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Comparative Advantage in (Non-)Routine Production

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Comparative Advantage in (Non-)Routine Production

Abstract

We illustrate a new source of comparative advantage that is generated by countries' different ability to adjust to technological change. Our model introduces substitution of workers in codifiable (routine) tasks with more efficient machines, a process extensively documented in the labor literature, into a canonical 2 × 2 × 2 Heckscher-Ohlin model. Our key hypothesis is that labor reallocation across tasks is subject to frictions, the importance of which varies by country. The arrival of capital-augmenting innovations triggers the movement of workers out of routine tasks, and countries with low labor market frictions become relatively abundant in non-routine labor. In the new equilibrium, more flexible countries specialize in producing goods that use non-routine labor more intensively. We document empirically that the ranking of countries with respect to the routine intensity of their exports is strongly related to labor market institutions and to cultural norms that influence adjustment to technological change, such as risk aversion or long-term orientation. The explanatory power of this mechanism for trade flows is especially strong for intra-EU trade.

JEL-Codes: F110, F140, F150.

Keywords: comparative advantage, resource allocation, routine tasks.

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1 Introduction

The labor literature has highlighted that workers perform tasks differing markedly in codifiability or routineness (Autor et al., 2003). Capital and computers are stronger substitutes for the labor input in routine tasks than in abstract tasks. Yet, technology adoption is not a frictionless process (Bresnahan et al., 2002). As the economy becomes more capital intensive with the arrival of labor-saving technologies, workers continuously need to transition from more routine to more abstract tasks (Acemoglu and Restrepo, 2018). We will show that an ability to facilitate such transitions gives countries a comparative advantage in industries that are intensive in non-routine tasks.

The classic theory of comparative advantage illustrates how differences in technology or factor endowments lead countries to specialize in the production of different goods. Recent developments in this literature highlight that differences in worker attributes and institutions can also influence specialization. Trade specialization has, among other factors, been linked to skill dispersion (Bombardini et al., 2012), attitudes towards obedience (Campante and Chor, 2017), labor market flexibility (Cuñat and Melitz, 2012), and the strength of contract enforcement (Nunn, 2007). Chor (2010) finds that institutional differences matter as much as traditional factor endowments of human and physical capital in determining trade patterns.

Our contribution is to relate an important feature of the production process that is highlighted in the labor literature, to trade theory. We start from a well-documented pattern associated with the process of technological change.[1] The continuous introduction of more efficient machines displaces workers in relatively more codifiable (routine) tasks where new machines are relatively more productive. Such automation frees up labor to perform less codifiable (non-routine) tasks. In principle, labor is infinitely substitutable with the new machines in routine tasks (Autor et al., 2003). Yet, most studies assume that substitution is finite, which we interpret as indicating the presence of adjustment costs. The equilibrium allocation of labor to routine and non-routine tasks depends on the magnitude of these costs. We show that cross-country variation in the ability to adjust to new technologies and to reallocate workers between tasks induces specialization, and thus becomes a novel source of comparative advantage.

Several studies already illustrate that flexible labor market institutions facilitate the speed and extent of adjustment to trade liberalization (Kambourov, 2009; Dix-

[1] See in particular Autor et al. (2003), Acemoglu and Autor (2011), Goos et al. (2014), Harrigan et al. (2016) and Acemoglu and Restrepo (2018).

Carneiro, 2014). Gains from trade are higher when workers can move more easily from import-competing to comparative advantage sectors. In our case, it is the adjustment flexibility itself—taken in the broad sense of all features that facilitate technology adoption and labor reallocation—that creates comparative advantage.

To illustrate this mechanism we incorporate task routineness into an otherwise canonical 2-country 2-good 2-factor Heckscher-Ohlin model. The final goods are produced with two factors: one routine and one non-routine. The available quantities of these factors are not given exogenously, but are determined by the equilibrium allocation of labor to routine and non-routine tasks. The flexibility of labor reallocation matters in this economy because we implicitly assume that there is an ongoing process of technological change which we model as an increase in the capital endowment.[2] As in Autor et al. (2003) and Autor and Dorn (2013), capital can only be used in routine tasks. As more capital becomes available, its relative price falls and the equilibrium capital intensity in routine input production rises. Consequently, labor can be released from routine tasks and reallocated to non-routine tasks.[3]

Acemoglu and Restrepo (2018) provide an explicit dynamic model where the continuous introduction of new capital or labor-saving technologies creates a permanent need for adjustment. We opt for a static model—taking the process of capital deepening to be exogenous and common across countries—to focus on the incidence of differences in adjustment costs on the extent of labor reallocation. Indeed, the novel ingredient in our model is that the reallocation of workers between tasks is subject to frictions, the importance of which varies by country.[4]

We model this variation as a country-specific elasticity of substitution between capital and labor in routine production. This assumption can be considered as a reduced form way of capturing differences in labor market regulations, worker bargaining power, or other factors that make it less likely for workers to switch employer. We include a stylized model to micro-found the assumption of a country-specific elasticity of substitution parameter. Countries share the same production

[2]The same results might also be obtained by modeling technological change as an increase in the capital productivity coefficient, but the normalization of the CES production function (discussed below) greatly complicates that approach.

[3]In Autor and Dorn (2013), workers performing routine tasks in manufacturing can only be reallocated to manual (non-routine) tasks in services. We follow the approach in Autor et al. (2003), where reallocation is possible between routine and non-routine tasks in manufacturing, but relax their assumption of perfect capital-labor substitutability in routine tasks.

[4]The magnitude of adjustment costs influences the propensity to invest in and adopt new technologies (Bartelsman et al., 2016). We expect this channel—missing in our static set-up—to reinforce our results as the country with low adjustment costs would invest relatively more and reallocate even more labor to non-routine tasks if the process of capital deepening were endogenized.

technology, but they differ in the real costs that are incurred when workers change jobs. Although we introduce the friction on the 'outgoing' labor side, we could also have introduced it on the 'incoming' capital side to capture cultural or institutional differences—such as behavioral norms in the workplace—that affect the costs of technology adoption. Specifically, we expect the elasticity of substitution to be decreasing in the magnitude of hiring, firing, as well as organizational and retraining costs associated with the adjustment of the workforce to the new machinery.[5]

The model predicts that countries which adjust more smoothly to technological change—i.e., countries with a higher elasticity of substitution—free up more labor from routine tasks and become non-routine labor abundant. As in the canonical Heckscher-Ohlin model, the abundance of non-routine labor leads them to specialize in goods that are non-routine labor intensive. As a result, the arrival of more capital or capital-biased technological change that triggers the process of labor reallocation, will endogenously differentiate countries. This new source of comparative advantage helps explain why countries with similar capital-labor endowments and technology specialize in different goods. Moreover, the welfare effects of trade also differ. While capital deepening increases the real wage in both countries, trade strengthens this effect for the high-σ country that specializes in non-routine production, but diminishes the beneficial effect for workers in the low-σ country.

We test the predictions on trade specialization using three annual cross-sections (1995, 2005, 2015) for two country samples: one for the 50 largest exporters in the world and a second for the 28 EU member states. Following the two-step approach of Costinot (2009), we show in a first step that the export bundles of different countries are rather distinct in terms of their relative routine intensity.

In a second step, we investigate whether the country-level routine specialization is related to institutional or cultural characteristics that are plausibly correlated with the ease of labor reallocation across tasks. The results indicate that the OECD's indicator for 'strictness of employment protection legislation' is a strong predictor on the EU sample. Countries with relatively strict regulations specialize in goods that are more routine intensive. In the more diverse sample of large global exporters, the following three variables predict routine specialization: (low) 'quality of the workforce' (Costinot, 2009) and two cultural features, risk aversion and long-term orientation (Hofstede, 1980).

We evaluate the predictive power of our mechanism by relating bilateral exports

[5]Preference heterogeneity, e.g. risk aversion or long-term orientation, would affect the propensity to invest in new technologies and could also lead to differences in perceived capital-labor substitutability.

at the industry level to an interaction between sectoral routine intensity and the relevant country endowments. We find the expected positive sign everywhere, but our mechanism is particularly informative in predicting trade patterns between EU member states. They tend to have similar factor endowments and level of technology and the more traditional sources of comparative advantage have only low predictive power. Importantly, while the extent of (non-)routine specialization across countries declines somewhat over time when using gross exports as the dependent variable, the effect remains strong if we use value added trade and thus account for the increased international fragmentation of production.

Our analysis contributes to the trade literature that seeks to uncover new mechanisms behind the pattern of specialization: Nunn and Trefler (2014) survey the theoretic and empirical literatures that consider domestic institutions as a source of comparative advantage, and we already mentioned the most relevant mechanisms. Labor market flexibility in particular has been shown by Cuñat and Melitz (2012) to induce specialization by conferring a comparative advantage in sectors where idiosyncratic shocks lead to high sales volatility. Our mechanism derives from the benefit that labor market flexibility confers in adjusting to pervasive capital-biased technological change. As capital deepening changes the equilibrium allocation of labor across tasks, a country's measured factor abundance, e.g. the ratio of skilled to unskilled labor, may itself be influenced by the interaction of institutions with the process of technological change.

Our analysis also speaks to the trade literature that links labor market flexibility to the magnitude of the gains from trade. Lower adjustment costs help countries reap the gains from trade liberalization (Dix-Carneiro, 2014). A novel implication of our model is that workers in the country with high capital-labor substitutability benefit relatively more from capital deepening in the open economy setting.

Our work is closely related to the rapidly growing literature in labor economics that documents how increased automation and outsourcing of codifiable tasks led to job polarization in developed economies. This literature explicitly links technological change to labor displacement from routine to non-routine tasks (Autor et al., 2003; Autor and Dorn, 2013; Bárány and Siegel, 2018). Our work also builds on the insights from the growth literature that connects capital-labor substitutability to capital accumulation (Klump and de la Grandville, 2000). Stokey (1996) shows in a model with capital-skill complementarity that the incentive to accumulate capital is increasing in the substitutability of capital with unskilled labor. Bartelsman et al. (2016) document how labor markets flexibility determines the gains from capital deepening by increasing the expected gain from investment in disruptive technology.

Our work explicitly connects the magnitude of adjustment costs to the perceived capital-labor substitutability. By embedding this mechanism in a Heckscher-Ohlin model, we pin down the impact of labor market flexibility on the magnitude of workers' gains from trade in the context of capital deepening.

The remainder of the paper is organized as follows. In Section 2 we present the main features of the stylized model and provide a possible micro-foundation for country differences in capital-labor substitutability. Next we derive the autarky equilibrium and the predictions regarding trade patterns. Section 3 describes the data and Section 4 the empirical model. Section 5 contains the estimation results that link trade patterns, in terms of (non-)routine specialization, to country characteristics. In Section 6 we draw some conclusions from the analysis.

2 The model

Our objective is to analyze in the simplest possible way the trade implications of differences in the ease of factor reallocation. We introduce this through heterogeneity of the substitution parameter σ in a production function that has been used extensively in the labor literature (Acemoglu and Autor, 2011). It is intended to capture a variety of adjustment frictions, e.g. firing costs, risk aversion, etc. in a reduced form way. Before solving the model, we provide a simple way to micro-found differences in σ.

The model is structured as the canonical $2 \times 2 \times 2$ Heckscher-Ohlin (HO) model where the pattern of trade is determined by the interaction of country-specific factor endowments and sector-specific factor intensities. Its distinguishing feature is that the endowments of the relevant production factors for the production of the two final goods, namely non-routine tasks and a routine intermediate, are endogenously determined ('produced') by the optimal allocation of labor to either task.[6] Two countries with identical endowments of 'primitive' factors, capital and labor, can have an incentive to trade, simply because they differ in the substitutability of capital and labor in the production of the routine tasks. A country with a higher elasticity of substitution parameter σ will be able to move labor more easily out of routine tasks when capital becomes abundant. It will specialize in the final good industry that uses the scarce, non-routine factor more intensely.

The comparative statics analysis considers how countries with different σ parameters adjust differentially to an exogenous increase in the capital stock that triggers

[6] All capital is dedicated to the production of the routine intermediate input.

capital-labor substitution and the reallocation of labor. To study this in a static model, we measure the change from an initial point of production where the equilibrium allocation is identical in the two countries. We will discuss that this requires a normalization of the CES function to make the same production plan attainable without requiring the other parameters than σ to be country specific.

In the following sub-sections we derive the trade implications in six steps: (1) the $2 \times 2 \times 2$ Heckscher-Ohlin set-up, (2) a micro-foundation for σ differences in the production function, (3) solving for the equilibrium allocations and production, (4) normalizing the CES-component in the production function, (5) the pattern of specialization, and (6) implications of opening up to trade.

2.1 Set-up

Denote two countries by $i \in \{A, B\}$; they have identical factor endowments of capital $\bar{K}$ and labor $\bar{L}$. Denote two final goods by $g \in \{1, 2\}$; they are produced with two factors, non-routine (abstract) labor L^a and a routine intermediate input M which is itself produced from capital K and routine labor L^m. The resource constraint on labor is $L^a + L^m \leq \bar{L}$. Note that assuming one type of labor to be perfectly mobile between abstract and routine work is a simplification that works against the mechanism we intend to illustrate.

As is common in the canonical HO model, the production function for final goods is Cobb-Douglas:

$$Y_{ig} \quad = \quad z_g \left(L^a_{ig}\right)^{1-\beta_g} \left(M_{ig}\right)^{\beta_g}, \tag{1}$$

where z_g is a productivity parameter and β_g the factor share of the routine input. Both parameters are common across countries. Let good 1 be non-routine intensive: i.e., $\beta_1 < \beta_2$.

Also standard is that consumers in both countries have identical, homothetic demand over the two final goods. For simplicity, we adopt a Cobb-Douglas utility function: $U_i = \sum_g \theta_g \ln(Q_{ig})$. Consumers maximize utility subject to the budget constraint $\sum_g P_{ig} Q_{ig} \leq r_i \bar{K} + w_i \bar{L}$, where w_i is the wage and r_i the rental rate of capital. It leads to constant budget shares for both final goods.

Given the focus on capital-labor substitutability in routine production, we simply assume that each unit of raw labor can directly produce either routine or abstract tasks and that this choice is reversible. In particular, one unit of routine labor can seamlessly be converted into one unit of abstract labor. We explicitly choose not to

focus solely on the difficulty for routine workers to acquire the necessary skills to perform abstract tasks. We are interested in any type of reallocation friction that makes capital-labor substitution less than infinite, such that a labor-saving machine cannot instantaneously replace all workers in routine production.[7]

We adopt a CES production function for the production of the routine intermediate:

$$M_i = Z \left[\alpha (K_i)^{\frac{\sigma_i - 1}{\sigma_i}} + (1-\alpha)(L_i^m)^{\frac{\sigma_i - 1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i - 1}}, \tag{2}$$

where Z and α are the efficiency and distribution parameters, and σ_i captures the ease of input substitutability.[8] We follow Autor et al. (2003) and Autor and Dorn (2013) and assume that capital and routine labor are more substitutable in routine production than is the case between non-routine labor and the routine input in the production of final goods, formally that $\sigma_i > 1$ (where one is the elasticity of substitution of the outer Cobb-Douglas). Let country A have relatively high input substitution in routine production such that $\sigma_A > \sigma_B > 1$.

In this set-up, country A will be non-routine labor abundant in autarky and will produce relatively more output in sector 1, which uses non-routine labor more intensively. Given identical, homothetic preferences, good 1 will be relatively cheap, giving country A a comparative advantage in it. The key element in our model is that the quantities of abstract labor and the routine intermediate are endogenously determined, depending on the optimal allocation of labor to routine and non-routine tasks.

