. As a result, the sectoral aggregate production function is then (2.1).

[2] Our assumption implies that there are frictions that limit the substitutability of employment and the workweek. This assumption can be supported by the data. For instance, in our sample the standard deviation of hours per worker growth is 0.02 and of employment is 0.06, suggesting the two margins should not be treated symmetrically.

Optimality Conditions The households' intra-temporal optimization problem leads to

$$H_{njt}G_h(H_{njt}, E_{njt}, U_{njt}) = E_{njt}G_e(H_{njt}, E_{njt}, U_{njt}).$$

Under the functional form adopted for $G(.)$, this condition implies that the choice of effort has a log-linear relationship with the choice of hours:

$$d\ln E_{njt} = \frac{\psi^h}{\psi^e} d\ln H_{njt}. \tag{3.6}$$

A similar expression can be derived for the relationship between the optimal choice of capital utilization and the optimal choice of hours:

$$\frac{H_{njt}G_h(H_{njt}, E_{njt}, U_{njt})}{U_{njt}G_u(H_{njt}, E_{njt}, U_{njt})} = \frac{W_{njt}L_{njt}}{R_{njt}K_{njt}}.$$

We know from the firms' problem that the right-hand side of the equation above is equal to the ratio of output elasticities $\alpha_j/(1-\alpha_j)$, which is a constant. As a result, the utilization rate also has a log-linear relationship with hours worked:

$$d\ln U_{njt} = \frac{\psi_h}{\psi_u} \ln H_{njt} \tag{3.7}$$

up to a normalization constant.

The properties (3.6)-(3.7) capture the idea that flexible inputs tend to move jointly in the same direction. The household intra-temporal first-order conditions therefore allow us express unobserved effort and capital utilization as a log-linear function of observed hours:

$$\alpha_j \eta_j d\ln U_{njt} + (1-\alpha_j)\eta_j d\ln E_{njt} = \zeta_j d\ln H_{njt}, \tag{3.8}$$

where $\zeta_j = \eta_j \left(\alpha_j \frac{\psi^h}{\psi^u} + (1-\alpha_j) \frac{\psi^h}{\psi^e} \right)$. In BFK, the choice between effort, utilization rates, and hours is made by firms facing upward-sloping supply curves of these dimensions of factor inputs. In contrast, we model the trade-off between these margins as being faced by households. These two modeling approaches lead to the same relationship (3.8) between unobservables and observables. Our approach has the advantage of being consistent with both the econometric estimation and the general equilibrium framework that we use for quantification.

Estimating Equation Plugging (3.8) into (3.1) yields the following estimating equation:

$$\begin{aligned} d\ln Y_{njt} &= \delta_j^1 \left(\alpha_j \eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln\left(H_{njt}N_{njt}\right) + (1-\eta_j) d\ln X_{njt}\right) \\ &\quad + \delta_j^2 d\ln H_{njt} + \delta_{nj} + d\ln Z_{njt}, \end{aligned} \tag{3.9}$$

where we also added country×sector fixed effects δ_{nj} to allow for country-sector specific trend output growth rates.

The estimation proceeds to regress real output growth on the growth of the composite observed input bundle and the change in hours per worker. The coefficient δ_j^1 is clearly an estimate of returns-to-scale γ_j. Equation (3.8) provides a structural interpretation for the coefficient $\delta_j^2 = \gamma_j \zeta_j$.[3]

In addition, conditional on these estimates and the log changes in the observed inputs, we obtain the TFP shocks $d\ln Z_{njt}$ as residuals. We use the estimate of ζ_j in two places, as we need it to construct the $d\ln\left[\left(K_{njt}^{\alpha_j} L_{njt}^{1-\alpha_j}\right)^{\eta_j} X_{njt}^{1-\eta_j}\right]$ term:

$$d\ln\left[\left(K_{njt}^{\alpha_j} L_{njt}^{1-\alpha_j}\right)^{\eta_j} X_{njt}^{1-\eta_j}\right] = d\ln\left(M_{njt}^{\alpha_j\eta_j} N_{njt}^{(1-\alpha_j)\eta_j} H_{njt}^{(1-\alpha_j)\eta_j+\zeta_j} X_{njt}^{1-\eta_j}\right),$$

where we substituted for unobserved inputs using (3.8). Then, the growth rate of GDP can be expressed in terms of observable and estimated values:

$$\begin{aligned} d\ln Y_{nt} \approx \sum_{j=1}^{J} w_{njt-1}^D \Bigg\{ & \underbrace{d\ln Z_{njt}}_{\text{True TFP}} + \underbrace{(\gamma_j - 1)\left[d\ln\left(M_{njt}^{\alpha_j\eta_j} N_{njt}^{(1-\alpha_j)\eta_j} H_{njt}^{(1-\alpha_j)\eta_j+\zeta_j} X_{njt}^{1-\eta_j}\right)\right]}_{\text{Scale effect}} \\ & + \underbrace{\left(\alpha_j\eta_j d\ln M_{njt} + (1-\alpha_j)\eta_j d\ln H_{njt} + (1-\alpha_j)\eta_j d\ln N_{njt}\right) + \zeta_j d\ln H_{njt}}_{\text{Utilization-adjusted primary inputs}} \Bigg\}. \end{aligned} \tag{3.10}$$

With this expression in hand, we can implement the decomposition of real GDP growth into TFP and input growth (2.4), and the covariance/correlation decompositions (2.10)-(2.11).

3.2 Identification

Because input usage will move with TFP shocks $d\ln Z_{njt}$, the regressors in (3.9) are correlated with the residual. To overcome this endogeneity problem, we consider three potential instruments that are plausibly orthogonal to true TFP shocks but have predictive power for the movements in inputs.

[3] BFK derive the same estimating equation by assuming instead that firms face an upward-sloping cost schedule for increasing effort, hours, or utilization holding other factors constant. While our framework is somewhat less general, an advantage is that we do not have to assume ad hoc convex cost functions for firm choices. Our framework can also easily be nested in standard IRBC models. The structural interpretation of the estimated parameters in our framework differs slightly from BFK, but we can still recover estimates of returns-to-scale and adjust for unobserved utilization.

The first is oil shocks, identified using the approach in Hamilton (1994), defined as the difference between the log oil price and the maximum log oil price in the preceding four quarters. This oil price shock is either zero, or is positive when this difference is positive, reflecting the notion that oil prices have an asymmetric effect on output. The annualized oil shock is the sum over the four quarters of the preceding year. The second instrument is the growth rate in real government defense spending, lagged by one year. Finally, the third instrument is the foreign monetary policy shock interacted with the exchange rate regime. This instrument follows di Giovanni and Shambaugh (2008) and di Giovanni, McCrary, and von Wachter (2009), who show that major country interest rates have a significant effect on countries' output when they peg their currency to that major country. The assumption in specifications that use this instrument is that for many countries, interest rates in the US, Germany, or the UK are exogenous.

In practice, we estimate two separate sets of regressions. The first is confined to only the G7 countries, and uses only the first two instruments (oil and military spending). This tends to lead to the strongest instruments and most precisely estimated coefficients. Since these are the major world economies, the foreign interest rate instrument is not appropriate here. Second, we estimate this equation on the full sample of countries excluding the "base" countries of US, Germany, and the UK, in which case we use all three instruments.[4]

Finally, following BFK, to reduce the number of parameters to be estimated, we restrict δ_j^2 to take only three values, according to a broad grouping of sectors: durable manufacturing, non-durable manufacturing, and all others.

3.3 Data

The data requirements for estimating equation (3.9) are growth of real output and real inputs for a panel of countries, sectors, and years. The dataset with the broadest coverage of this information is KLEMS 2009 (O'Mahony and Timmer, 2009).[5] This database contains gross output, value added, labor and capital inputs, as well as output and input deflators. In a limited number of instances, we supplemented the information available in KLEMS with data from the WIOD Socioeconomic Accounts, which contains similar variables. After data quality checking and cleaning, we retain a sample of 29 countries, listed in Appendix Table A1. The database covers all sectors of the economy at a level slightly more aggregated than the 2-digit ISIC revision 3, yielding, after harmonization, 30 sectors listed in Appendix Table A2. In the best cases we have 38 years of data, 1970-2007,

[4]BFK face a similar identification problem when estimating the utilization-adjusted series for the US. They use a monetary policy shock identified in a VAR, an oil price shock, and the growth in real defense spending. Our instruments are similar in spirit.

[5]This is not the latest vintage of KLEMS, as there is a version released in 2016. Unfortunately, however, the 2016 version has a shorter available time series, as the data start in 1995, and also has many fewer countries. A consistent concordance between the two vintages is not possible without substantial aggregation.

although the panel is not balanced and many emerging countries do not appear in the data until the mid-1990s.

The oil price series is the West Texas Intermediate, obtained from the St. Louis Fed's FRED database. We have also alternatively used the Brent Crude oil price, obtained from the same source. Military expenditure comes from the Stockholm International Peace Research Institute (SIPRI). The exchange rate regime classification along with information on the base country comes from Shambaugh (2004), updated in 2015. Finally, base country interest rates are proxied by the Money Market interest rates in these economies, and obtained from the IMF International Financial Statistics.

The quantitative analysis in Section 5 requires additional information on the input linkages at the country-sector-pair level, as well as on final goods trade. This information comes from the 2013 WIOD database (Timmer et al., 2015), which contains the global input-output matrix.

4 Empirical Results

Production Function Estimates Our baseline production function parameter estimates rely only on the G7 sample of countries, as these estimates are the least noisy. For these countries, the modified monetary policy (exchange-rate based) instrument cannot be used. We therefore employ the oil shock and defense spending instruments. Table 1 summarizes the results of estimating equation (3.9). The returns to scale parameters vary from about 0.7 to 0.9 in durable manufacturing, from 0.3 to 1 in non-durable manufacturing, and from 0.4 to nearly 2 in the quite heterogeneous non-manufacturing sector. Thus, the estimates show departures from constant returns to scale in a number of industries, consistent with existing evidence. The coefficient on hours per worker ($d \ln H_{njt}$) is significantly different from zero in two out of three industry groups, indicating that adjusting for unobserved utilization is important in the manufacturing industries. Appendix Table A3 reports the complete set of industry-specific production function estimates within each of these three broad groups.

We have multiple instruments and multiple endogenous variables in our estimation. The appropriate test statistic for diagnosing the weak instruments problem is the Sanderson-Windmeijer F, which is designed for a setting with multiple instruments and endogenous variables. The SW-F statistic is 7.97, suggesting that the instruments are not weak. In 2 sectors, Mining and Quarrying and Food, Beverages and Tobacco returns to scale coefficient point estimates are negative. We drop those sectors from the estimation sample.

While the point estimates of both the returns to scale for our sectors and the coefficients on the utilization adjustment term will naturally not coincide perfectly with those in BFK, they are similar to the estimates in that paper in many cases. For instance, our coefficients (s.e.'s) on the utilization adjustment term are 1.420(0.389), 2.929(1.771) and 0.260(0.643) for durables, non-durables and non-manufacturing respectively. The comparable estimates in BFK Table 1 are 1.34(0.22), 2.13(0.38) and 0.64(0.34) respectively.

TABLE 1: Summary of Production Function Parameter Estimates

Industry Group	Median Returns to Scale	Utilization Adjustment
Durables	0.806	1.420
	[0.701,0.895]	(0.389)
Non-durable manufacturing	0.753	2.929
	[0.291,0.926]	(1.771)
Non-durable non-manufacturing	1.244	0.260
	[0.451,1.864]	(0.643)