Plugging (2) into (1), we obtain the following two-tiered production function:

$$Y_{ig} = z_g \left(L_{ig}^a\right)^{1-\beta_g} \left\{ Z \left[\alpha (K_{ig})^{\frac{\sigma_i - 1}{\sigma_i}} + (1-\alpha)(L_{ig}^m)^{\frac{\sigma_i - 1}{\sigma_i}} \right]^{\frac{\sigma_i}{\sigma_i - 1}} \right\}^{\beta_g}. \tag{3}$$

In Appendix A we discuss estimates of a nested production function of the form of (3). The analysis uses the KLEMS dataset that has country-sector-year observations and measures abstract and routine labor input by the number of high or low-skilled employees, which is not ideal, but can serve as an approximation. To

[7]Redeploying routine labor to abstract tasks could require a human capital investment, but we do not model this explicitly, as it would lead to task-specific wages. The σ parameter is a reduced form way of representing various frictions associated with labor reallocation across tasks.

[8]Note that the Z and α parameters are assumed common across countries. For two countries with the same endowments but different σ_i parameters to be able to produce the same output bundle, requires a normalization, see for example Klump et al. (2012). We discuss this in greater detail in Section 2.4.

evaluate the appropriateness of our assumptions, we initially allow for country-sector specific β and σ parameters, exploiting only time variation in the estimation. An ANOVA analysis indicates that country dummies have the most explanatory power for the elasticity of substitution estimates $\hat{\sigma}$, while sector dummies have more explanatory power for the output elasticity of the routine intermediate estimates $\hat{\beta}$. It suggests that our assumptions on the country respectively sector-specificity of these two parameters is broadly consistent with the observed variation between outputs and inputs in the KLEMS data.

2.2 Micro-foundation for differences in σ

The elasticity of substitution parameter σ in a CES production function is generally considered to be a representation of technology. Here we show that countries with the same production technology, but with different (labor market) institutions adjust their input choices to a different extent when hit by the same exogenous shock. It illustrates how a labor market friction can give rise to variation in the elasticity of substitution, i.e., how easy it is in practice to substitute between capital and labor.

We consider a lay-off cost to be paid by any firm that seeks to reduce its workforce, for example in response to an increase in the relative price of labor. Given that ours is a real trade model, the lay-off cost has to be paid directly in terms of output of the firm. It means that

$$y + p\,C(L)\,y \;=\; F(K, L), \tag{4}$$

where p is a country-specific cost shifter that we use in the comparative statics to vary the importance of this friction. $C(L)$ is the lay-off cost that satisfies $C(\bar{L}) = 0$, $C'(L) < 0$, and $C''(L) > 0$ for any $L < \bar{L}$.[9] In words, the cost kicks in when the firm reduces labor input below its initial level $\bar{L}$, the marginal cost is positive for lay-offs (negative changes in L), and the cost is convex, i.e. the marginal cost increases in the amount of workers the firms seeks to shed, which is a standard assumption.[10] Combining technology and institutions leads to the following modified production function:

$$y \;=\; \frac{F(K, L)}{1 + p\,C(L)}. \tag{5}$$

[9] In the analysis of comparative advantage, we consider an increase in the capital stock which tends to increase the relative wage. Hence, the relative adjustment involves reducing labor input.

[10] Small employment reductions can often be accommodated relatively easily by not replacing retiring workers or by natural job attrition, and thus incur smaller than proportional costs.

We view the real lay-off cost in (4) as representative for a variety of institutional differences between countries that can be modelled in a reduced form way by a heterogeneous elasticity of substitution parameter. In addition to a lay-off cost per se, the cost parameter can be interpreted in alternative ways. It can stand, for example, for a legal obligation by the former employer to provide retraining to workers who are dismissed. Cross-country differences in the fraction of such costs borne by individual firms, and not by a public system, have similar effects as a variation in severance pay. Another interpretation is as equilibrium compensation to workers for the risk involved in job transitions.[11] Due to mobility barriers between regions and sectors or due to transitory unemployment spells, many dismissed workers will experience a period of lower earnings with variation across countries in its duration and the amount of income lost. Going beyond differences in transition costs, the equilibrium compensation accompanying dismissals can also vary if workers differ in their risk aversion. They will regard the risk of not finding an equally well paid job in the non-routine sector differently, and hence their certainty equivalent of switching to the other sector will differ. We therefore regard the set-up in (4) as representing a wider class of models where adjustments in total labor input to exogenous shocks involve real costs.

Similarly, institutional or cultural differences can also introduce costs associated with adjustments in the capital stock, e.g. as firms invest in new technology. Augmenting the capital stock might increase its productivity with a probability close to, but short of one. If decision-makers differ across countries in their risk aversion, or in the extent to which they take a long-term perspective in investment decisions, the benefit of increasing the capital stock will be assessed differently. If the new production plan involves a change in the capital stock, such a mechanism would also give rise to a modified, country-specific production function, of a form similar to (5):

$$y = \frac{F(K,L)}{1-\tilde{p}\,\tilde{C}(K)},$$

We now show the effect of a difference in the lay-off cost friction p on the elasticity of substitution for the modified production function (5). The latter is defined as

$$\sigma_{L,K} = \frac{d(L/K)}{dMRTS}\frac{MRTS}{L/K}.$$

[11] Bewley (2009) provides evidence that compensation for dismissals in the United States tends to be much higher than legally required. Many managers discuss existing practices as equilibrium compensation for job transition costs that dismissed employees are likely to incur.

We derive in Appendix B for the special case of perfect substitution between inputs in the underlying production function, i.e., for $F(K, L) = K + L$, that $\sigma_{L,K}$ for the modified production function is finite if $p\,C'' > 0$. Moreover, the derivative of $\sigma_{L,K}$ with respect to the cost shifter p equals

$$\frac{\partial \sigma_{L,K}}{\partial p} = \frac{-pC'(L)y - 1}{L} + \frac{-pC'(L)y - 1 + 2(pC'(L)y)^2}{K}. \tag{6}$$

The first term is negative as long as $-pC'(L)y < 1$, or the marginal friction does not exceed the marginal product of labor, which must be satisfied for the adjustment to be optimal. The second term is a polynomial of order two which is negative for $-pC'(L)y \in (-1, 1/2)$; that is, the marginal friction does not exceed half the marginal product of labor. Since the terms are weighted by $1/L$ and $1/K$ respectively, this constraint is relaxed at higher K and lower L. As long as the friction is not excessive, we thus find a negative effect of the cost shifter p—which measures the importance of the friction—on the elasticity of substitution. In other words, a more severe friction reduces the optimal (from the firm's perspective) substitution of capital for labor.

The above mechanism links labor market frictions in the form of a convex layoff cost to lower substitutability of capital and labor. Several recent papers have documented large and highly heterogeneous adjustment costs when workers switch occupations. Dix-Carneiro (2014) finds for the median Brazilian worker switching jobs a cost ranging from 1.4 to 2.7 times the average annual wage.[12] Autor et al. (2014) even find that adjustment costs may be prohibitively high for less skilled and older workers and shocks can lead to a permanent exit from the labor force.[13]

While adjustment cost are likely to vary in importance across workers, we will focus on institutional characteristics that determine a country-specific component in the adjustment cost. Several papers have suggested that more stringent labor market regulation reduces the speed of adjustment of an economy to structural change. For example, Wasmer (2006) shows that countries with more rigid labor markets perform better in the steady state as workers are more productive, but following structural shocks they experience a longer and more costly transition period. Comparing the adjustment to trade liberalization in Mexico and Chile, Kambourov (2009) shows that high firing costs in Mexico slowed down the process of worker reallocation to comparative advantage activities. Artuç et al. (2015) estimate the magnitude

[12] Artuç et al. (2010) report even higher costs for the median U.S. worker, but they have less detailed controls for worker characteristics.

[13] Pierce and Schott (2016) report that one third of workers who lost employment in U.S. manufacturing as a consequence of import competition from China transition to inactivity.

of switching costs for workers and document that countries with relatively high switching costs also adjust more slowly to trade shocks.

2.3 Solving the model

After providing a motivation for the production function, we solve the model by finding the relative supply and demand of the two 'produced' factors, the routine intermediate and abstract labor. The solution to the model delivers the optimal allocation of labor to routine and non-routine tasks. We show here the main steps to solve the model and provide further details in Appendix C.

On the supply side, we have three types of price-taking firms, producing the routine intermediate input and both final goods. The cost and thus the optimal input combinations must be the same for routine inputs used in either final goods sector. Cost minimization of the CES production function in (2) gives conditional factor demands for capital and routine labor. Substituting them in the production function and then in the objective function gives the unit cost of the routine input in terms of factor prices. Given the assumption of perfect competition, this also equals the price of the routine input:

$$P_i^m \;=\; C(w_i, r_i) \;=\; \frac{1}{Z}\left[\alpha^{\sigma_i} r_i^{1-\sigma_i} + (1-\alpha)^{\sigma_i}\, w_i^{1-\sigma_i}\right]^{\frac{1}{1-\sigma_i}}. \tag{7}$$

Cost minimization of the Cobb-Douglas production function in (1) leads to a straightforward expression of unit costs of the final goods, and thus prices P_{ig}, again as a function of the relevant factor prices, i.e., the price of the routine input and the wage rate:

$$P_{ig} \;=\; C_{ig}(w_i, P_i^m) \;=\; \frac{1}{z_g}\left(\frac{w_i}{1-\beta_g}\right)^{1-\beta_g}\left(\frac{P_i^m}{\beta_g}\right)^{\beta_g}, \quad \forall g \in \{1,2\}. \tag{8}$$

By combining (7) and (8), we can express the final goods prices in terms of w_i and r_i, see equation (C5) in the Appendix. Hence, we can express the price ratio P_{i1}/P_{i2} in terms of the 'primitive' factor price ratio w_i/r_i, as in the canonical HO model.

Next, note that capital can only be used in routine production. The capital demand in routine production, i.e., the first-order condition for K, provides an expression for the optimal quantity of the routine intermediate as a function of the capital endowment and the relative factor price ratio. The production function of the routine intermediate then determines how much labor to allocate to routine tasks.

Labor market clearing then gives the total quantity of abstract labor as a function of the labor endowment and factor prices: $L_i^a = \bar{L} - L_i^m(w_i/r_i; \bar{K})$. Optimal factor use in routine production together with market clearing for labor and capital determines the relative supply of the two produced factors, which is the relevant factor ratio available to the two final goods sectors taken together. The ratio of produced factors can then be expressed as a function of primitive endowments and the prices of the primitive factors as follows:

$$\frac{L_i^a}{M_i} = \frac{\frac{\bar{L}}{\bar{K}} - \left[\frac{w_i/(1-\alpha_i)}{r_i/\alpha_i}\right]^{-\sigma_i}}{Z\alpha_i^{\frac{\sigma_i}{\sigma_i-1}}\left\{1 + \frac{w_i}{r_i}\left[\frac{w_i/(1-\alpha_i)}{r_i/\alpha_i}\right]^{-\sigma_i}\right\}^{\frac{\sigma_i}{\sigma_i-1}}} \tag{9}$$

We now turn to the demand side of the economy to derive an expression for the relative demand for produced factors. We have assumed a Cobb-Douglas utility function that implies constant budget shares. Substituting the expressions for final goods prices (8), we find an expression for relative final good consumption as a function of the produced factor prices:

$$\frac{Q_{i1}}{Q_{i2}} = \frac{\theta_1 z_1 \beta_1^{\beta_1}(1-\beta_1)^{1-\beta_1}}{\theta_2 z_2 \beta_2^{\beta_2}(1-\beta_2)^{1-\beta_2}} \left(\frac{w_i}{P_i^m}\right)^{\beta_1-\beta_2} \tag{10}$$

Using the production function and market clearing for final goods, we can express the output ratio in (10) in terms of the allocation of the produced factors to both sectors:

$$\frac{Q_{i1}}{Q_{i2}} = \frac{Y_{i1}}{Y_{i2}} = \frac{z_1 {L_{i1}^a}^{1-\beta_1} {M_{i1}}^{\beta_1}}{z_2 {L_{i2}^a}^{1-\beta_2} {M_{i2}}^{\beta_2}}. \tag{11}$$

Plugging in the first order conditions of the final good producers and of the consumers, we find that the allocation of production factors to both sectors depends only on the preference and technology parameters.[14] As a result, the relative factor demand takes the following simple form:

$$\frac{L_i^a}{M_i} = \frac{\sum_g \theta_g(1-\beta_g)}{\sum_g \theta_g \beta_g} \frac{P_i^m}{w_i} \tag{12}$$

This is the familiar HO equation that connects relative factor abundance to relative

[14]The simple form of these expressions is a result of the Cobb-Douglas functional form for both preferences and the production function that leads to constant expenditure shares for consumers and constant cost shares for producers.

factor prices in final good production. The only difference in our model is in terms of interpretation, namely, the production factors in this equation are produced rather than exogenously given.

We combine the relative factor supply equation (9) with the relative factor demand equation (12) to pin down the equilibrium factor price ratio. Because the second relationship is expressed in terms of produced factor prices, we still need to use (7) to eliminate P_i^M. Equating the two expressions, we get an implicit solution for the equilibrium factor price ratio $\omega^* = (w_i/r_i)^*$ as a function of parameters and of 'primitive' factor endowments. We can write this expression as

$$F_i\left(\omega_i^*\right) \;=\; \frac{c}{\omega_i^*} + (1+c)\left(\frac{\alpha}{1-\alpha}\,\omega_i^*\right)^{-\sigma_i} - \frac{\bar{L}}{\bar{K}} \;=\; 0, \tag{13}$$

where $c = (\sum_g \theta_g(1-\beta_g))/(\sum_g \theta_g\beta_g)$ summarizes information on factor use in final good production and consumers' preferences over final goods.

It is straightforward to establish existence and uniqueness of the equilibrium real wage. The function $F_i(\omega_i)$ attains a positive value for the lowest value in the domain, $\lim_{\omega_i\to 0} F_i\left(\omega_i\right) = +\infty$, and a negative value for the highest value, $\lim_{\omega_i\to\infty} F_i\left(\omega_i\right) = -\bar{L}/\bar{K}$. As the function is continuous, it must equal zero for at least one positive, but finite value of ω_i.

Moreover, the function is monotonically decreasing in ω_i as the derivative

$$\frac{\partial F(\omega_i)}{\partial \omega_i} \;=\; -c\,\omega_i^{-2} - \sigma_i(1+c)\left(\frac{\alpha}{1-\alpha}\right)^{1-\sigma_i}\omega_i^{-\sigma_i-1} \;<\; 0 \tag{14}$$

is negative for all positive real wage rates, which guarantees that the solution is unique. This is useful for the comparative statics that follow, as we do not need to worry about factor intensity reversals.

2.4 Normalizing the CES function

Before we can derive comparative statics of how the σ parameter influences the equilibrium allocation and international trade, it is necessary to normalize the CES function (2). This is because a high σ has two different effects. First, it facilitates producing with a more unequal K/L^m input ratio. With a higher σ parameter, the marginal product of a production factor declines more slowly if the amount of that factor increases. The second effect of a higher σ parameter is to make routine production more efficient overall. The output of intermediate M is increasing in σ

for any given bundle of production factors.

Our objective is to study how countries that start from the same initial situation can develop a comparative advantage as they adjust to the same external shock, for example in response to an increase in the capital stock. The substitution effect is the one of interest, as it directly influences how much labor will be reallocated from routine to non-routine tasks. The second, efficiency effect is more of a nuisance, as it makes it more complicated to determine whether two countries with different σ parameters are initially able to produce the same output bundle.

Klump et al. (2012) have shown that normalizing the CES production function makes it possible to focus on the structural effect of higher substitutability.[15] The rationale behind the normalization follows from the defining property of a CES production function, namely that $\sigma = d\ln(K/L)/d\ln(F_k/F_l)$ is constant. The elasticity of substitution is defined as a point elasticity, valid for a particular point on a particular isoquant. It is fundamentally a second-order differential equation of $F(K, L)$. Solving this equation to find F introduces two integration constants. Both are fixed once the following two boundary conditions are imposed on the resulting CES production function: (1) It must be able to produce an initial production plan, a combination of output and inputs; (2) The initial allocation must be cost minimizing, i.e., the isoquant is tangent to the initial relative factor price ratio.

If a CES isoquant has to go through one particular point, its integration constants will depend on σ and cannot be chosen freely. The elasticity of substitution σ_i is the only structural parameter for country i; together with the boundary conditions it determines the other two parameters, $Z_i = Z(\sigma_i)$ and $\alpha_i = \alpha(\sigma_i)$.

To implement the normalization, we reformulate two key relationships that we derived earlier in terms of deviations from an initial production plan. That way, we can investigate how countries with a different σ adjust differentially to an external shock, starting from the same point of normalization. Denote the optimal factor allocation in routine input production by $\kappa_i^* = \bar{K}/(L_i^m)^*$ and indicate quantities and prices at the point of normalization with a subscript 0. The normalized first order condition in routine production, equation (C1) in the Appendix, then becomes

$$\frac{\kappa_i^*}{\kappa_0} = \left(\frac{\omega_i^*}{\omega_0}\right)^{\sigma_i}. \tag{15}$$

Equation (15) illustrates the key property of a CES production function: the

[15] de la Grandville (1989) shows that the substitution effect can always be written as a σ-multiple of the efficiency effect.

sensitivity of relative factor use to a change in relative factor prices is increasing in σ_i. If labor becomes more expensive than at the point of normalization, routine production will become more capital intensive and this change will be especially strong in the high-σ country. Or inversely, a given change in the capital-labor ratio will lead to a smaller change in the relative factor price ratio in the high-σ country.

Substituting (15) back in the original first order condition, we find that α varies with σ_i and equals $\alpha(\sigma_i) = \frac{\kappa_0^{1/\sigma_i}}{\kappa_0^{1/\sigma_i}+\omega_0}$. From the routine production function at the point of normalization, we can solve for the productivity term Z_i as $Z(\sigma_i) = \frac{M_0}{L_0^m}\left(\frac{\kappa_0^{1/\sigma_i}+\omega_0}{\kappa_0+\omega_0}\right)^{\frac{\sigma_i-1}{\sigma_i}}$. As mentioned, a country-specific σ_i parameter will in general require country-specific Z_i and α_i parameters in order to make the same initial production plan feasible. Using this expression for α_i, the function $F(\cdot)$ in (13) becomes

$$F_i\left(\omega_i^*; \sigma_i, \frac{\bar{L}}{\bar{K}}, c, \kappa_0\right) \;=\; \frac{c}{\omega_i^*} + \frac{1+c}{\kappa_0}\left[\frac{\omega_i^*}{\omega_0}\right]^{-\sigma_i} - \frac{\bar{L}}{\bar{K}} \;=\; 0. \tag{16}$$

As we imposed the same Z and α coefficients in the intermediate goods production function (2) for all countries, it will not generally be possible for all countries with different σ_i parameters to produce the same output bundle from the same $\bar{K}/\bar{L}$ endowments. There is, however, one endowment ratio for which the same production plan is always feasible. It is straightforward to see from (13) or (16) that the same equilibrium factor price will obtain if $\omega_0\,\alpha/(1-\alpha) = 1$ or equivalently if $w_0/(1-\alpha) = r_0/\alpha$, irrespective of the σ_i parameter. In that case, cost minimization in routine production also implies that $\kappa_0 \equiv \bar{K}_0/L_0^m = 1$. It makes the choice of how much labor to allocate to routine tasks independent of the elasticity of substitution.[16]

We can now show how the relative wage ω_i^* changes when factor endowments deviate from the point of normalization. Consider a change in the stock of capital $\bar{K} \gtrless \bar{K}_0$, holding the labor endowment fixed at $\bar{L} = \bar{L}_0$. We apply the implicit function theorem to $F_i(\cdot)$ in (16) and find that[17]

$$\frac{\partial \omega_i^*}{\partial K} \;=\; -\frac{\partial F_i(\cdot)/\partial K}{\partial F_i(\cdot)/\partial \omega_i^*} \;>\; 0. \tag{17}$$

[16] In that point of normalization, $\alpha_i = 1/(1+\omega_0)$ and $Z_i = M_0/L_0^m$, and both do not vary with σ_i.

[17] The derivative in the numerator is positive for our production function. The derivative in the denominator is negative for all wage rates, see equation (14).

The relative wage unambiguously rises above its value at the point of normalization whenever the stock of capital exceeds its initial level:

$$\bar{K} \gtreqless \bar{K}_0 \quad \Rightarrow \quad \frac{\omega_i^*}{\omega_0} \gtreqless 1. \tag{18}$$

The direction of change does not depend on σ_i, but the extent of the change will. The differential adjustment in the two countries will determine the relative abundance of the produced factors and the relative price of final goods. We next determine how this new equilibrium allocation depends on σ_i as both countries adjust away from the point of normalization.

2.5 Pattern of specialization

We want to find out how σ influences the relative specialization of two economies. Recall that we defined a point of normalization where both countries produce the same equilibrium production plan. The question is how their allocations will differ when they move away from this point in response to an increase in the capital stock. We apply the implicit function theorem to (16) one more time and find

$$\frac{\partial \omega_i^*}{\partial \sigma} = -\frac{\partial F_i(\cdot)/\partial \sigma}{\partial F_i(\cdot)/\partial \omega_i^*}.$$

We already established that the denominator is negative. Hence, the sign of this expression is determined by the sign of the numerator,

$$\frac{\partial F_i(\cdot)}{\partial \sigma} = -\ln\left(\frac{\omega_i^*}{\omega_0}\right)\frac{(1+c)}{\kappa_0}\left[\frac{\omega_i^*}{\omega_0}\right]^{-\sigma},$$

which depends on the equilibrium relative wage relative to the relative wage at the point of normalization.

It follows that when the price of labor increases relatively to the point of normalization, which will happen following an increase in the capital stock, labor will be relatively cheap in the high-σ country in the new equilibrium. Hence,

$$\begin{cases} \frac{\partial \omega_i^*}{\partial \sigma} < 0 & \Leftrightarrow \quad \bar{K} > K_0 \text{ or } \omega_i^* > \omega_0 \\ \frac{\partial \omega_i^*}{\partial \sigma} = 0 & \Leftrightarrow \quad \bar{K} = K_0 \text{ or } \omega_i^* = \omega_0 \\ \frac{\partial \omega_i^*}{\partial \sigma} > 0 & \Leftrightarrow \quad \bar{K} < K_0 \text{ or } \omega_i^* < \omega_0. \end{cases} \tag{19}$$

A higher σ dampens the effect of a change in factor endowments on the equilibrium relative wage. The relative wage increases, but it increases relatively less in the

high-σ country A: $\omega_0 < \omega_A^* < \omega_B^*$.

Recall from (12) that it is sufficient to establish in which country the relative price of the routine intermediate is relatively high in autarky to determine relative abundance of 'produced' factors. It is intuitive and straightforward to show that $d(P_i^m/w_i)/d\omega_i < 0$.[18] In combination with the results in (19), it implies that the relative price of the routine input is increasing in σ for all capital stocks that exceed the level at the point of normalization and vice versa:

$$\begin{cases} \frac{d(P_i^m/w_i)^*}{d\omega_i^*}\frac{\partial\omega_i^*}{\partial\sigma} > 0 & \& \quad \frac{d(L^a/M)}{d\sigma} > 0 \quad \Leftrightarrow \quad \bar{K} > K_0 \\ \frac{d(P_i^m/w_i)^*}{d\omega_i^*}\frac{\partial\omega_i^*}{\partial\sigma} = 0 & \& \quad \frac{d(L^a/M)}{d\sigma} = 0 \quad \Leftrightarrow \quad \bar{K} = K_0 \\ \frac{d(P_i^m/w_i)^*}{d\omega_i^*}\frac{\partial\omega_i^*}{\partial\sigma} < 0 & \& \quad \frac{d(L^a/M)}{d\sigma} < 0 \quad \Leftrightarrow \quad \bar{K} < K_0 \end{cases} \tag{20}$$

The intuition is as follows. When labor becomes more scarce than in the normalization point, it will be expensive and the routine input relatively cheap. The price changes are needed to clear both factor markets after a capital injection, but they are especially pronounced in the low-σ country. It makes labor relatively more expensive in the low-σ country and the routine intermediate expensive in the high-σ country. It follows that after capital deepening, the high-σ country A becomes relatively abundant in non-routine labor: $(L^a/M)_A^* > (L^a/M)_B^*$. More flexible substitution between capital and labor helps the economy to use more efficiently the 'primitive' production factor that has become more scarce (labor), where scarcity is defined relative to the point of normalization.

As countries accumulate capital, which we interpret as a reduced-form representation of capital-biased technological change, they reallocate labor from routine to non-routine tasks.[19] A high-σ country frees up more labor for non-routine tasks and becomes non-routine labor abundant. This holds even though the high-σ country is relatively efficient in routine production, i.e. for the same input bundle it can produce more output in routine production.[20] As the substitution effect dominates the efficiency effect, a country with higher σ will specialize, at least relatively, in non-routine intensive goods. In the new equilibrium, capital intensity in routine

[18] From equation (7) we can derive $\frac{d(P_i^m/w_i)^*}{d\omega_i^*} = \frac{-\alpha^{\frac{\sigma}{\sigma-1}}}{Z\left(\omega^*\right)^2}\left[1+\left(\omega^*\right)^{1-\sigma}\left(\frac{1-\alpha}{\alpha}\right)^{\sigma}\right]^{\frac{\sigma}{\sigma-1}} < 0.$

[19] Note that the opposite pattern obtains if the capital-labor ratio is reduced from the initial point of normalization: a high-σ country frees up more labor to do routine tasks and becomes routine input abundant. When we turn to the trade predictions, our maintained assumption is that a rising capital-labor ratio is a pervasive pattern of real-world technological change. Hence, the empirically relevant case is the one where labor is becoming more and more scarce.

[20] This is a feature of the CES production function: holding the input bundle constant, output is strictly increasing in σ (Klump et al., 2012).

production will be higher in both countries, but increases especially in the high-σ country. Its higher elasticity parameter implies less of a productivity penalty for an unbalanced factor ratio.

2.6 Implications of opening up to trade

We now investigate the effect of substitutability between capital and labor in routine production on the pattern of comparative advantage. To accomplish this in a static model, we compare how countries with different σ parameters adjust to the same exogenous shock. In particular, we consider an increase in the capital stock which requires a reallocation of labor to achieve a new equilibrium. To abstract from other channels of comparative advantage, we assume that both countries have identical endowments of primitive factors, capital and labor, at all times. It is the optimal allocation of labor to routine or non-routine tasks that determines the available quantities of produced factors, abstract labor and routine intermediates, that are used in the two final goods sectors. The equilibrium is fully determined by the relative factor price ratio that clears labor and capital markets.

After a capital injection, the difference in substitutability creates an incentive to trade, even for countries with identical endowments that initially produce the same output bundle. The pattern of comparative advantage that arises can be determined from the comparative statics of the relative factor price ratio with respect to σ. However, as we illustrate in Appendix D, without normalizing the CES function this leads to a circularity. The impact of σ on the pattern of trade depends on the effective labor cost, i.e., whether w_i/r_i exceeds $(1-\alpha_i)/\alpha_i$ or not, while α_i depends on σ itself.

Hence, we need to work with the normalized CES function. Given the pattern of specialization in autarky, establishing the main result is straightforward. We have already shown that in response to capital deepening, the equilibrium $(L_i^a/M_i)^*$ ratio is increasing in σ. As capital accumulates and labor becomes more scarce, the high-σ country becomes relatively abstract labor abundant (compared to the low-σ country). Higher substitutability dampens the necessary factor price change that is needed to absorb a shock to factor endowments. Capital deepening raises the relative wage in both countries, but less so in the high-σ country which adjusts more in quantities and less in prices.

The direction of trade then follows from the usual reasoning in the HO model. Both countries acquire a comparative advantage in the good that is intensive in their abundant factor. We obtain an adjusted HO prediction in this case, as the

relevant production factors for the two final good sectors are not exogenously given, but produced through the equilibrium labor allocation. After a capital increase, the high-σ country specializes in the good intensive in abstract labor. More generally, the high-σ country specializes in the good that uses more intensively the produced factor that itself requires relatively more of the relatively scarce primitive factor. In this condition, the relative scarcity of the primitive factor is defined in terms of deviation from the point of normalization, while the relative intensity of use of the produced factor is determined by technology, in the canonical HO way.

Three implications of the free trade equilibrium are worth highlighting. First, equalization of final good prices is obtained through further divergence between countries of the capital intensity in routine production. In the autarky equilibrium, capital accumulation creates a wedge between the marginal product ratios (MP_{L^m}/MP_K) for the two countries that differ in input substitutability. In turn, this leads to a wedge in the relative produced factor prices (w/P^m) and thus a wedge in the relative final good prices in the two countries.[21] Once they open up to trade, the only way that the wage to routine input price ratio can increase in the high-σ country is by increasing its relative real wage ω_A/ω_B. This requires a movement of labor out of routine production.[22] Hence, the high-σ country—where capital deepening leads to a comparative advantage in the non-routine intensive good—is characterized by relatively high capital intensity in routine production in autarky, and this relative capital intensity increases further when the countries open up to trade.

Second, as in the canonical HO model, opening up to trade equalizes the final good prices which leads to factor price equalization for w/P^m, the relative price ratio for the produced factors. Factor price equalization does not obtain for the primitive factors, however. The gap in the relative price of the primitive factors w/r will be lower than under autarky, but not be eliminated entirely. This can be seen from equation (7) which shows that the price for the routine input is a CES price index of the two primitive factor prices. Hence, the relationship between w/P^m and w/r depends on the σ_i parameter. When the first ratio equalizes between countries, the second cannot. In our model, there is no factor price equalization for the primitive factors because institutional or cultural differences that affect the flexibility of input substitution lead to different production technologies in the two countries. These

[21]The high-σ country will have a lower relative wage, MP_{L^m}/MP_K ratio, wage to routine input price ratio, and a lower relative price for the final good that is intensive in non-routine tasks.

[22]The relative wage rate will equal labor's marginal productivity in routine production and this is increasing in capital intensity.

patterns are shown formally in Appendix E.

Third, we already discussed that capital deepening raises real wages, but less so in the high-σ country. At the same time, there is an efficiency effect associated with σ in the CES function: holding the other parameters (α and Z) fixed, increasing the production factors raised output M more with higher σ. As a result, capital deepening produces higher total benefits in the high-σ country, but compared to the low-σ country they flow more to capital owners and less to workers. The standard HO finding that gains from trade flow disproportionately to the scarce factor still applies and this favors workers in the high-σ country. As a result, we cannot tell in general in which country workers gain most from capital deepening, but we know that workers gain relatively more in the high-σ country under free trade than under autarky.