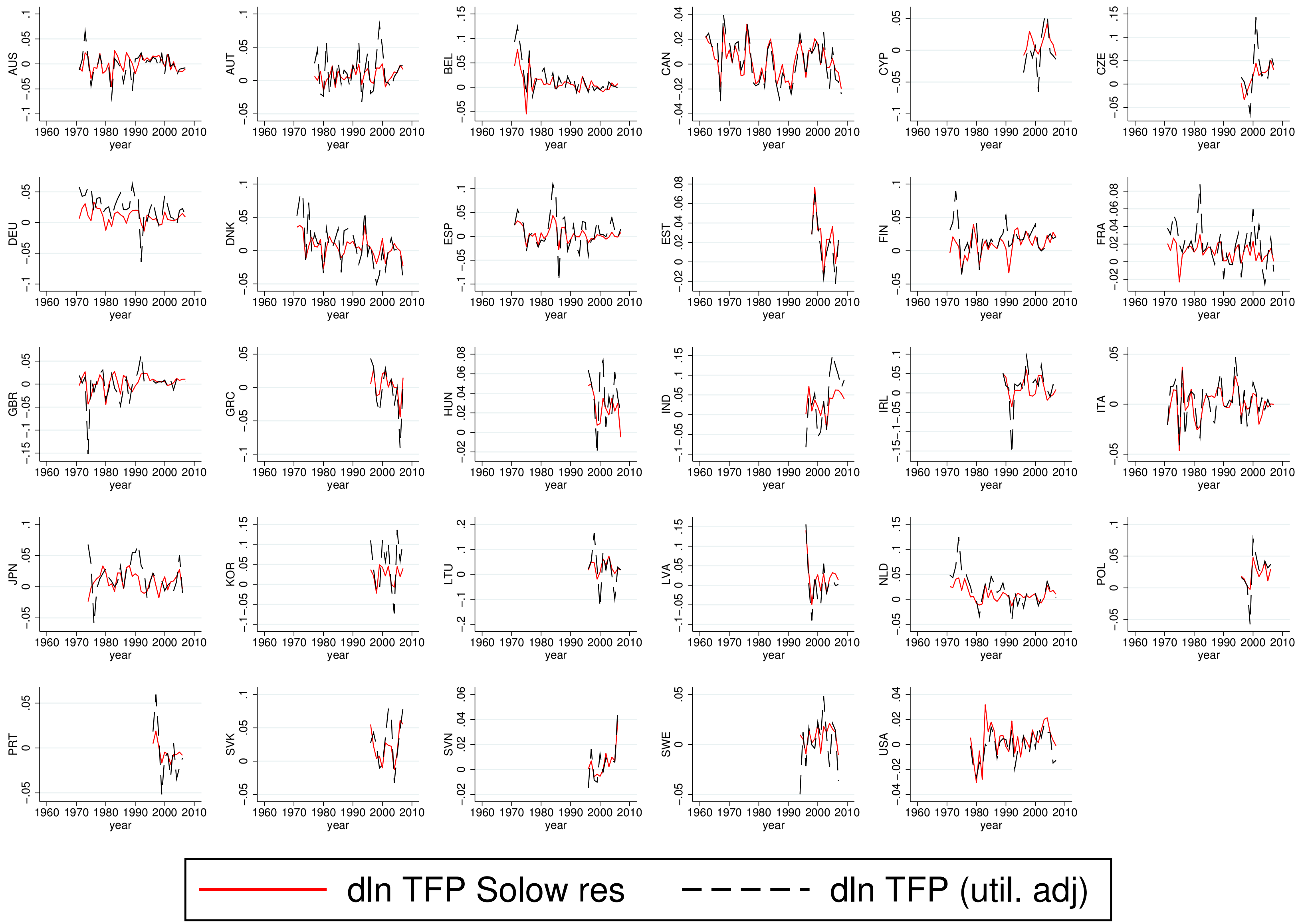
Notes: This table reports the range of estimates of γ_j in the three broad groups of sectors, and the estimates of ζ_j along with their standard errors clustered at the country-sector in parentheses.

Utilization-Adjusted TFP Series Figure 1 contrasts the Solow residual with the utilization-adjusted TFP series for all the countries in our sample. The time series for the utilization adjusted TFP estimates by country are available for download online. While we do find that the utilization-adjusted TFP series is less volatile than the Solow residual for the US, as in BFK, for the large majority of other countries the adjusted TFP series is more volatile. In fact, the mean (median) variance of the TFP series is .0015 (0.0009), while for the Solow residual it is 0.0004 (0.0003).

Sensitivity We construct TFP series directly using the coefficient estimates in BFK (applied to all countries), and correlate that series to our TFP series. Appendix Table A4 reports the results. The TFP series based on the BFK coefficients have an 86% correlation with ours. To assuage concerns that for some countries these instruments might individually be weak, we estimate the coefficients excluding each of the G7 countries one after another, and construct TFP series with those alternative coefficients. Table A4 presents the pairwise correlations between our baseline TFP series, and all TFP series dropping an individual country. With the partial exception of dropping Canada, excluding individual G7 countries from production function estimation leads to TFP series quite correlated with our baseline. All in all, the TFP series are highly correlated across all approaches, suggesting our estimates are not driven by any country in particular.

Finally, we estimate the production function parameters using the full 29-country sample. In this sample, we introduce a third instrument, which is the foreign monetary policy shock interacted with the exchange rate regime. This instrument follows di Giovanni and Shambaugh (2008) and di Giovanni, McCrary, and von Wachter (2009), who show that major country interest rates have

Figure 1: Comparison between Utilization-Adjusted TFP and the Solow Residual



Notes: This figure displays the log changes in the Solow residual and in the utilization-adjusted TFP series for every country in our sample.

a significant effect on countries' output when they peg their currency to that major country. The assumption in specifications that use this instrument is that for many countries, interest rates in the US, Germany, or the UK are exogenous. We exclude the "base interest rate" countries themselves (the US, Germany, and the UK) from the sample. Table A4 correlates the resulting TFP estimates to with our baseline. This alternative TFP series is positively correlated with the baseline, with a coefficient of 0.6.

Our TFP estimation process also provides us with series for utilization rates by sector. In the US, the Federal Reserve Board (FRB) also publishes series of industry-level utilization for manufacturing industries only. These series are constructed by dividing an index of industrial production by an index of estimated industrial capacity. The FRB series are constructed using a number of sources including survey data from the US Census Bureau. The FRB cautions that these series should not be compared across industries (in contrast to our estimates). See Boehm and Pandalai-Nayar (2019) for a discussion.

The left panel of Appendix Figure A1 compares our industry-level estimates to these public series. The two are positively correlated, despite the different underlying data sources and methodology used for constructing them. The right panel of the figure compares our estimates for the country-level average utilization growth rate against the country-level utilization based on the FRB data for the US, and Eurostat data for some European countries. Again, we find a positive correlation.

International Correlation Decomposition Table 2 presents the basic summary statistics for the elements of the GDP decomposition in equation (2.4). These results are useful for highlighting the role of the TFP shocks and comparing them to the Solow residual. The top panel reports the correlations among the G7 countries. The average correlation of real GDP growth among these countries is 0.36. The second line summarizes correlations of the TFP shocks. Those are on average close to zero, if not negative. By contrast, input growth is positively correlated, with a mean of 0.25. The left panel of Figure 2 depicts the kernel densities of the correlations of real GDP, TFP, and inputs. There is a clear hierarchy, with the real GDP being most correlated, and the TFP the least correlated and centered on zero.