Finally, our findings imply that higher capital-labor substitutability mitigates resource scarcity. It reflects the efficiency of resource allocation in the economy when reallocation is needed, as in the adjustment to factor-biased technological growth. The corollary for the pattern of trade is that the high-σ country specializes in the final good that uses the relatively scarce factor—which we assumed to be labor—more intensively. This is a restatement of the result in Arrow et al. (1961), studied in a growth context by Klump and de la Grandville (2000), that economies with higher labor substitution are better able to mitigate labor scarcity and achieve higher welfare because they have more incentive to accumulate capital. Endogenizing capital accumulation is left for future work, but it is likely to reinforce our results.[23]

3 Data

As is standard since Bowen et al. (1987) and Debaere (2003), our empirical analysis is based on three types of data. Bilateral export flows at the product level are used to construct the dependent variable. The explanatory variables are interactions of industry-level indicators of input intensity, in particular the routine-intensity, and country-level indicators of the corresponding endowments, including factor endowments, quality of institutions, and cultural differences.

[23]We find that the return to capital falls by less in the high-σ country under capital deepening, giving it *ceteris paribus* higher incentives to accumulate capital. This process would lead to a further release of labor from routine tasks, further increasing the relative abundance of abstract labor in the high-σ country but also reducing the wedge in the autarky factor prices. Stokey (1996) performs a related exercise, but in a one-sector model where no trade is possible.

Bilateral exports

Bilateral exports are reported in the UN Comtrade database and we use the 2017 release of the BACI harmonized version. Gaulier and Zignago (2010) describe an earlier release. The model predicts the cross-sectional export specialization, but we keep three years in the sample—1995, 2005, and 2015—to investigate whether the fit of the model has improved or deteriorated over the last two decades. We average exports over two adjacent years to smooth out annual fluctuations.[24] Products are observed at the 6-digit detail of the Harmonized System (HS) and mapped into 4-digit NAICS sectors using a concordance constructed by Pierce and Schott (2012).

We construct two separate samples that are limited to two different groups of exporters. In the 'large exporters sample' we keep bilateral exports that originate from the 50 largest exporters in the world (excluding fossil fuels). On the import-side, we keep trade flows towards those same 50 destinations separate and aggregate the remaining countries, which together account for less than 10% of global trade, into 10 separate regional blocs. In the 'EU sample', we keep only exports from the 28 EU members states (Belgium and Luxembourg are combined) and use the same set of countries on the import side.

As a robustness check, we also use value added trade as dependent variable. For this analysis we rely on the sectoral information in the *World Input-Output Database* (WIOD).[25] We follow Los et al. (2016) who illustrate how to construct a measure of value added trade from the input-output table using an intuitive 'hypothetical extraction' method. It takes the difference between observed GDP in a country and what would have resulted if final demand from a single trading partner were removed from the world economy, leaving all other sources of demand and input-output relationships unaffected.

Industry-level input intensity

The key explanatory variable is the routine task intensity by industry, which is represented by the parameter β_g in the model. We use the ranking of routine intensity constructed by Autor et al. (2003) for 77 U.S. industries at the 4-digit NAICS level. It is a weighted average of the routine task intensity by occupation using the employment shares of occupations in each industry in 1977 as weights. By using employment shares that pre-date the recent process of automation, the ranking is intended to capture sectors' technological features that determine routine

[24] For 1995 and 2005 we use the average export flows for 1995-1996 and 2005-2006; given that 2015 is the last year included in the dataset we average with the preceding year: 2014-2015.

[25] We used the latest release, for 2016, which can be downloaded from `http://www.wiod.org/`.

intensity.[26]

As control variables, we include additional industry characteristics that represent other dimensions of the production technology. Physical capital and human capital intensity are included to capture the effects of the traditional HO mechanism. Following Nunn (2007) and Chor (2010), we measure these by the U.S.' values for the real capital stock per employee and the ratio of non-production workers to total employment from the NBER-CES database.

We further include two characteristics that capture industries' reliance on domestic institutions. External capital dependence, introduced by Rajan and Zingales (1998), is measured as the fraction of total capital expenditures not financed by internal cash flow. This is calculated at the firm level in the Compustat database. The median value within each ISIC 2-digit industry is assigned to the corresponding 4-digit NAICS industries. Finally, the fraction of differentiated inputs in total input expenditure, using the liberal definition, is taken directly from Nunn (2007).

Country-level endowments

We follow the literature regarding endowments that are expected to give countries a comparative advantage along the four dimensions of factor intensity that we control for. Physical and human capital endowments are constructed from the *Penn World Tables*.[27] The physical capital stock is measured using constant national prices and converted into USD at current exchange rates. To obtain a capital-labor ratio, we divide by the number of employees multiplied by the average annual hours worked. Human capital is proxied by average years of schooling.

Two dimensions of institutional quality, financial development and rule of law, are conducive to industries with, respectively, a high external capital dependency and a high fraction of differentiated inputs. Financial development is measured by the amount of credit extended by banks and non-bank financial intermediaries to the private sector, normalized by GDP. This is taken from the most recent version of the World Bank's *Financial Development and Structure Dataset*.[28] The ability and effectiveness of contract enforcement is proxied by the 'rule of law' index published as part of the *World Bank Governance Indicators database*.[29]

[26] Autor et al. (2003) show that routine intensive industries, measured this way, replaced labor with machines and increased demand for nonroutine labor at above-average rates.

[27] The 9.1 version was downloaded from `https://www.rug.nl/ggdc/productivity/pwt/`.

[28] The July 2018 version was downloaded from `https://www.worldbank.org/en/publication/gfdr/data/financial-structure-database/`.

[29] Available online at `https://info.worldbank.org/governance/wgi/`.

We use time-varying information on endowments for the same three years as the export flows—1995, 2005, and 2015—and similarly use two-year averages to smooth out annual fluctuations.

There exists no literature that establishes which country-level endowments give a comparative advantage in (non-)routine intensive production. We will investigate for a number of observable characteristics whether they have predictive power for the routine specialization that we estimate in a first stage. According to our theory, these would be factors that determine the ease of substituting between capital and labor in production. Throughout, we include GDP per capita (taken from the Penn World Tables) as a general control for development.

First, we consider whether the widely used rule of law indicator predicts routine specialization. Following the labor literature, we next consider the role of formal labor market institutions, as measured by the stringency of employment protection legislation (EPL). This index is constructed by the OECD and discussed in Nicoletti et al. (2000). We also use a broad index of labor quality, the 'ability to perform' measure also used in Costinot (2009) and developed by a private firm, *Business Environment Risk Intelligence*. It is a synthetic index of worker attributes that combines behavioral norms in the workforce, such as work ethic, with the quality of human capital and physical characteristics, such as healthiness.

The degree of internal mobility measures the prevalence of adjustment in a geographic dimension. It is measured as the fraction of the population residing in a different region than their place of birth, a coarse measure of workforce mobility.[30] If workers tend to move easily between locations, they might display a similar flexibility substituting between sectors or occupations. Finally, we consider two cultural traits that could pre-dispose workers to move between sectors if opportunities present themselves. From the six dimensions of national culture introduced by Hofstede (1980), we consider 'long-term orientation' and 'uncertainty avoidance' most suitable in our context.

Where possible, we use the values of the country characteristics for the same year as the trade flows. Most variables, e.g. the rule of law index, change only slightly over time and the cultural traits do not have any time variation. This stability is not unexpected and is consistent with our interpretation of these measures as exogenously given, relatively immutable country characteristics that help determine sectoral specialization.

[30]This information is taken from OECD's *Labor Market Statistics* database.

4 Empirical model

Our empirical strategy follows the two-step approach of Costinot (2009). In a first step, we estimate for each country the extent of revealed comparative advantage in sectors that are intensive in routine tasks. In a second step, we regress the obtained ranking on country characteristics that are likely to be correlated with the ease of labor reallocation across tasks. In a final analysis, once we have determined which endowments or institutions are conducive to (non-)routine production, we show results for a single-step analysis, including the interaction between routine intensity and the relevant country characteristic.

The first step in evaluating the predictions of our model is to recover the direction of export specialization of each country with respect to routine intensity. We estimate the following equation

$$\ln X_{ijg} \quad = \quad \gamma_i \, r_g + \sum_{t \in k,h,f,c} \gamma_t \, I_i^t \, t_g + \tau_{ij} + \tau_{jg} + \epsilon_{ijg}. \tag{21}$$

The dependent variable is bilateral exports from exporter i to importer j in industry g. The comparative advantage in the routine dimension is captured by the country-specific coefficient γ_i that interacts with the sectoral routine task intensity r_g, a country-invariant measure of sectoral technology. A high (positive) value for γ_i indicates that the composition of country i's export bundle is correlated positively with the the routine-intensity of those sectors.

To control for other mechanisms that can explain the exporter-sector specialization, we include four interaction terms between a sector-specific technology dimension (t_g) and a country-specific endowment (I_i^t). The four terms are for the two traditional HO mechanisms, physical (k) and human capital (h) intensity times endowment, as well as external capital dependence of the industry times financial development of the country (f), and importance of differentiated inputs times the quality of contract-enforcing institutions (c).

Equation (21) includes a pair of interaction fixed effects to control for alternative explanations of trade volumes. The bilateral exporter-importer fixed effects τ_{ij} absorb gravity effects, including exporter and importer country characteristics, e.g. size or multilateral resistance, as well as any form of bilateral trade friction, e.g. proximity or historical ties. The destination-sector fixed effects τ_{jg} capture variation in import barriers, preferences, or business cycles in importing countries. We do not exploit the time dimension, but estimate equation (21) separately for the three years that we consider. This allows both sets of fixed effects and the γ_i coefficients to vary

entirely flexibly over time.

The second step in our analysis is to connect the estimated routine intensity of exports to one or more country characteristics. We wish to find out whether observables that are plausible proxies for the country-specific ease of reallocating labor across tasks (the σ parameter in our model) have the predicted correlation with export specialization. We regress $\hat{\gamma}_{it}$, the countries' ranking by routine intensity estimated using specification (21) by year, on the various candidate institutional dimensions I_{it}^r:

$$\hat{\gamma}_{it} \quad = \quad \delta_0 + \delta_1 \, \text{GDP/capita}_{it} + \delta_r \, I_{it}^r + \gamma_t + \epsilon_i, \tag{22}$$

for $r \in \{1, ..., 6\}$.

We include GDP per capita to control for the level of development as well a time fixed effects. The coefficient of interest is δ_r, which we expect to be negative for dimensions that are expected to have a positive correlation with σ, i.e., rule of law, quality to perform, long-term orientation, and internal mobility. For country characteristics with an expected negative correlation with σ, i.e., the stringency of employment protection legislation and uncertainty avoidance, we expect a positive sign as they are likely to induce specialization in routine-intensive sectors.

In a final analysis, we perform the estimation in a single step:

$$\ln X_{ijg} \quad = \quad \gamma_r \, I_i^r \, r_g + \sum_{t \in k,h,f,c} \gamma_t \, I_i^t \, t_g + \tau_{ij} + \tau_{jg} + \epsilon_{ijg}. \tag{23}$$

Compared to specification (21), we replaced the country-specific coefficient γ_i with $\gamma_r \, I_i^r$, inserting the country endowment found to predict routine specialization in specification (22). This specification is estimated separately by year.

Finally, taking into account the increased international integration of supply chains, especially in the EU context, we use value added trade instead of gross exports as the dependent variable to test our hypothesis, and as a further robustness check.

5 Results

5.1 Step 1: Revealed comparative advantage in routine tasks

We estimate each country's specialization in routine versus non-routine tasks using specification (21). Figure 1 shows the estimates of γ_i on the sample of 50 largest exporters and Figure 2 the estimates on the EU sample. Table F.1 and Table F.2 in the Appendix contain all point estimates and standard errors for both samples.

Before estimation, we standardize all variables by subtracting the mean and dividing by the standard deviation over the respective samples. As a result, the magnitudes of the coefficients are in terms of standard deviations: How many standard deviations do exports change on average when the routine-intensity indicator is one standard deviation higher? This interpretation is only approximate due to the fixed effects, which all need to be held constant when evaluating the effect of a change in routine intensity.

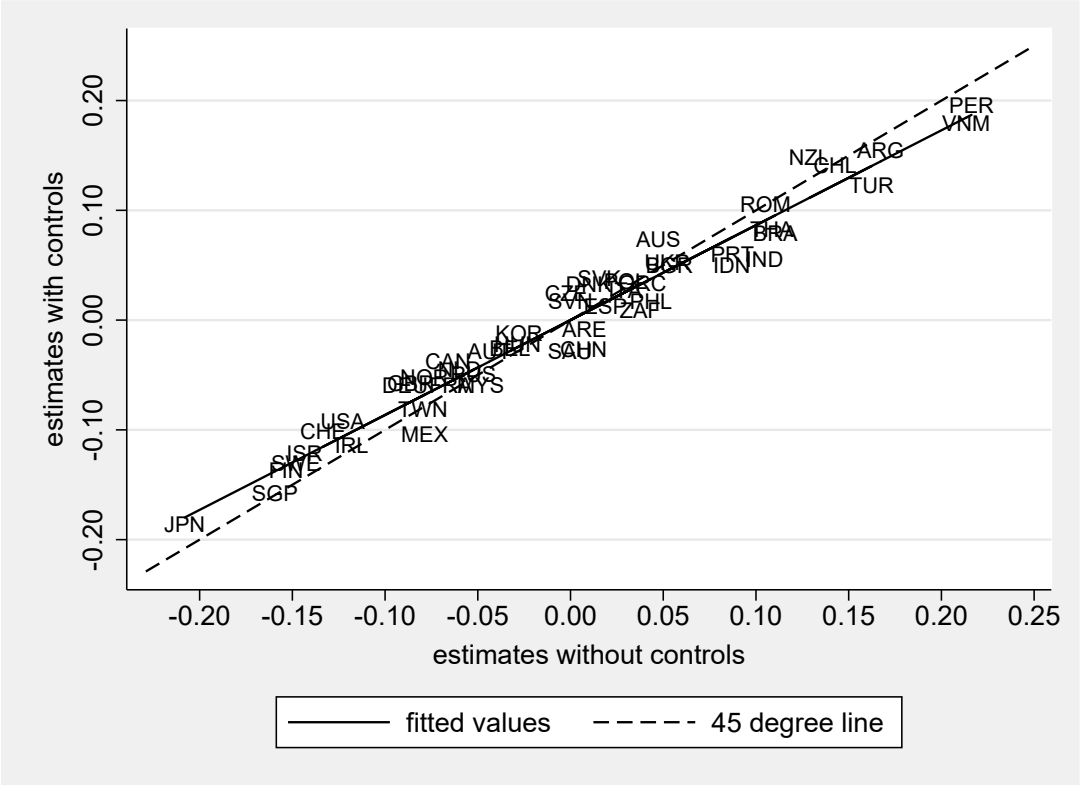
The included fixed effects implicitly normalize the γ_i estimates to average zero over the entire sample.[31] A negative coefficient only implies that the country specializes less in routine-intensive industries than the average country. Given that the sample is almost balanced over exporters, by construction half of the countries show positive and the other half negative point estimates.

The top panel in Figure 1 shows the country-average of the estimates obtained using separate regressions for each of the three years. The estimates without the $I_i^t\, t_g$ interaction controls are on the horizontal axis and the corresponding estimates including the controls are on the vertical axis. The countries towards the left, in particular Japan, Singapore, Finland, Sweden, and Israel, tend to specialize in non-routine intensive products. The next cluster of countries is also intuitive, with Ireland, Switzerland, and the United States. At the other end of the spectrum (on the right), are countries with a revealed comparative advantage in routine-intensive industries. Here we find more developing or emerging economies, first Peru and Vietnam, followed by Argentina and Chile. Exports of New Zealand, which is well-known to specialize in primary products, and Turkey, which is an assembly hub for EU-bound exports, are also highly routine intensive.