Section 2 shows that the Solow residual can be written as a sum of the aggregate TFP growth and the aggregated variable utilization change $d\ln\mathcal{U}_{nt}$. Thus, it is an empirical question to what degree correlations in the Solow residual reflect true technology shock correlation as opposed to endogenous input adjustments. Table 2 shows that the Solow residual has an average correlation of about 0.09 in the G7 countries. If Solow residuals were taken to be a measure of TFP shocks, we would have concluded that TFP is positively correlated in this set of countries. As we can see, this conclusion would be misleading. Indeed, the correlation in the utilization term $\mathcal{U}_{nt}$, which is the difference between the true TFP shock $d\ln Z_{nt}$ and the Solow residual, accounts for all of the correlation in the

Table 2: Correlations Summary Statistics

	Mean	Median	25th pctile	75th pctile
	G7 Countries (N. obs. = 21)			
$d\ln Y_{nt}$	0.358	0.337	0.242	0.565
$d\ln Z_{nt}$	0.012	-0.008	-0.080	0.150
$d\ln \mathcal{I}_{nt}$	0.252	0.190	0.071	0.450
$d\ln S_{nt}$	0.086	0.120	-0.022	0.300
$d\ln \mathcal{U}_{nt}$	0.133	0.128	-0.020	0.243
	All countries (N. obs. = 406)			
$d\ln Y_{nt}$	0.190	0.231	-0.027	0.437
$d\ln Z_{nt}$	-0.005	0.002	-0.200	0.218
$d\ln \mathcal{I}_{nt}$	0.084	0.081	-0.147	0.330
$d\ln S_{nt}$	0.052	0.083	-0.150	0.296
$d\ln \mathcal{U}_{nt}$	0.025	0.036	-0.172	0.234

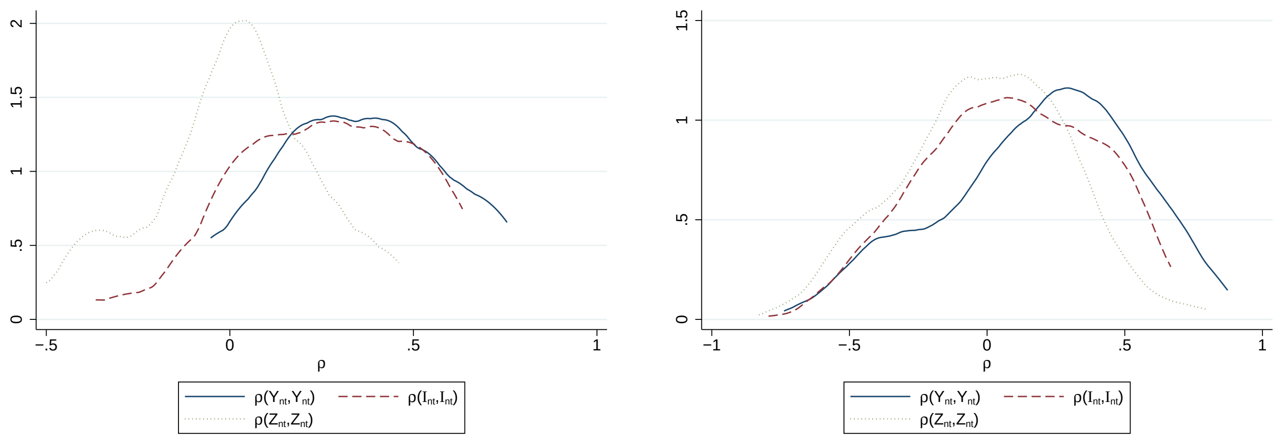
Notes: This table presents the summary statistics of the correlations in the sample of G7 countries (top panel) and full sample (bottom panel). Variable definitions and sources are described in detail in the text.

Solow residual, on average. This indicates that the correlation in the Solow residual is in fact driven by unobserved input utilization and scale adjustments.

The bottom panel of Table 2 repeats the exercise in the full sample of countries. The basic message is the same as for the G7 but quantitatively the picture is not as stark and the variation is greater. It is still the case that $d\ln Z_{nt}$ has a zero average correlation. It is also still the case that the inputs $d\ln \mathcal{I}_{nt}$ have greater correlation, and that their correlation is on average about half of the average real GDP correlation. The Solow residuals are also more correlated than $d\ln Z_{nt}$, and part of the difference is accounted for by the fact that the unobserved inputs are positively correlated. The right panel of Figure 2 displays the kernel densities of the correlations in the full sample.

To summarize, real GDP growth is significantly positively correlated in our sample of countries, especially in the G7. TFP growth has an average zero correlation. By contrast, correlations in input growth have the same order of magnitude as real GDP correlations. Finally, using Solow residuals as a proxy for TFP growth can be quite misleading. In our sample of countries, it would lead us to conclude that productivity growth is noticeably positively correlated across countries, whereas in fact correlation in the Solow residuals appears to be driven mostly by correlation in the unobserved

Figure 2: Correlations: Kernel Densities



G7 Countries (N. obs. = 21) All countries (N. obs. = 406)

Notes: This figure displays the kernel densities of real GDP growth, the utilization-adjusted TFP, and input correlations in the sample of G7 countries (left panel) and full sample (right panel). Variable definitions and sources are described in detail in the text.

inputs.

This is of course only an accounting decomposition. Factor usage will respond to TFP shocks at home and abroad. Since the growth in $\mathcal{I}_{nt}$ has not been cleaned of the impact of technology shocks, we cannot conclude that TFP shocks do not contribute to international comovement at all. We next turn a quantitative model of international shock propagation to assess the complete role of TFP shocks for comovement.

5 General Equilibrium

While commonly used IRBC models typically do not feature an input-output structure, to be consistent with our estimation above, we incorporate sectors into our quantitative model. Our quantitative exercise considers an international version of the network propagation model following Acemoglu et al. (2012). This exercise emphasizes the role of the input-output linkages in amplifying or dampening the underlying contemporaneous sectoral shocks. Appendix A presents the full model and equilibrium conditions. Though non-linear, this model is very similar to quantitative trade models and can be solved exactly or by linearizing.

The advantage of the network model is that it it transparent on the role of input linkages in shock propagation, and can be implemented on a large set of countries and a limited time series like we have in our data. The disadvantage is that it rules out dynamic responses of capital accumulation and intertemporal labor adjustment to the shocks. In related work (Huo, Levchenko, and Pandalai-Nayar, 2020), we use a similar quantitative model to show that delayed propagation of shocks contributes relatively little to overall comovement. Appendix A.2 develops a dynamic model and implements it on the G7 countries. Adding dynamics does not qualitatively affect our main finding on the ability of TFP shocks to generate GDP correlations.

5.1 Calibration

In implementing the network model, we only need to take a stand on the value of a small number of parameters, and use our data to provide the required quantities. Table 3 summarizes the parameter assumptions for the static model and data sources. In Huo, Levchenko, and Pandalai-Nayar (2020) we estimate the substitution elasticities in final and intermediate use. Based on these estimation results, the final consumption Armington elasticity ρ is set to either 2.75 or 1, and the intermediate input substitution elasticity ε to 1. Two parameters ψ_e and ψ_h govern the elasticity of different margins of labor supply (hours and effort). As we lack evidence that the elasticity with respect to hours should differ from that for effort, we set them both to 4, implying the Frisch labor supply elasticity is 0.5 as advocated by Chetty et al. (2013). This value is conservative relative to the elasticity of 2 common in the business cycle literature. Raising the Frisch elasticity leads to greater transmission of shocks and higher GDP correlations in our model. We have less guidance to set the capital supply parameter ψ_u. Our TFP estimation procedure coupled with our choices of ψ_e and ψ_h provides an overidentification restriction for ψ_u, evident in (3.8). However, the range of values that satisfy this restriction is large, and includes values that imply very elastic and inelastic capital supply. We therefore choose a baseline value of 4, implying a relatively inelastic capital supply, but also assess the performance of the model for a value of 1.01 – a highly elastic capital supply.

All other parameters in the static model have close counterparts in basic data and thus we compute them directly. Capital shares in total output α_j come from KLEMS, and are averaged in each sector across countries and time. The scale parameters γ_j come from our own production function estimates reported in Appendix Table A3. We initialize both the static and dynamic models in the same steady state. Steady state input shares $\pi^x_{mi,nj}$ and final consumption shares π^f_{mnj} are computed from WIOD as time averages.

Recall that we could not estimate the returns to scale coefficient for two sectors in Section 4. For these sectors, in the quantitative exercise we set their returns to scale coefficient to 1. The utilization adjustment coefficient $(\widehat{\delta}^2_j)$ for those sectors is set equal to the utilization adjustment coefficient estimated for the group of sectors to which they belong, non-durable manufacturing for Food, Beverages and Tobacco, and non-manufacturing for Mining and Quarrying.

Table 3: Parameter Values

Param.	Value	Source	Related to
ρ	2.75 or 1	Huo, Levchenko, and Pandalai-Nayar (2020)	final substitution elasticity
ε	1	Huo, Levchenko, and Pandalai-Nayar (2020)	intermediate substitution elasticity
ψ_e, ψ_h	4	Chetty et al. (2013)	Frisch elasticity
ψ_u	4 or 1.01	Our estimates	capital supply elasticity
α_j, β_j		KLEMS	labor and capital shares
γ_j		Our estimates	returns to scale
π^f_{mnjt}		WIOD	final use trade shares
$\pi^x_{mi,njt}$		WIOD	intermediate use trade shares
ω_{nj}		WIOD	final consumption shares

Notes: This table summarizes the parameters and data targets used in the quantitative model, and their sources.

5.2 Model GDP Correlations

Table 4 reports GDP correlations in our model simulated with TFP shocks. As our model can only be implemented on a balanced panel, we report results both for a longer G7-only version of the model spanning years 1978-2007, as well as an all-countries version spanning 1995-2007– the longest timespan for which data are available for all 29 countries. For the G7 group, TFP shocks produce mean correlations of 0.028, less than one-tenth of the level found in the data. For the full sample of countries, TFP shocks produce mean correlations of essentially zero.

Sensitivity Appendix Table A7 contains several robustness exercises for the static model results. The first row reports the model correlations under a lower final-goods substitution elasticity, $\rho = 1$. The second row runs the model with unbalanced trade, by introducing exogenous deficits as in Dekle, Eaton, and Kortum (2008). The next two rows implement two variations on the capital utilization curvature parameter ψ_u: (i) the value implied by the production function coefficient estimates and (3.8); (ii) a low value of 1.01, implying very high elasticity of utilization supply. Finally, the last row simulates the model with a higher Frisch elasticity of 2. The resulting correlations are higher than the baseline in some of the alternative exercises, such as with a lower final-goods substitution elasticity, but they explain at most about 40% of the comovement on average for the G7 and about one-tenth for the all-countries sample.

Comovement with the Solow Residual In Section 4, we highlighted that the Solow residual is more correlated than true TFP, and that its properties are quite different from true TFP. We now explore the implications of feeding in the Solow residual as a measure of technology shocks

Table 4: GDP Correlations in the Data and in the Model with TFP Shocks

	Mean	Median	25th pctile	75th pctile
	G-7 countries (N. obs. = 21)			
Data	0.358	0.337	0.242	0.565
Model, U-TFP	0.028	-0.005	-0.048	0.141
Model, Solow TFP:	0.075	0.090	-0.050	0.299
	All countries (N. obs. = 406)			
Data	0.190	0.231	-0.027	0.437
Model, U-TFP	0.005	0.017	-0.215	0.218
Model, Solow TFP:	0.045	0.024	-0.201	0.305

Notes: This table presents the summary statistics of the correlations of $d \ln Y_{nt}$ in the sample of G7 countries for 1978-2007 (top panel) and full sample for 1995-2007 (bottom panel) in the data and the model with utilization-adjusted TFP shocks. Variable definitions and sources are described in detail in the text.

into our model where factor utilization can vary. This exercise helps assess the consequences of mismeasurement – if the true model features unobserved factor utilization, and the Solow residual is mistakenly used as the measure of technology innovations, then what would we conclude about the role of technology shocks for comovement? The rows labeled "Model, Solow TFP" of Table 4 report GDP comovement with the Solow residual as the shock. For both the longer G7 sample and the shorter all countries sample, comovement is higher with the Solow residual than true TFP . In all cases, GDP correlations under the Solow residual are still not close to that seen in the data, but these results suggest that TFP mismeasurement does affect our understanding of the role of TFP shocks in generating comovement.

6 Conclusion

We measured two types of shocks in the data for a large sample of countries and sectors: utilization-adjusted TFP and the standard Solow Residual. When some margins of factor utilization are unobservable, the Solow residual is a misleading measure of technology innovations. While using utilization-adjusted series is common in the research on the US economy, thus far studies in international macroeconomics have focused on the Solow residual. We provide a new dataset containing utilization-adjusted series for use in open-economy macroeconomics. We illustrate that these series have different international correlation properties from the standard Solow residual. The variation is also different across countries – in many cases these series are more volatile than the Solow residual, though for the US the series is less volatile. We set up a quantitative model to assess the role of utilization-adjusted TFP shocks for comovement. We find that they do not generate substantial correlation in GDP growth rates across countries.