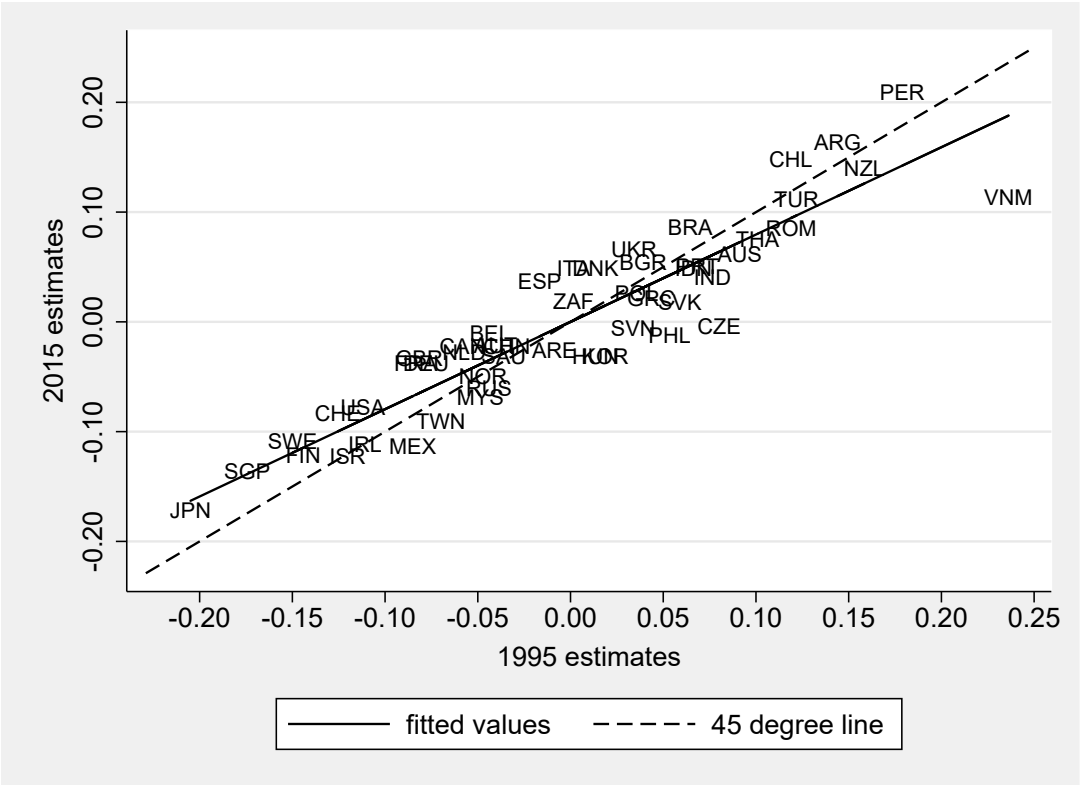
It is intuitive that the estimates with controls on the vertical axis are lower in absolute value than those without controls. Estimates on the left tend to lie

[31] Because of the two sets of fixed effects, which include both the i and g dimension, one of the country-specific γ_i coefficients cannot be estimated and is normalized to zero. The point estimates in the figures are re-normalized to have an average of zero over the different countries.

Figure 1: (Non-)Routine export specialization in sample of 50 largest exporters



(a) Estimates with and without Heckscher-Olin interaction terms



(b) Estimates for 1995 versus 2015 (with controls)

above the 45-degree line and on the right below the dashed line. The solid, fitted line confirms that the results change towards zero if controls are included, but the average change is minor. The adjustment is most notable for countries with lower capital endowments or lower institutional quality than their most important trading partners, such as Mexico, India, and Turkey. Overall, however, the pattern of routine specialization is relatively unaffected by the inclusion of the four sets of interaction controls that capture alternative explanations for export specialization.

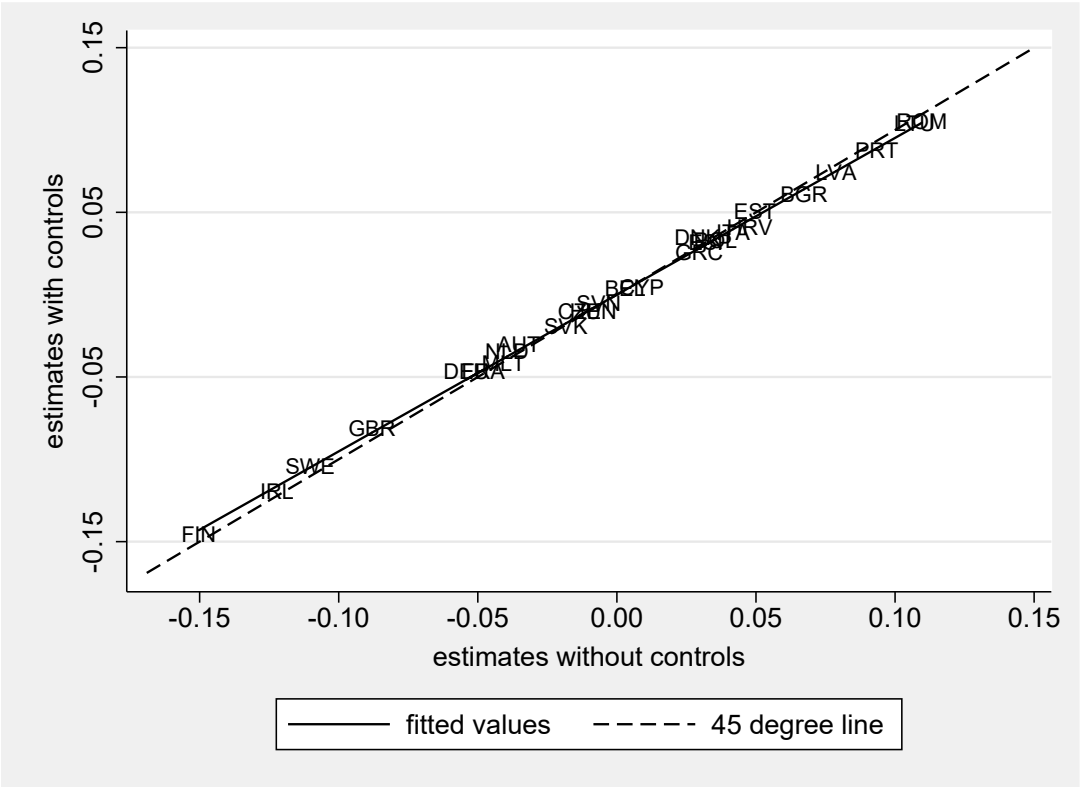
One more notable pattern is the large difference in specialization between some countries that share similar levels of development. Finland and Sweden have much lower (more negative) point estimates than Norway or Denmark. The contrast between France and Italy or between Spain and Portugal is also quite large. The same holds on the other continents: in Latin America, Mexico is much less specialized in routine-intensive industries than Argentina or Chile; in Asia, Malaysia much less than Thailand.

The bottom panel of Figure 1 plots the point estimates for 2015 on the vertical axis against the corresponding estimates for 1995 on the horizontal axis, including the HO interaction controls in both years.[32] Over this twenty year period, countries' specialization by routine-intensity is relatively stable. Large deviations from the 45-degree line are rare. The two largest changes are for Vietnam and the Czech Republic which both specialize away from the routine-intensive sectors. Spain, the United Kingdom and Italy are among the countries with the largest change in the opposite direction, towards routine-intensive industries. The flattening of the solid line suggests that in 2015 the routine intensity of a sector has somewhat less predictive power for a country's exports than in 1995.

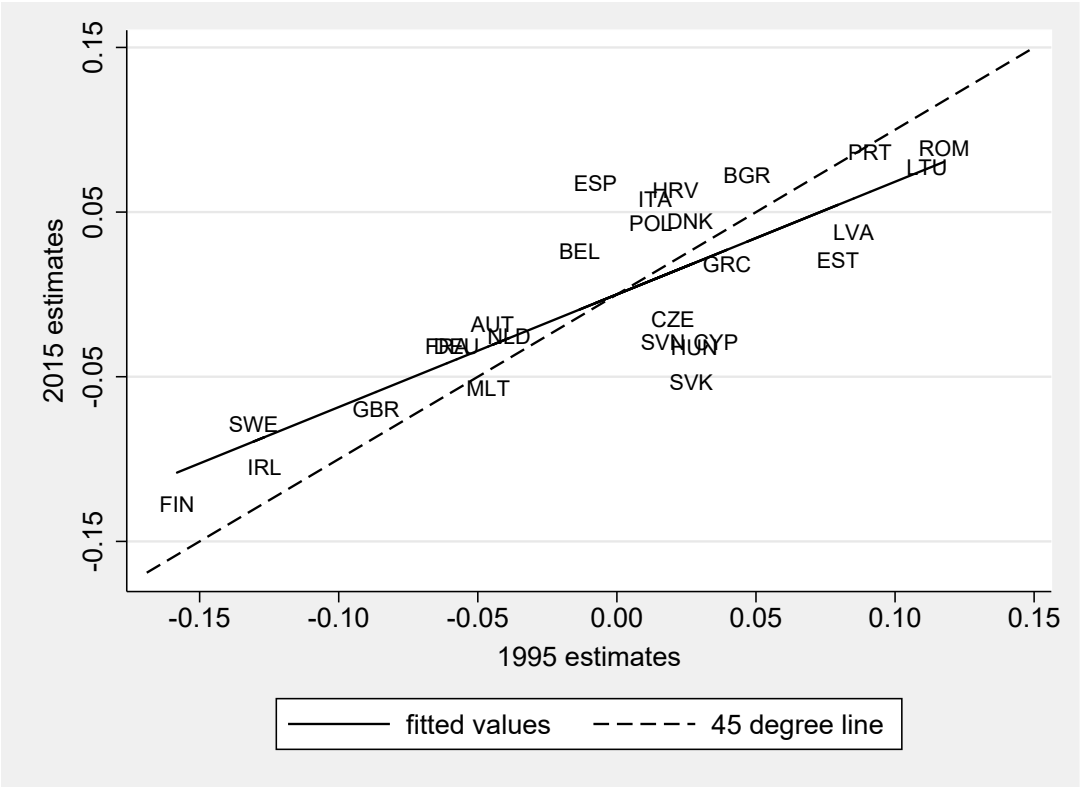
In Figure 2, we show comparable estimates on the sample of EU countries, including only intra-EU trade in the dependent variable. The relative ranking of countries is broadly consistent with Figure 1, suggesting that the overall and intra-EU export bundles of most countries are highly correlated. This is not surprising as the intra-EU share of exports is very high for most member states. Among the countries that appear in both samples, only the United Kingdom and Slovakia show a notably lower specialization towards routine-intensive sectors on the intra-EU sample. The difference is especially large for Slovakia, indicating that its intra-EU exports are systematically different from its extra-EU exports. The emergence of a large Slovak automotive industry notably shifted its intra-EU specialization towards non-routine industries, with the point estimate declining from 0.027 to -0.053.

[32]For almost all countries, the 2005 estimates are intermediate, as shown in Table F.2.

Figure 2: (Non-)Routine export specialization among EU member states



(a) Estimates with and without Heckscher-Olin interaction terms



(b) Estimates for 1995 versus 2015 (with controls)

A few other changes over time are worth pointing out. In the full sample, the United Kingdom, France, and Germany specialized moderately in non-routine industries in 1995, each with a coefficient of around -0.08 (at rank 10 to 12). This specialization diminished for all three countries by 2015, the coefficient estimates rose to around -0.035 (at rank 14 to 16). Limited to EU trade, we see the same evolution for France and Germany, both dropping 3 places in the ranking among EU countries, while the United Kingdom maintained its specialization and its rank. Similarly as France and Germany, a few other older member states go down in the ranking. Belgium, Italy, and Spain had a negative or in the case of Italy a very low positive coefficient in 1995, but by 2015 they all three show a clear revealed comparative advantage in routine-intensive industries. Given that we only uncover a relative specialization, the reverse pattern must hold for some other countries. The point estimates decline for Cyprus, Hungary, Estonia, and Slovenia.

In the top panel of Figure 2, it is remarkably how invariant the estimates are to the inclusion of the HO control interactions. Results are almost identical with or without; the fitted line lies almost on top of the dashed 45-degree line. It implies that the predictive power of routine intensity for trade flows is orthogonal to the most important endowment or institution-based explanations in the literature.

The bottom panel of Figure 2 shows a convergence in export orientation. Countries with negative coefficients in 1995 are systematically above the 45-degree line in 2015 and the reverse is true for countries with positive coefficients in 1995. Most countries see their γ_i coefficient shrink towards zero. As a result, routine-intensity has less predictive power for countries' export bundle in 2015 than in 1995. This also appears as a decline in the standard deviation across the point estimates in Table F.1 from 0.072 to 0.060. However, in the middle of the graph we see two clusters of countries with relatively similar export orientation in 1995, but a different evolution in the next 2 decades. Spain, Belgium, and Italy, as mentioned already, but also Croatia and Poland specialize more in routine-intensive industries, while Slovakia, Hungary, Cyprus, Slovenia, and the Czech Republic change in the opposite direction.

While there is a negative correlation between GDP per capita and specialization, it is by no means perfect. In particular, Italy sees a much stronger and Slovakia a much weaker specialization in routine-intensive products than would be predicted by their level of development. We next evaluate which observable differences between countries help explain the different specializations.

5.2 Step 2: Country characteristics that predict (non-)routine specialization

To learn which country characteristics correlate with the pattern of routine versus non-routine specialization that was recovered in step 1, we report the estimates of specification (22) in Table 1. Each of the six country characteristics is introduced separately in columns 1–6 and jointly in column 7. In the last regression we omit the two characteristics with most missing observations to preserve the sample size. The reported estimates are standardized β-coefficients to make the absolute magnitudes of coefficients on the different variables comparable.

GDP per capita is always included as a control variable because countries at different levels of development are likely to have different institutional quality and industrial structure. Because most country characteristics that we consider are correlated to some extent with the level of development, we include an explicit control to facilitate interpretation. Not surprisingly, GDP per capita is always negatively related to the extent of specializing in routine-intensive industries.

More surprising is the insignificant coefficient on the rule of law variable in the top panel, for the sample of large exporters. To some extent, this is due to the high correlation with GDP per capita, showing a partial correlation coefficient of 0.61. Without the control, the coefficient on rule of law becomes -0.455 and significant at the 1% level. The same pattern is true on the EU sample. With GDP per capita included, the coefficient on rule of law is -0.313 and barely significantly different from zero. Without the control variable it becomes -0.670 with a t-statistic of 4.5. These results highlight that interpreting the effects of rule of law warrants some caution.

The other columns in panel (a) indicate that four of the five observables have predictive power, even when we control for the level of development. Countries with a high workforce quality are especially likely to specialize in sectors that are not intensive in routine tasks. The 'ability to perform' variable captures a variety of workforce features such as worker behavior (e.g. punctuality), workplace norms (e.g. taking responsibility), human capital, and good health. It explains fully 44% of the variation in the dependent variable.[33]

More interestingly, the two dimensions of national culture are correlated with export specialization in the predicted direction. Countries where workers are more

[33]The high significance is in spite of an even stronger correlation with GDP per capita than rule of law, showing a partial correlation statistic of 0.75 overall and even 0.88 in 1995.