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Table A1: Country Sample

Australia	Germany	Netherlands
Austria	Greece	Poland
Belgium	Hungary	Portugal
Canada	India	Slovak Republic
Cyprus	Ireland	Slovenia
Czech Republic	Italy	Spain
Denmark	Japan	Sweden
Estonia	Republic of Korea	UK
Finland	Latvia	USA
France	Lithuania	

Table A2: Sector Sample

agriculture hunting forestry and fishing	basic metals and fabricated metal	financial intermediation
mining and quarrying	machinery nec	real estate activities
food beverages and tobacco	electrical and optical equipment	renting of m&eq and other business activities
textiles textile leather and footwear	transport equipment	public admin and defense; compulsory social security
wood and of wood and cork	manufacturing nec; recycling	education
pulp paper paper printing and publishing	electricity gas and water supply	health and social work
coke refined petroleum and nuclear fuel	construction	other community social and personal services
chemicals and chemical products	hotels and restaurants	sale maintenance and repair of motor vehicles
rubber and plastics	transport and storage	wholesale trade and commission trade
other nonmetallic mineral	post and telecommunications	retail trade except of motor vehicles

Table A3: Production Function Estimation Results

Industry	Returns to Scale ($\widehat{\delta}_j^1$)	Utilization ($\widehat{\delta}_j^2$)	Industry	Returns to Scale ($\widehat{\delta}_j^1$)	Utilization ($\widehat{\delta}_j^2$)
Durables			**Non-durable non-manufacturing**		
wood and of wood and cork	0.750***		sale maintenance and repair of motor	1.652***	
	(0.133)		vehicles and motorcycles; retail sale of fuel	(0.316)	
basic metals and fabricated metal	0.701**		wholesale trade and commission trade	1.471***	
	(0.329)		except of motor vehicles and motorcycles	(0.167)	
machinery nec	0.791***		retail trade except of motor vehicles	0.870*	
	(0.241)	1.420***	and motorcycles; repair of household goods	(0.454)	
electrical and optical equipment	0.711**	(0.389)	transport and storage	1.079***	
	(0.300)			(0.163)	
transport equipment	0.843***		post and telecommunications	0.633***	
	(0.207)			(0.150)	
manufacturing nec; recycling	0.895***		real estate activities	0.451	
	(0.129)			(0.329)	
			renting of m&eq and other business activities	1.225***	
				(0.233)	0.260
			agriculture hunting forestry and fishing	1.714*	(0.643)
				(0.892)	
Non-durable manufacturing			electricity gas and water supply	1.811	
				(1.374)	
textiles textile leather and footwear	0.291		construction	1.037***	
	(0.523)			(0.224)	
pulp paper paper printing and publishing	0.507		hotels and restaurants	1.267***	
	(0.431)			(0.429)	
coke refined petroleum and nuclear fuel	0.832	2.929*	financial intermediation	1.331***	
	(1.022)	(1.771)		(0.366)	
chemicals and chemical products	0.808*		public admin and defense;	1.864	
	(0.427)		compulsory social security	(1.510)	
rubber and plastics	0.926***		education	0.671***	
	(0.279)			(0.247)	
other nonmetallic mineral	0.698		health and social work	1.363	
	(0.487)			(2.179)	
			other community social and personal services	0.750***	
				(0.199)	

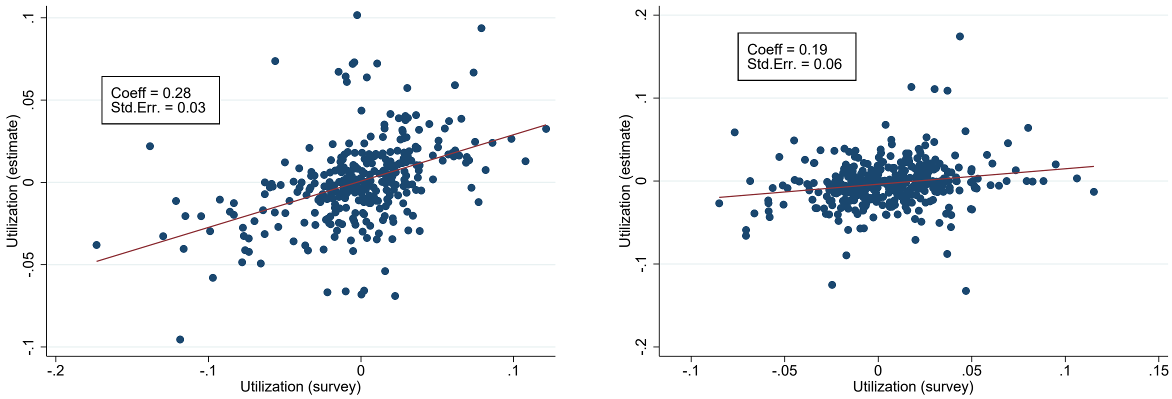
Notes: This table contains the results from the production function estimation described in Section 3. Standard errors in parentheses. Significance levels are indicated by *** $p<0.01$, ** $p<0.05$, * $p<0.1$. SW-F statistic for the first stage is 7.97.

Table A4: Correlation between Alternative TFP Estimates

	Baseline	BFK coefficients	ex-USA	ex-UK	ex-Canada	ex-Germany	ex-France	ex-Italy	ex-Japan	29-country estimation
Baseline	1.000									
BFK coefficients	0.862	1.000								
ex-USA	0.955	0.787	1.000							
ex-UK	0.897	0.743	0.796	1.000						
ex-Canada	0.523	0.467	0.371	0.614	1.000					
ex-Germany	0.963	0.877	0.920	0.831	0.616	1.000				
ex-France	0.957	0.829	0.970	0.761	0.324	0.922	1.000			
ex-Italy	0.893	0.804	0.821	0.854	0.466	0.831	0.831	1.000		
ex-Japan	0.830	0.765	0.734	0.717	0.614	0.841	0.733	0.696	1.000	
29-country est.	0.612	0.553	0.603	0.532	0.440	0.684	0.543	0.549	0.602	1.000

Notes: This table report the correlations of the estimated TFP series using a number of different approaches."BFK estimate" refers to TFP series for all countries using the coefficient estimates in Basu, Fernald, and Kimball (2006) and "ex-COUNTRY" refers to TFP series using the production function coefficient estimates from a sample that, excludes the G7 country in question. "29-country estimation" refers to the TFP series using the production function estimation based on 29 countries.

Figure A1: Comparison between Estimated Utilization and Survey Data



US sectoral data

Country average

Notes: This figure compares our estimated utilization growth rate and the change in the survey measure of utilization of capacity. The left panel plots growth rates of the sector-level utilization series for the US based on our procedure against the FRB utilization survey. The right panel plots the growth rate of the country-level average utilization rate based on our procedure against utilization growth rates based on surveys by the FRB for the US and Eurostat for European countries. Both plots include the OLS fit, and report the coefficient point estimate and the standard error.

Appendix A Model and Quantitative Results

A.1 Complete Model Equations

Here we fully specify the quantitative model, which nests our estimation framework, that we use to perform counterfactuals. We assume financial autarky, and that trade is balanced period by period.

Goods and Trade Trade is subject to iceberg costs τ_{mnj} to ship good j from country m to country n (throughout, we adopt the convention that the first subscript denotes source, and the second destination).