Table 1: Country determinants for routine versus non-routine export specialization

	Dependent variable is the country-specific extent of specialization in routine-intensive industries estimated in the first stage						
	(1a)	(2a)	(3a)	(4a)	(5a)	(6a)	(7a)
(a) Sample of 50 largest exporters							
log(GDP/capita)	-0.541***	-0.061	-0.667***	-0.603***	-0.621***	-0.662***	-0.091
	(.120)	(.127)	(.118)	(.075)	(.072)	(.121)	(.163)
Rule of law	-0.081						0.122
	(.108)						(.119)
Ability to perform		-0.721***					-0.590***
		(.115)					(.119)
Strictness of EPL			0.053				
			(.091)				
Uncertainty avoidance				0.202***			0.137*
				(.067)			(.077)
Long-term orientation					-0.294***		-0.324***
					(.065)		(.065)
Internal migration						-0.172*	
						(.092)	
Observations	150	120	102	150	150	90	120
Adjusted R2	0.285	0.425	0.257	0.324	0.371	0.265	0.525
	(1b)	(2b)	(3b)	(4b)	(5b)	(6b)	(7b)
(b) Sample of EU member states							
log(GDP/capita)	-0.542**	-0.174	-0.788***	-0.790***	-0.884***	-0.516***	-0.454
	(.218)	(.313)	(.139)	(.121)	(.120)	(.184)	(.225)
Rule of law	-0.313*						-0.229
	(.160)						(.172)
Ability to perform		-0.450**					
		(.207)					
Strictness of EPL			0.358***				0.289***
			(.099)				(.105)
Uncertainty avoidance				0.226**			0.158
				(.089)			(.119)
Long-term orientation					0.063		0.027
					(.088)		(.097)
Internal migration						-0.358***	
						(.123)	
Observations	81	48	63	81	81	54	63
Adjusted R2	0.437	0.242	0.414	0.455	0.412	0.267	0.443

Note: The dependent variable is the country-specific estimates of routine-specialization in exports (the point estimates reported in Tables F.1 and F.2). EPL stands for employment protection legislation. Regressions include year fixed effects. The reported statistics are standardized β-coefficients which measure effects in standard errors. Standard errors are in brackets. ***, **, * indicate statistical significance at the 1%, 5%, 10% level.

risk averse or have a more short-term orientation tend to specialize relatively more in routine-intensive tasks. It is plausible that both of these features are inversely related to the σ coefficient in the model that governs the capital-labor substitution. The extent to which countries adjust their production structure when more productive capital is introduced is likely to be lower when workers and managers are highly risk averse and have no long-term outlook.

In the micro-foundation of our production function, we showed that firing restrictions naturally have such an effect. The strictness of employment protection legislation (EPL) has the predicted positive sign on both samples, but it is only a significant predictor of export specialization on the EU sample with countries that are relatively similar in most other dimensions. Among EU countries, EPL is the most robust predictor of export specialization when different dimensions are included simultaneously. Countries that enacted laws and regulations to make firing workers more costly and to restrict temporary employment tend to specialize in more routine-intensive tasks. Note that these results should not be interpreted causally. While EPL might have caused or contributed to the trade specialization, as in our model, it is also possible that labor regulations were enacted in response to sectoral specialization.

The last variable, the extent of internal migration, has the predicted negative sign in both samples. It is only observed for two thirds of the countries in the sample, though, and it is unlikely to have the same interpretation in large and small countries.

Because the dependent variable has no clear cardinal interpretation, we also implemented a more flexible estimation approach as a robustness check. We can treat the dependent variable as an ordinal variable and estimate specification (22) as an ordered probit model. This follows the spirit of the rank comparisons in Bowen et al. (1987). It makes the point estimates not comparable and harder to interpret, but the signs for the different country characteristics are always unchanged. In this case, it is preferable to estimate separate specifications for each year, rather than pooling and including time fixed-effects, but most of the t-statistics did not decline much even on samples only one third the size.[34]

[34]Results available upon request.

5.3 Single-step estimation

Now that we have a sense which attributes make countries specialize in routine-intensive industries, we can include an interaction between the routineness indicator r_g and the preferred country 'endowment' I_i^r directly in the initial regression. Based on the results for the EU sample, we interact r_g with the EPL measure. The results on the large exporters sample highlighted the importance of national culture and we interact r_g with the average of uncertainty avoidance and short-term orientation. Results in Table 2 are shown separately for the two samples and for each of the three years.

On the sample of large exporters, human capital is the most important determinant of countries' export specialization. Capital intensity and the ability to enforce contracts for differentiated inputs also show the predicted positive sign in most specifications, but their predictive power is much lower. The combination of routine task intensity and the national culture indicator is remarkably important as well. It is easily the second most important predictor. Even routineness interacted with EPL turns out to be a strong predictor of export specialization, even on this sample.

On the sample of EU countries, results are rather similar. Both mechanisms that we have introduced show the expected sign and point estimates are remarkably large. The interaction of routine intensity and EPL predicts export specialization equally well as human capital. Culture is not as important as on the broader sample of panel (a), but it still shows a robust and strong effect. Especially in the last year of the sample, when EU countries have probably converged in economic structure and institutions, the interaction of culture and routine-intensity has become the most important predictor.

5.4 Results using value added trade

As a final robustness check, we investigate whether the results differ using as dependent variable value added trade rather than gross exports. Due to integration of production processes across borders, the gross export flows in the official statistics are often not representative of the underlying exchange of value added. Given that our model abstracts away from trade in intermediate goods, it is more representative of value added trade. In addition, using value added trade allows us to avoid the so-called Rotterdam effect in Europe, where trade is shipped through a port in another country.

This analysis is limited to the level of detail in the WIOD. It contains 43 coun-

Table 2: Relative importance of different Heckscher-Ohlin mechanisms

	Dependent variable is the country-specific extent of specialization in routine-intensive industries estimated in the first stage					
	1995		2005		2015	
	(1a)	(2a)	(3a)	(4a)	(5a)	(6a)
(a) Sample of 50 largest exporters						
Routineness	0.139***		0.115***		0.115***	
* employment protection regulation	(.011)		(.010)		(.009)	
Routineness		0.224***		0.217***		0.189***
* culture		(.009)		(.008)		(.007)
Capital-intensity	0.004	0.038***	0.0004	0.032***	0.003	0.036***
* K/L ratio for entire economy	(.004)	(.004)	(.004)	(.003)	(.004)	(.003)
Human capital-intensity	0.424***	0.358***	0.450***	0.369***	0.478***	0.426***
* School enrollment	(.012)	(.008)	(.011)	(.008)	(.012)	(.009)
Differentiated input share	0.046***	0.111***	-0.002	0.089***	-0.005	0.068***
* rule of law	(.005)	(.004)	(.004)	(.003)	(.004)	(.003)
External capital dependency	-0.025***	-0.037***	0.004	-0.014***	0.020***	0.001
* financial development	(.003)	(.002)	(.003)	(.002)	(.003)	(.002)
Observations	160,694	219,894	177,821	253,409	183,935	265,276
	(1b)	(2b)	(3b)	(4b)	(5b)	(6b)
(b) Sample of EU member states						
Routineness	0.169***		0.202***		0.162***	
* employment protection regulation	(.019)		(.018)		(.017)	
Routineness		0.098***		0.099***		0.111***
* culture		(.017)		(.016)		(.014)
Capital-intensity	0.002	0.001	-0.012	0.016**	-0.008	0.025***
* K/L ratio for entire economy	(.009)	(.008)	(.009)	(.007)	(.008)	(.007)
Human capital-intensity	0.236***	0.198***	0.185***	0.164***	0.180***	0.039
* School enrollment	(.025)	(.025)	(.024)	(.024)	(.024)	(.024)
Differentiated input share	0.157***	0.159***	0.055***	0.098***	0.041***	0.060***
* rule of law	(.010)	(.008)	(.008)	(.007)	(.007)	(.006)
External capital dependency	-0.042***	-0.049***	-0.018***	-0.025***	-0.001	0.003
* financial development	(.005)	(.005)	(.005)	(.005)	(.006)	(.004)
Observations	40,899	48,988	43,962	54,561	44,977	56,556

Note: Dependent variable is the log of bilateral exports at the industry level. Explanatory variables are the interactions between industry-level intensities and country-level endowments. "Culture" is the average between uncertainty avoidance and short-term orientation. All regressions include destination-industry and origin-destination fixed effects. The dependent and explanatory variables are standardized Z-variables such that the effects are measures in standard deviations. Standard errors in brackets. ***, **, * indicate statistical significance at the 1%, 5%, 10% level.

tries and 56 sectors in total, but for comparability with the earlier results, we only use a subset. We estimate specification (21) on the following two samples. The intersection between the WIOD and the 50 largest exporters that we studied before is a first sample of 36 countries. On the import side we include information from the 'rest-of-the-world' aggregate and we combine the imports from 7 small EU countries. The second sample consists of the same 27 EU member states as before and we again restrict it to intra-EU trade. Of the 56 sectors, only 17 are in manufacturing, for which we observe the routineness indicator which we need to aggregate to this level.

In Figure F.1 in the Appendix, we plot the estimates obtained on the WIOD data for 2014 (the latest year in the WIOD) on the vertical axis against the 2015 estimates for gross exports on the horizontal axis. These estimates differ somewhat from those reported in Figures 1 and 2 due to the different country sample and industry detail. Overall, the ranking of countries is very similar with a partial correlation of more than 0.8.

Most countries are fairly close to the 45-degree line and the broad ranking is maintained. A few countries, in particular Denmark, the United States, and Taiwan, are found to specialize more in non-routine industries based on the value added trade measure. In the case of Denmark, it moves the country closer to the position of the other Scandinavian countries and also the other two changes are plausible. We find the reverse pattern for Slovakia: it is found to specialize more in routine industries for value added trade than for gross exports. This difference is caused by the lower weight on its automotive sector, as gross exports are much higher than value added trade for this highly non-routine product. This industry also explains Slovakia's greater specialization in non-routine products for within-EU than for global trade that we mentioned before.

On the EU sample, in the bottom panel of Figure F.1, deviations from the 45-degree line are somewhat larger. But the relationship between the two sets of estimates is also very strong in this case. Their partial correlation is 0.91 and the Spearman rank correlation is equally large at 0.89. Using the value added trade measure does not change the earlier conclusions materially.

One interesting pattern is that the routineness indicator looses less of its predictive power over time for value added trade. When using gross exports as the dependent variable, the country-specific γ_i coefficients are estimated closer to zero on the 2015 data than on the 1995 data, especially for the EU sample. In panel (b) of Figure 2, the slope of the fitted values line is clearly less steep than the 45-degree line. In column (1) of Table 3, we show the standard deviation across countries of the estimated $\hat{\gamma}_i$ coefficients. While the mean is always normalized to zero due to

Table 3: Standard deviation of $\hat{\gamma}_i$ estimates for EU countries

	BACI data (76 sectors)		WIOD data (17 sectors)	
	Gross exports		Gross exports	Value added trade
	(1)		(2)	(3)
1995	3.12	2000	4.52	4.04
2005	3.47	2007	4.45	4.15
2015	2.56	2014	4.11	4.27

Note: The average estimate is always (implicitly) normalized to zero.

the included fixed effects, the standard deviation is lower in 2015 than in 1995.

In columns (2) and (3) of Table 3, we report comparable standard deviations estimated on the WIOD data. This dataset has less sectoral detail, but we can use both dependent variables on the same sample. The results based on gross exports, in column (2), show a decline in dispersion, in line with the pattern in column (1). The extent to which countries' export bundles can be explained by the routineness of sectors declines over time. In sharp contrast, the results based on value added trade in column (3) do not show such a decline. If anything, the extent to which we can predict countries' trade patterns using sectoral routineness has improved over time. Given that the value added content of trade better captures the production taking place in the exporting country, it strengthens our findings.

6 Conclusion

We pin down a new mechanism behind comparative advantage that is based on countries' different ability to adjust to technological change. We build on a pattern extensively documented in the labor literature, whereby more efficient machines displace workers from codifiable (routine) tasks, and introduce the hypothesis that the reallocation of labor across tasks is subject to frictions the importance of which differs by country. Once we incorporate task routineness into a canonical $2 \times 2 \times 2$ Heckscher-Ohlin model, the key feature of our model is that the relevant factor endowments for the final good sectors are determined endogenously by the equilibrium allocation of labor to routine and non-routine tasks.

The exact allocation depends on the ease of reallocating labor. We provide a microfoundation that helps explain why the parameter that captures capital-labor substitutability—which is generally perceived as an exogenous characteristic of the production technology—may in fact be determined by the institutional environment. Specifically, we show that any type of institutional characteristic that increases a firm's cost of adjusting the labor input, such as the rigidity of labor market institu-

tions or the lack of publicly-financed active labor market policies, may increase the shadow cost of switching to more productive capital. Hence, it will result in a lower perceived capital-labor substitutability in routine production.

The key theoretical prediction of our model is that with capital deepening, countries with flexible reallocation of labor become relatively abundant in non-routine labor. As a result, they specialize in goods that use non-routine labor more intensively.

We follow the two-step approach of Costinot (2009) to verify this prediction in the data. We first estimate the revealed comparative advantage in routine versus non-routine products for each country and we next relate them to country-level characteristics of labor market institutions and cultural norms likely to influence adjustment to new technology.

For a sample of the 50 largest exporters, we find that an index of labor force quality ('ability to perform') and a cultural indicator of 'long-term orientation' both correlate strongly with the revealed (non-)routine comparative advantage measure. For the sample of EU countries, the correlation is strongest for strictness of employment protection legislation.

To compare the predictive power of our new mechanism relative to other Heckscher-Ohlin mechanisms, we can also evaluate its prediction in a single step. For the sample of large exporters, we find that only human capital is a better predictor of trade flows than the interaction of routineness with the cultural measure. For EU countries, the interaction term of routiness and EPL predicts on par with the human capital variable.

To account for the increased importance of global value chains, we use value added trade data from the World Input-Output Database as a robustness check. The estimated measures of comparative advantage are found to correlate highly with our baseline findings. Importantly, while the explanatory power of routiness for gross exports declines over time, this is not the case for value added trade. That is, the channel we have put forward in this paper keeps its explanatory power, when we take into account the increased trade in intermediate products.

Our results have important policy implications. They illustrate that governments can play a key role to ensure that the process of labor reallocation from tasks that are substitutable with machines to tasks that are complementary with machines proceeds quickly and smoothly. Indeed, workers are shown to benefit relatively more from the process of technological change and from trade integration in institutional environments that succeed in reducing the costs of labor reallocation across tasks.

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Appendix A Support for parameter assumptions

We estimate a separate production function for each country-sector to provide support for the assumed parameter heterogeneity in the model. We use the 2009 release of the EU KLEMS database that is described in O'Mahony and Timmer (2009). It contains information on output, capital and labor use for 25 countries, 30 sectors, and 25 years. While not ideal, we rely on observed schooling levels to distinguish between abstract and routine labor input: routine labor is equated with employment of workers with a low schooling level and abstract labor with the two higher schooling levels, middle and high.[35] Real output and an index of capital services are reported directly in the database.

The production function technology in equation (3) incorporates heterogeneity along two dimensions. First, it assumes that sectors differ in the relative intensity they use abstract labor and the routine input intermediate, which is captured by the parameter β_g. The assumption that industries can be ranked according to their routine intensity has been adopted widely since the seminal work of Autor et al. (2003) who pioneered measures of the task content of occupations. A sectoral measure of routine intensity is constructed by weighting the routine task intensity of occupations by the composition of the workforce of each sector.