The final use in the economy, denoted $\mathcal{F}_{nt} \equiv C_{nt} + \sum_j I_{njt}$, is a Cobb-Douglas aggregate across sectors. The functional form and its associated price index are given by

$$\mathcal{F}_{nt} = \prod_j \mathcal{F}_{njt}^{\omega_{jn}}, \qquad P_{nt} = \prod_j \left(\frac{P_{njt}^f}{\omega_{jn}} \right)^{\omega_{jn}},$$

where $\mathcal{F}_{njt}$ is the final use of sector j in country n, and P_{njt}^f is the final use price index in sector j and country n. Within each sector, aggregation across source countries is Armington, and the sector price index is defined in a straightforward way:

$$\mathcal{F}_{njt} = \left[\sum_m \vartheta_{mnj}^{\frac{1}{\rho}} \mathcal{F}_{mnjt}^{\frac{\rho-1}{\rho}} \right]^{\frac{\rho}{\rho-1}}, \qquad P_{njt}^f = \left[\sum_m \vartheta_{mnj} P_{mnjt}^{1-\rho} \right]^{\frac{1}{1-\rho}},$$

where $\mathcal{F}_{mnjt}$ is final use in n of sector j goods coming from country m, and P_{mnjt} is the price of $\mathcal{F}_{mnjt}$. For goods j, the expenditure share for final goods imported from country m is given by

$$\pi_{mnjt}^f = \frac{\vartheta_{mnj} \left(P_{mnjt} \right)^{1-\rho}}{\sum_k \vartheta_{knj} \left(P_{knjt} \right)^{1-\rho}}. \tag{A.1}$$

Let P_{njt} denote the price of output produced by sector j in country n,[6] and let $P_{mi,njt}$ be the price paid in sector n, j for inputs from m, i. Due to the competitiveness assumption, the prices "at the factory gate" and the price at the time of final or intermediate usage are related by:

$$P_{mi,njt} = P_{mnit} = \tau_{mni} P_{mit},$$

where τ_{mni} is the iceberg trade cost.

In a competitive market, primary factors and inputs receive compensation proportional to

[6] Note this is not the same as the ideal price index P_{njt}^f of sector j final consumption in n, which aggregates imports from the other countries.

their share in total input spending. This implies:

$$\begin{aligned} R_{njt}K_{njt} &= \alpha_j \eta_j P_{njt} Y_{njt} \\ W_{njt}L_{njt} &= (1-\alpha_j)\,\eta_j P_{njt} Y_{njt} \\ P_{mi,njt}X_{mi,njt} &= \pi^x_{mi,njt}\,(1-\eta_j)\,P_{njt}Y_{njt}, \end{aligned} \tag{A.2}$$

where $\pi^x_{mi,njt}$ is the share of intermediates from country m sector i in total intermediate spending by n, j, given by:

$$\pi^x_{mi,njt} = \frac{\mu_{mi,nj}\left(\tau_{mni}P_{mit}\right)^{1-\varepsilon}}{\sum_{k,l}\mu_{kl,nj}\left(\tau_{knl}P_{klt}\right)^{1-\varepsilon}}.$$

Within a period, the supply curves are isoelastic in the factor prices relative to the consumption price index. The log of supply of hours, up to a normalization constant, is given by:

$$\left(\psi_h - 1 - \frac{\psi_h}{\psi_e}\right)\log H_{njt} = -\log \xi_{nj} + \log\left(\frac{W_{njt}}{P_{nt}}\right).$$

Equilibrium An equilibrium in this economy is a set of goods and factor prices $\{P_{njt}, W_{njt}, R_{njt}\}$, factor allocations $\{M_{njt}, N_{njt}, H_{njt}, E_{njt}, U_{njt}\}$, and goods allocations $\{Y_{njt}\}$, $\{C_{nt}, I_{njt}, X_{mi,njt}\}$ for all countries and sectors such that (i) households maximize utility; (ii) firms maximize profits; and (iii) all markets clear.

At sectoral level, the following market clearing condition has to hold for each country n sector j:

$$P_{njt}Y_{njt} = \sum_m P_{mt}\mathcal{F}_{mt}\omega_{mj}\pi^f_{nmjt} + \sum_m\sum_i (1-\eta_i)P_{mit}Y_{mit}\pi^x_{nj,mit}. \tag{A.3}$$

Meanwhile, a direct implication of financial autarky is that each country's expenditure equals the sum of value added across domestic sectors

$$P_{mt}\mathcal{F}_{mt} = \sum_i \eta_i P_{mit}Y_{mit}. \tag{A.4}$$

Combining with equation (A.3), we have

$$P_{njt}Y_{njt} = \sum_m\sum_i \eta_i P_{mit}Y_{mit}\omega_{mj}\pi^f_{nmjt} + \sum_m\sum_i (1-\eta_i)P_{mit}Y_{mit}\pi^x_{nj,mit}. \tag{A.5}$$

Note that once we know the share of value added in production η_j, the expenditure shares ω_{mj}, π^f_{nmjt}, and $\pi^x_{nj,mit}$ for all n, m, i, j, we can compute the nominal output $P_{njt}Y_{njt}$ for all country-sector pairs (n, j) after choosing a numeraire good. There is no need to specify all the details of the model.

The main text reports the results of simulating output growth rates in a setting where machines M_{njt} and employees N_{njt} are held constant. For this static model we can obtain the exact nonlinear solution using the hat algebra approach of Dekle, Eaton, and Kortum (2008), or a first-order linear solution. As we will linearize the model in the dynamic exercise below, for consistency we report the results of static model simulation via a first-order approach. Huo, Levchenko, and Pandalai-Nayar (2020) provides a comparison between the GDP growth rates implied by the first-order approach and the exact GDP growth rates in a related static framework. It turns out that in that setting, the exact and first-order approximation solutions are very close to each other, with a correlation between the two GDP growth rates of 0.999.

A.2 Dynamic Responses

The main text presents the results in an environment in which machines M_{njt} and employment N_{njt} are kept constant. In that setting, the model is an international extension of the canonical static network propagation model. We could solve the model exactly, without approximation, and study how output across countries and sectors responds to contemporaneous shocks. By construction, past shocks had no effect on current output correlations. In this section, we allow households to adjust machines and employment endogenously as in Section 3.1. Consequently, a shock to sector j in country n can have persistent effects on other countries and sectors, and the properties of output correlations also depend on the dynamic propagation of shocks over time and across regions.

In particular, the first-order condition with respect to capital accumulation is

$$\Psi'_{nt} = \beta \mathbb{E}_t \left[\Psi'_{nt+1} \left(\frac{R_{njt+1}}{P_{nt+1}} U_{njt+1} + 1 - \delta_j \right) \right], \tag{A.6}$$

where Ψ'_{nt} stands for the marginal utility of final goods consumption in country n period t. This condition is similar to the standard Euler equation but is sector-specific and adjusted by the utilization rate.