The second dimension of heterogeneity in the production function is cross-country variation in the ease of substitution between (routine) labor and capital in the production of the routine intermediate, which is represented by the parameter σ_i. Existing studies have assumed or estimated different rates of substitution between inputs in the production of the routine input aggregate. For example, Autor et al. (2003) and Acemoglu and Restrepo (2018) assume perfect substitutability ($\sigma = +\infty$), Autor and Dorn (2013) assume $\sigma > 1$, while Goos et al. (2014) estimate the elasticity of substitution between the tasks required to generate industry output and find a value slightly below one.[36] Importantly, each of these studies looks at a single country and assumes a constant value for the elasticity of substitution.

We evaluate whether the assumptions of sectoral heterogeneity in β_g and cross-country heterogeneity in σ_i are consistent with the data. We estimate a separate production function for each country-sector combination, exploiting only variation over time. Following Klump et al. (2012), we use the explicitly normalized version

[35] There is a strong negative correlation between the skill intensity and the routine intensity of occupations, especially within manufacturing sectors.

[36] Goos et al. (2014) impose a capital-labor substitutability equal to one in the production of each task.

of the embedded CES function to guarantee that the estimated parameters have an unambiguous structural interpretation.[37] This is also convenient given that the flow of real capital services is measured as a time index. Omitting the country-sector subscripts on the variables and parameters, we estimate the following equation,

$$Y_t = A\left[L_t^a \right]^{1-\beta} \left[(1-\pi_0)\left(\frac{L_t^m}{L_0^m}\right)^{\frac{\sigma-1}{\sigma}} + \pi_0 \left(\frac{K_t}{K_0}\right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\beta\,\sigma}{\sigma-1}}, \qquad \text{(A1)}$$

to recover two coefficients, β and σ, for each country-sector pair. There is a lot of heterogeneity in the estimated parameters. The median elasticity of substitution ($\hat{\sigma}$) in routine production is 1.75, but the interquartile range is $(0.3, 20)$. The median routine intensity ($\hat{\beta}$) is 0.19 and the interquartile range is $(0.05, 0.40)$.

We next investigate which dimension, country or sector, has the most explanatory power for the variation in either production function parameter. In the top panel of Table A.1, we first show a reduced-form analysis using two input factor ratios that can be observed without any estimation.

The share of abstract labor in total employment is directly influenced by the β coefficient that captures the relative routine intensity of the sector. The σ parameter plays only an indirect role. Regressing this variable on a full set of country and sector-fixed effects shows that the sector dummies have the most explanatory power. They explain 54.2% of the total sum of squares against only 28.5% for the country dummies. Note that even if the β parameter was the same for all countries, we would still expect the country dimension to have some explanatory power. Sectoral specialization by country (for example driven by the mechanism in our model) would still generate variation in the average employment ratio across countries.[38]

In contrast, the capital to routine labor ratio does not depend on the β coefficient. This ratio has increased over time almost everywhere, but for a given change in the factor price ratio (which is controlled for by year-fixed effects), its variation is a function of the elasticity of substitution, i.e. of the σ parameter. The results in Table A.1 indicate that the country dummies explain a lot more of the variation in this ratio than sector-fixed effects.

Finally, in panel (b) of Table A.1, we confirm these results with a similar exercise, but now directly explaining variation in the two estimated production function

[37] We force the β coefficient to lie between 0 and 0.6 and the σ coefficient between 0 and $+\infty$.

[38] Moreover, the three skill levels are defined based on the country-specific schooling levels, which itself introduces some cross-country variation in the average share of the skilled workforce over all sectors.

Table A.1: ANOVA analysis of input ratios and production function parameters

	Sum of squares: level (and share)				F-statistic (and p-value)		
	Dep. Var.	Sector (33)	Country (20)	Year (25)	Sector	Country	Year
(a) Observable variables[(i)]							
$\left(\frac{L^a}{L^a+L^m}\right)$	9.98	5.41	2.84		62.03	53.69	
	(100%)	(54.2%)	(28.5%)		(0.00)	(0.00)	
$\ln\left(\frac{K}{L^m}\right)$	3843	466	789	1118	114.73	320.63	363.49
	(100%)	(12.1%)	(20.5%)	(29.1%)	(0.00)	(0.00)	(0.00)
(b) Estimated parameters							
$\hat{\beta}_{ig}$	25.52	5.30	2.67		6.03	5.01	
		(20.8%)	(10.5%)		(0.00)	(0.00)	
$\hat{\sigma}_{ig}$[(ii)]	1636	191	217		1.03	1.93	
		(11.7%)	(13.3%)		(0.43)	(0.01)	

[(i)] The average input shares over the period are used
[(ii)] Only includes country-sector observations with $\hat{\sigma}_{ig} < 20$

coefficients. The β coefficient is predicted better by the sector dummies, while the σ coefficient varies mostly across countries. In the latter case, the fraction of the sum of squares that is explained by either set of fixed effects is relatively similar, but there are many fewer countries than sectors and the F-statistic—which takes the degrees of freedom into account—is almost twice as high for the country dummies. If we follow the approach in the literature and constrain the routine intensity β to be an industry-characteristic common to all countries, the contrast becomes even larger. In that case the country-fixed effects explain four times as much of the variation in the $\hat{\sigma}_{ig}$ estimates.

Appendix B Derivative of $\sigma_{L,K}$ with respect to the lay-off friction

Here, we show the effect of a change in the lay-off cost friction p on the elasticity of substitution of the modified production function $y = F(K, L)/(1 + pC(L))$.

The elasticity is defined as

$$\sigma_{L,K} = \frac{d(L/K)}{dMRTS} \frac{MRTS}{L/K}.$$

Since the lay-off cost is specified as a function of labor, we first need to relate changes in L/K to changes in L. To do so, observe that staying on the isoquant of the modified production function (5) implies:

$$dK = \frac{y\,p\,C'(L) - MP_L}{MP_K}\,dL.$$

In addition, we have

$$d(L/K) = \frac{1}{K}\,dL - \frac{L}{K^2}\,dK,$$

and substituting for dK then yields

$$d(L/K) = \left(\frac{1}{K} + \frac{L}{K^2}\frac{MP_L}{MP_K} - \frac{L}{K^2}\frac{p\,C\,F'(L)\,y}{MP_K}\right) dL. \tag{B1}$$

We are now in a position to consider the elasticity of substitution, and to conduct comparative statics with respect to the parameter p that measures the importance of the labor market friction. In general, the marginal rate of technical substitution for our modified production function takes the form:

$$MRTS = \frac{MP_K}{MP_L - p\,C'(L)\,y}.$$

Differentiating with respect to L/K gives:

$$\frac{dMRTS}{d(L/K)} = \frac{\frac{dMP_K}{d(L/K)}}{MP_L - p\,C'(L)\,y} - \frac{MP_K\left(\frac{dMP_L}{d(L/K)} - p\,C''(L)\,y\,\frac{dL}{d(L/K)}\right)}{(MP_L - p\,C'(L)\,y)^2} \tag{B2}$$

In order to simplify the analysis, consider the case of perfect substitutes, i.e. $F(K, L) = K + L$, which implies that both MP_K and MP_L equal one. Absent any

labor market friction, the $MRTS$ in this case is one, its derivative with respect to L/K zero, and the elasticity of substitution infinite. This is clearly a limiting case, but it serves as a useful illustration that introducing a labor market friction will reduce the elasticity of substitution even in this case.

In the presence of a friction, the derivative of the marginal rate of substitution (B2) in this case simplifies to:

$$\frac{dMRTS}{d(L/K)} = \frac{p\,C''(L)\,K^2}{(1-p\,C'(L)\,y)^2}.$$

Note that because of the (strictly) convex cost, this derivative is (strictly) positive. The lower the factor input ratio L/K, the lower the derivative or slope of the isoquant. Based on this derivative, the elasticity of substitution takes the form:

$$\sigma_{L,K} = \frac{(1-p\,C'(L)\,y)^2/L + (1-p\,C'(L)\,\bar{y})^3/K}{p\,C''(L)\,y}. \tag{B3}$$

Appendix C Solving the model: step-by-step

The model features three types of price-taking firms: one type produces the routine intermediate, the other two types produce the two final goods. We solve the model by deriving the cost-minimizing input choices for a representative firm of each of the three types.

C.1 Routine production

The production function of an atomistic firm in routine production is:

$$M_{if} \;=\; Z\left[\alpha(K_{if})^{\frac{\sigma_i-1}{\sigma_i}} + (1-\alpha)(L^m_{if})^{\frac{\sigma_i-1}{\sigma_i}}\right]^{\frac{\sigma_i}{\sigma_i-1}} \tag{2}$$

with w_i the wage and r_i the cost of capital. Its cost minimization problem is:

$$\begin{cases} \min\limits_{L^m,\,K} \; w_i L^m_{if} + r_i K_{if} \\ \text{s.t.} \;\; M_{if} \;\leq\; Z\left[\alpha(K_{if})^{\frac{\sigma_i-1}{\sigma_i}} + (1-\alpha)(L^m_{if})^{\frac{\sigma_i-1}{\sigma_i}}\right]^{\frac{\sigma_i}{\sigma_i-1}} \end{cases}$$

The ratio of the two first order conditions defines the relative factor demand as a function of the factor price ratio:

$$\frac{L^m_{if}}{K_{if}} \;=\; \left[\frac{w_i}{r_i}\,\frac{\alpha}{1-\alpha}\right]^{-\sigma_i}. \tag{C1}$$

We use this expression with the production function to write the conditional factor demands as a function of output M_{if} and the factor price ratio:

$$K_{if} \;=\; \frac{M_{if}}{Z}\left[\frac{r_i}{\alpha}\right]^{-\sigma_i}\left[\alpha^{\sigma_i} r_i^{1-\sigma_i} + (1-\alpha)^{\sigma_i} w_i^{1-\sigma_i}\right]^{-\frac{\sigma_i}{\sigma_i-1}} \tag{C2}$$

$$L^m_{if} \;=\; \frac{M_{if}}{Z}\left[\frac{w_i}{1-\alpha}\right]^{1-\sigma_i}\left[\alpha^{\sigma_i} r_i^{-\sigma_i} + (1-\alpha)^{\sigma_i} w_i^{1-\sigma_i}\right]^{-\frac{\sigma_i}{\sigma_i-1}}. \tag{C3}$$

We then obtain the cost function for intermediate input producers by substituting these conditional factor demands in the objective function. Dividing through by the routine intermediate quantity M_{if} gives the unit cost, which equals the intermediate input price

$$P^m_i \;=\; C(w_i, r_i) \;=\; \frac{1}{Z}\left[\alpha^{\sigma_i} r_i^{1-\sigma_i} + (1-\alpha)^{\sigma_i}\, w_i^{1-\sigma_i}\right]^{-\frac{1}{1-\sigma_i}}. \tag{7}$$

C.2 Final good production

The production function of a firm producing final good g is:

$$Y_{igf} \;=\; z_g \left(L^a_{igf}\right)^{1-\beta_g} \left(M_{igf}\right)^{\beta_g}, \tag{1}$$

with factor prices P^m_i and w_i as given. Its cost minimization problem is

$$\begin{cases} \min\limits_{L^a,\, M} \; w_i L^a_{igf} + P^m_i M_{igf} \\ \text{s.t.} \;\; Y_{igf} \;\leq\; z_g \left(L^a_{igf}\right)^{1-\beta_g} \left(M_{igf}\right)^{\beta_g} \end{cases}$$

The ratio of the two first order conditions defines the relative factor demand as a function of the factor price ratio:

$$\frac{L^a_{igf}}{M_{igf}} \;=\; \frac{1-\beta_g}{\beta_g}\,\frac{P^m_i}{w_i}. \tag{C4}$$

Again, plugging this expression in the production function, we can write the conditional factor demands as a function of output Y_{igf} and the factor price ratio:

$$\begin{aligned} L^a_{igf} &= \frac{Y_{igf}}{z_g}\left[\frac{w_i}{P^m_i}\,\frac{\beta_g}{1-\beta_g}\right]^{-\beta_g} \\ M_{igf} &= \frac{Y_{igf}}{z_g}\left[\frac{w_i}{P^m_i}\,\frac{\beta_g}{1-\beta_g}\right]^{1-\beta_g} \end{aligned}$$

We obtain the cost of production by substituting these conditional factor demands in the objective function. Dividing through by the final good quantity gives the unit cost, which with perfect competition is also the final good price:

$$P_{ig} \;=\; C_{ig}(w_i, P^m_i) \;=\; \frac{1}{z_g}\left(\frac{w_i}{1-\beta_g}\right)^{1-\beta_g}\left(\frac{P^m_i}{\beta_g}\right)^{\beta_g}, \qquad \forall g \in \{1,2\}. \tag{8}$$

By replacing the price of the routine intermediate in (8) by its function of primitive factor prices (7), we can express the price of each final good in terms of the primitive factor prices, the wage and rental rate of capital:

$$P_{ig} \;=\; \frac{1}{z_g\, Z^{\beta_g}}\left[\frac{w_i}{1-\beta_g}\right]^{1-\beta_g}\left[\frac{\left(\alpha^{\sigma_i} r^{1-\sigma_i} + (1-\alpha)^{\sigma_i} w_i^{1-\sigma_i}\right)^{\frac{1}{1-\sigma_i}}}{\beta_g}\right]^{\beta_g} \tag{C5}$$

C.3 Relative supply of 'produced' factors

We next use the resource constraints for capital and labor. Capital market clearing is straightforward because capital can only be used in routine production: $\sum_f K_{if} = \bar{K}$. We can rewrite the capital demand in routine production, equation (C3), as

$$K_{if} \;=\; \frac{M_{if}}{Z}\left[1+\frac{w_i}{r_i}\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]^{-\frac{\sigma_i}{\sigma_i-1}}.$$

From this we find the optimal quantity of the routine intermediate M_i, and thus how much labor to allocate to routine tasks, as a function of the capital endowment and the relative factor price ratio by summing across all firms

$$\sum_f M_{if} \;=\; M_i \;=\; Z\,\bar{K}\,\alpha^{\frac{\sigma_i}{\sigma_i-1}}\left[1+\frac{w_i}{r_i}\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]^{\frac{\sigma_i}{\sigma_i-1}}.$$

Labor market clearing then gives the total quantity of abstract labor that can be used in the final good sectors as a function of the labor endowment and factor prices: $L_i^a = \bar{L} - \sum_f L_{if}^m(w_i, r_i; K_{if})$. The necessary expression for L_{if}^m is given directly by the ratio of first order conditions in routine production (C1).