The optimality condition with respect to N_{njt+1} is

$$\mathbb{E}_t \left[\Psi'_{nt+1} \left(\xi_{nj} G(H_{njt+1}, E_{njt+1}, U_{njt+1}) + \left(\frac{N_{njt+1}}{\psi_n} \right)^{\psi_n - 1} \right) \right] = \mathbb{E}_t \left[\Psi'_{nt+1} \frac{W_{njt+1}}{P_{nt+1}} H_{njt+1} E_{njt+1} \right].$$

Note that N_{njt+1} is chosen in period t before observing shocks in period $t+1$. The left hand-side is the expected marginal disutility of a unit increase in sector j employment, while the right-hand side is the corresponding marginal utility gain due to higher labor income.

The dynamic model has a large number of state variables (shocks to each country-sector as well as employment and machines in each country-sector), and so cannot be solved exactly. To examine the dynamic responses of the model and how it affects the output correlation, we proceed by solving the log-linearized model. In the linearized model, the taste parameters ϑ_{mnj} and $\mu_{mi,nj}$ and the trade cost τ_{mni} affect the dynamics only via the the final use and the intermediate use trade shares. Once we match the trade shares as in the data, there is no need to pin down the trade costs and taste parameters separately. The dynamic model requires a small set of additional parameters relative to the static model. We adopt values standard in the business cycle literature. The model period is a year; we set the discount rate to $\beta = 0.96$. The period utility is $\Psi(\cdot) = \log(\cdot)$, and the depreciation rate is $\delta_j = 0.10$. We set $\psi_n = \psi_h = 4$ as in the baseline specification, and vary the value of ψ_n. For the elasticity of substitution, we employ the baseline specification as in the static model, that is, $\rho = 2.75$ and $\varepsilon = 1$.

The final input into the calibration is shock processes for different countries and sectors. The perceived shock processes matter for the intertemporal decisions of households. We estimate shock processes for the utilization-adjusted TFP shocks. For non-G7 countries, the panel is too short to obtain reliable estimates of the shock processes. Therefore in the dynamic analysis we narrow the focus to the G7 countries, for which we have the longest panel of shocks. We assume that the country-sector technology shocks follow a vector autoregressive process. However, due to the large number of countries and sectors, it is not feasible to estimate the fully unrestricted VAR. Thus, we impose a parsimonious structure on the shock process, that allows for contemporaneous spillovers between country-sectors, but restricts the structure of lagged spillovers. Log TFP shocks are assumed to follow:

$$\ln Z_{njt} = \rho^z_{nj} \ln Z_{njt-1} + \zeta^z_n \mathbf{1}\left(m = n, k \neq j\right) \ln Z_{mkt-1} + \theta^z_{njt}. \tag{A.7}$$

That is, we permit a country-sector specific lagged autoregressive parameter, so country-sector shocks can be persistent. We restrict lagged spillovers to be common within a country (across sectors), and zero otherwise.[7] We allow for a full variance-covariance matrix of the error terms, which amounts to assuming completely unrestricted contemporaneous spillovers: $\boldsymbol{\theta}_t \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{\Sigma}\right)$, that is, there is a full covariance matrix. The processes (A.7) is estimated separately for each country-sector. Table A5 summarizes the estimation results. The sample variance-covariance matrix of the residuals from estimating equation (A.7) for the period 1978-2007 serves as the estimate of the covariance matrix $\boldsymbol{\Sigma}$ of the shock innovations.

The choice of restrictions strikes a balance between relative parsimony, which improves the precision of the parameters estimates, and sufficient flexibility to replicate the measured shock correlations in the data. We experimented with other processes using methods such as LASSO regressions without much change to the simulated shock correlations. In particular, we have modified the equations above to also include a sector-specific lagged spillover term, but these coefficients were all insignificant, and so we use the more parsimonious process in the baseline analysis.

Table A6 displays the results of the dynamic model. In the baseline specification with $\psi_n = 4$, the output growth correlations are about three times higher than the static model in Table

[7] We also experimented with including within-sector spillover terms and dependence on other past variables, but it turns out that most of these terms are not significant.

Table A5: TFP Shock Processes: Autoregressive Parameters

	Mean	Median	25th pctile	75th pctile
		$\ln z_{njt}$		
TFP (util adj.)				
Own lag (ρ^z_{nj})	0.860	0.854	0.830	0.889
Spillover lag (δ^z_n)	-0.000	-0.001	-0.002	0.001

Notes: This table presents results from estimating the shock stochastic processes (A.7). The measures are summary statistics of the coefficients in the sample of sectors and countries.

Table A6: GDP Growth Correlations in the Dynamic Model

	Mean	Median	25th pctile	75th pctile
Data	0.358	0.337	0.242	0.565
TFP (util adj.)				
Model, $\psi_n = 4$	0.098	0.143	-0.215	0.339
Model, $\psi_n = 2$	0.095	0.143	-0.238	0.296
Model, $\psi_n = 20$	0.101	0.142	-0.194	0.336

Notes: This table presents the summary statistics of the correlations of $d \ln Y_{nt}$ in the sample of G7 countries for years 1978-2007 in various calibrations of the dynamic model and under the TFP shocks. Variable definitions and sources are described in detail in the text.

4, but still explain less than a third of overall comovement. When $\psi_n = 20$, employment moves much less, and capital is the main input factor responsible for dynamic transmission. When $\psi_n = 2$, the employment is much more responsive. Throughout, the correlations remain similar to the baseline dynamic model.

A.3 Quantitative Results: Robustness

Table A7: Static Model: Robustness

	Mean	Median	25th pctile	75th pctile
	G7 Countries (N. obs. = 21)			
Data	0.358	0.337	0.242	0.565
$\rho = 1$	0.149	0.143	-0.010	0.267
Structural ψ_u^j	0.033	0.014	-0.042	0.155
$\psi_u^j = 1.01$	0.068	0.029	-0.020	0.197
Frisch = 2	0.052	-0.001	-0.024	0.178
	All countries (N. obs. = 406)			
Data	0.190	0.231	-0.027	0.437
$\rho = 1$	0.016	0.019	-0.219	0.235
Unbalanced Trade†	0.004	0.017	-0.209	0.216
Structural ψ_u^j	0.001	0.006	-0.223	0.231
$\psi_u^j = 1.01$	0.026	0.040	-0.210	0.254
Frisch = 2	0.018	0.039	-0.216	0.239

Notes: This table presents the summary statistics of the correlations of $d \ln Y_{nt}$ in the sample of G7 countries for 1978-2007 (top panel) and full sample for 1995-2007 (bottom panel) in the data and the static model with our measured TFP shocks for various robustness exercises. Variable definitions and sources are described in detail in the text.

† The unbalanced trade robustness exercise requires information on deficits from the WIOD, which is only available for years 1995-2007. Therefore, this counterfactual is only run for years 1995-2007.