Optimal factor use in routine production together with market clearing for labor and capital determines the relative supply of the produced factors. We express it as a function of primitive endowments and the prices of the primitive factors as follows:

$$\frac{L_i^a}{M_i} \;=\; \frac{\bar{L}-L_i^m}{M_i} \;=\; \frac{\bar{L}-\left[\frac{w_i/(1-\alpha)}{r_i/\alpha}\right]^{-\sigma_i}\bar{K}}{Z\bar{K}\alpha^{\frac{\sigma_i}{\sigma_i-1}}\left\{1+\frac{w_i}{r_i}\left[\frac{w_i/(1-\alpha)}{r_i/\alpha}\right]^{-\sigma_i}\right\}^{\frac{\sigma_i}{\sigma_i-1}}}. \tag{9}$$

Equivalently, we can use (7) to write the relative factor supply as a function of the wage and of the price of the routine input:

$$\frac{L_i^a}{M_i} \;=\; \frac{\bar{L}-\left[\frac{\alpha}{1-\alpha}\right]^{\frac{\sigma_i}{\sigma_i-1}}\left[\left(\frac{P_i^m}{w_i}\right)^{1-\sigma_i}(1-\alpha)^{-\sigma_i}Z^{1-\sigma_i}-1\right]^{-\frac{\sigma_i}{\sigma_i-1}}\bar{K}}{Z\bar{K}\alpha^{\frac{\sigma_i}{\sigma_i-1}}\left[1-\left(\frac{P_i^m}{w_i}\right)^{-(1-\sigma_i)}(1-\alpha)^{\sigma_i}Z^{-(1-\sigma_i)}\right]^{-\frac{\sigma_i}{\sigma_i-1}}}. \tag{C6}$$

C.4 The demand side

We have assumed a standard Cobb-Douglas utility function to represent preferences over the two final goods: $U_i = \sum_g \theta_g \ln(Q_{ig})$. The budget constraint is $\sum_g P_{ig}Q_{ig} \leq r_i\bar{K} + w_i\bar{L}$. The ratio of a representative consumer's two first order conditions gives an expression of total expenditure on one good as a function of relative income shares of each good and expenditure on the other good:

$$P_{i2}Q_{i2} = \frac{\theta_2}{\theta_1}P_{i1}Q_{i1}. \tag{C7}$$

By substitution in the final good prices (8), we can re-write this expression as a function of the wage rate and the price of the routine input:

$$\frac{Q_{i1}}{Q_{i2}} = \frac{\theta_1 z_1 \beta_1^{\beta_1}(1-\beta_1)^{1-\beta_1}}{\theta_2 z_2 \beta_2^{\beta_2}(1-\beta_2)^{1-\beta_2}} \left(\frac{w_i}{P_i^m}\right)^{\beta_1-\beta_2}. \tag{10}$$

Alternatively, we can also write this expression as a function of the primitive factor prices by using equation (C5) instead to eliminate the final good prices:

$$\frac{Q_{i1}}{Q_{i2}} = \frac{\theta_1 z_1 \beta_1^{\beta_1}(1-\beta_1)^{1-\beta_1}}{\theta_2 z_2 \beta_2^{\beta_2}(1-\beta_2)^{1-\beta_2}} \left(Zw_i\right)^{\beta_1-\beta_2} \left[\alpha^{\sigma_i} r^{1-\sigma_i} + (1-\alpha)^{\sigma_i} w_i^{1-\sigma_i}\right]^{\frac{\beta_2-\beta_1}{1-\sigma_i}}. \tag{C8}$$

C.5 Relative demand for 'produced' factors

We now combine optimal factor allocation in the production of both final goods with goods market clearing. We start from the market clearing condition $Q_{ig} = Y_{ig}$ and the upper nest of the production function (1) to express relative demand for the two goods as a function of the factors used in their production:

$$\frac{Q_{i1}}{Q_{i2}} = \frac{Y_{i1}}{Y_{i2}} = \frac{z_1 {L_{i1}^a}^{1-\beta_1} {M_{i1}}^{\beta_1}}{z_2 {L_{i2}^a}^{1-\beta_2} {M_{i2}}^{\beta_2}}. \tag{11}$$

Using the first order conditions in final goods production (C4), we can eliminate one of the production factors from both the numerator and the denominator and replace it by a function of the other factor and the relative factor price ratio. We do this twice, first for the routine intermediates M_{i1} and M_{i2} and then for both abstract

labor inputs:

$$\begin{aligned}\frac{Q_{i1}}{Q_{i2}} &= \left[\frac{w_i}{P_i^m}\right]^{\beta_1-\beta_2} \frac{z_1 L_{i1}^a \left[\beta_1/(1-\beta_1)\right]^{\beta_1}}{z_2 L_{i2}^a \left[\beta_2/(1-\beta_2)\right]^{\beta_2}} \\ \frac{Q_{i1}}{Q_{i2}} &= \left[\frac{w_i}{P_i^m}\right]^{\beta_1-\beta_2} \frac{z_1 M_{i1} \left[(1-\beta_1)/\beta_1\right]^{1-\beta_1}}{z_2 M_{i2} \left[(1-\beta_2)/\beta_2\right]^{1-\beta_2}}.\end{aligned}$$

We then equate both of these expressions to (10), the ratio of first order conditions from the consumers' problem, where the final goods prices have already been replaced by the factor prices. The two resulting expressions determine the allocation of abstract labor and the routine input to the two final goods sectors:

$$\frac{L_{i1}^a}{L_{i2}^a} = \frac{\theta_1(1-\beta_1)}{\theta_2(1-\beta_2)} \quad ; \quad \frac{M_{i1}}{M_{i2}} = \frac{\theta_1\beta_1}{\theta_2\beta_2}. \tag{C9}$$

Given the Cobb-Douglas functional form assumptions on both the preferences and technology, this allocation depends solely on preference and production function parameters β_g and θ_g.

Factor market clearing for abstract labor and the routine input across their use in the two final good sectors implies $L_{i2}^a = L_i^a - L_{i1}^a$ and $M_{i2} = M_i - M_{i2}$. Substituting in (C9) and rearranging, we find

$$L_{i1}^a = \frac{\theta_1(1-\beta_1)}{\sum_g \theta_g(1-\beta_g)} L_i^a \quad ; \quad M_{i1} = \frac{\theta_1\beta_1}{\sum_g \theta_g\beta_g} M_i. \tag{C10}$$

Next, we take the ratio of the two factor demands (C10) for sector 1 and equate it to the first order condition ratio (C4). After rearranging, we find the familiar HO equation that connects relative factor abundance to relative factor prices. The only difference in our model is that of interpretation: the factors on the LHS are produced rather than exogenously given:

$$\frac{L_i^a}{M_i} = \frac{\sum_g \theta_g(1-\beta_g)}{\sum_g \theta_g\beta_g} \frac{P_i^m}{w_i} \tag{12}$$

We denote $c = \frac{\sum_g \theta_g(1-\beta_g)}{\sum_g \theta_g\beta_g}$ and replace the price of the routine input by its value in (7) to find the relative factor demand in terms of the primitive factor prices

$$\frac{L_i^a}{M_i} = c\left[\frac{w_i}{r_i} Z\alpha^{\frac{\sigma_i}{\sigma_i-1}}\right]^{-1} \left[1 + \left(\frac{w_i}{r_i}\right)\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]^{\frac{1}{1-\sigma_i}}. \tag{C11}$$

C.6 The equilibrium factor price ratio

The final step is to solve for the equilibrium factor price ratio by equating the relative factor supply and demand. We have derived expressions for both equations in terms of the primitive factor prices—(9) and (C11)—and in terms of the produced factor prices—(C6) and (12). We equate the first two equations and find

$$\left(\frac{w_i}{r_i}\right)^{-1} c\left[1+\left(\frac{w_i}{r_i}\right)\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]^{\frac{1}{1-\sigma_i}} = \frac{\left[\frac{\bar{L}}{\bar{K}}-\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]}{\left[1+\left(\frac{w_i}{r_i}\right)\left(\frac{w_i/(1-\alpha)}{r_i/\alpha}\right)^{-\sigma_i}\right]^{\frac{\sigma_i}{\sigma_i-1}}}.$$

Rearranging and simplifying gives an implicit solution for the equilibrium factor price ratio $\omega_i^* = (w_i/r_i)^*$:

$$\omega_i^* = c\left[\frac{\bar{L}}{\bar{K}}-(1+c)\left(\frac{1-\alpha}{\alpha}\right)^{\sigma_i}(\omega_i^*)^{-\sigma_i}\right]^{-1}. \tag{C12}$$

Appendix D Comparative statics results

Given that the effective relative cost of labor is given by $[w_i/(1-\alpha_i)]\,/\,[r_i/\alpha_i]$, we can establish that, without normalization,

$$\begin{cases} \frac{\partial(w_i/r_i)^*}{\partial\sigma} < 0, & \frac{w_i}{r_i} > \frac{1-\alpha_i}{\alpha_i} \\ \frac{\partial(w_i/r_i)^*}{\partial\sigma} = 0, & \frac{w_i}{r_i} = \frac{1-\alpha_i}{\alpha_i} \\ \frac{\partial(w_i/r_i)^*}{\partial\sigma} > 0, & \frac{w_i}{r_i} < \frac{1-\alpha_i}{\alpha_i}. \end{cases}$$

When labor is scarce and the equilibrium wage exceeds $(1-\alpha_i)/\alpha_i$, labor will be relatively cheap in the high-σ country. Note this refers to a ratio-of-ratios: the *relative* real wage is lower in the high-σ country. Conversely, when labor is abundant and cheap, it will be relatively expensive in the high-σ country.

A complication with these comparative statics results is that they hinge on the effective cost of labor and α_i is itself a function of σ_i. To break this circularity and pin down the effect of σ on the equilibrium factor price ratio as a function of only endowments and parameters, it is necessary to normalize the CES function.

Appendix E Free trade equilibrium

E.1 Factor price equalization for produced factors

We focus on the case where both countries $i = \{A, B\}$ produce both final goods $g = \{1, 2\}$. As in the canonical HO model, trade then leads to the equalization of the relative factor prices for the 'produced' factors that are the inputs for the two final goods. To see this, we start from the fact that the ratios of both final goods' prices equalize in the two countries, i.e.,

$$\frac{P_{A1}}{P_{A2}} = \frac{P_{B1}}{P_{B2}}.$$

Given perfect competition in the final goods sectors, we already established that prices equal production costs, i.e. that

$$P_{ig} = \frac{1}{z_g \beta_g^{\beta_g} (1-\beta_g)^{1-\beta_g}} (P_i^m)^{\beta_g} (w_i)^{1-\beta_g}. \tag{8}$$

Substituting these expressions for the final good prices in the above ratios yields

$$\left(\frac{P_A^m}{w_A}\right)^{\beta_1-\beta_2} = \left(\frac{P_B^m}{w_B}\right)^{\beta_1-\beta_2}, \tag{E1}$$

and we see that the produced factor price ratios equalize in the two countries.

E.2 No factor price equalization for primitive factors

Importantly, however, opening up to trade does not lead to equalization of the factor price ratios for the 'primitive' factors, capital and labor, that countries are endowed with. This can be seen directly from equation (7) which reflects that price equals marginal costs in the perfectly competitive routine sector, i.e.,

$$P_i^m = \frac{1}{Z} \left[\alpha^{\sigma_i} r_i^{1-\sigma_i} + (1-\alpha)^{\sigma_i} w_i^{1-\sigma_i}\right]^{-\frac{1}{1-\sigma_i}}. \tag{7}$$

By factoring out $w_i^{1-\sigma_i}$ from both terms, we can rewrite the expression as

$$\frac{P_i^m}{w_i} = \frac{1}{Z} \left[\alpha^{\sigma_i} \left(\frac{r_i}{w_i}\right)^{1-\sigma_i} + (1-\alpha)^{\sigma_i}\right]^{-\frac{1}{1-\sigma_i}}. \tag{E2}$$

Equalization of the produced factor price ratio in (E1), makes it impossible for the primitive factor price ratio on the right-hand side of equation (E2) to be the same for two countries that differ in σ_i.

E.3 Trade reduces the wedge in the primitive factor price ratio

We established that the relative price of the primitive factors is not equalized in the free trade equilibrium. Now we show that the wedge becomes smaller under free trade than in autarky.

We first express the relative price of the two final goods as a function of the ratio of the two real wages $\nu = \omega_B/\omega_A$. We start by substituting the price of the routine intermediate (7) into the expression for the price of the final good (8) and take the ratio of the two final good prices:

$$\frac{P_{i1}}{P_{i2}} = \frac{z_2\beta_2^{\beta_2}(1-\beta_2)^{1-\beta_2}Z^{\beta_2}}{z_1\beta_1^{\beta_1}(1-\beta_1)^{1-\beta_1}Z^{\beta_1}}\left(\alpha^{\frac{\sigma_i}{\sigma_i-1}}\frac{w_i}{r_i}\right)^{\beta_2-\beta_1}\left[1+\left(\frac{w_i}{r_i}\right)^{1-\sigma_i}\left(\frac{1-\alpha}{\alpha}\right)^{\sigma_i}\right]^{\frac{\beta_2-\beta_1}{\sigma_i}}.$$

We simplify the expression by grouping all country-invariant terms under a constant B, replacing $\omega_i = w_i/r_i$, imposing the normalization $\alpha = 1/(1+\omega_0)$, and bringing the first ω_i term into the square brackets:

$$\frac{P_{i1}}{P_{i2}} = B(1+\omega_0)^{\frac{\sigma_i}{\sigma_i-1}(\beta_1-\beta_2)}\left[\omega_i^{\sigma_i-1}+\omega_0^{\sigma_i}\right]^{\frac{\beta_2-\beta_1}{\sigma_i}}.$$

Note that the derivative of this relative price ratio with respect to the relative wage ω_i is positive if good 1 is non-routine abundant ($\beta_1 < \beta_2$).

The relative final goods' price ratio in the two countries is then

$$\frac{P_{A1}/P_{A2}}{P_{B1}/P_{B2}} = (1+\omega_0)^{\frac{\sigma_A(1-\sigma_B)}{\sigma_B(1-\sigma_A)}(\beta_2-\beta_1)}\left[\omega_A^{\sigma_A-1}+\omega_0^{\sigma_A}\right]^{\frac{\beta_2-\beta_1}{\sigma_A}}\left[\omega_B^{\sigma_B-1}+\omega_0^{\sigma_B}\right]^{\frac{\beta_1-\beta_2}{\sigma_B}}.$$

Using $\omega_B/\omega_A = \nu$, we can write it as

$$\frac{P_{A1}/P_{A2}}{P_{B1}/P_{B2}} = \left\{(1+\omega_0)^{\frac{\sigma_A(1-\sigma_B)}{\sigma_B(1-\sigma_A)}}\frac{\left[(\omega_B/\nu)^{\sigma_A-1}+\omega_0^{\sigma_A}\right]^{\frac{1}{\sigma_A}}}{\left[\omega_B^{\sigma_B-1}+\omega_0^{\sigma_B}\right]^{\frac{1}{\sigma_B}}}\right\}^{\beta_2-\beta_1}. \tag{E3}$$

This equation reflects how a difference in the relative prices for final goods between the two countries is reflected in a wedge between their real wages. Given that the

exponent on $1/\nu$ is positive—because $\sigma_i > 1$ and $\beta_2 > \beta_1$—it implies that the derivative of the RHS of expression (E3) is negative. This means that the relative price of the non-routine intensive good in the high-σ country A is decreasing in ν.

In the case of capital deepening in autarky, we have established that both countries will reach a new equilibrium with $\nu > 1$. To equate the relative final good price ratio in both countries once they open up to trade, the price of the non-routine good needs to rise relatively in the high-σ country A. To increase the relative price ratio and equation (E3) still holding, ν must be reduced such that country A's relative real wage rises. We have already shown, however, that primitive factor prices do not equalize entirely and $\nu > 1$ remains true in the free trade equilibrium.

Appendix F Additional results

F.1 First-stage point estimates for benchmark results

Table F.1: (Non-)Routine export specialization among EU member states

	1995		2005		2015	
	Coef.	**St.Dev.**	**Coef.**	**St.Dev.**	**Coef.**	**St.Dev.**
FIN	-0.158	(.016)	-0.151	(.015)	-0.127	(.013)
IRL	-0.127	(.016)	-0.128	(.015)	-0.105	(.013)
SWE	-0.131	-	-0.104	-	-0.079	-
GBR	-0.087	(.016)	-0.087	(.015)	-0.070	(.013)
FRA	-0.061	(.016)	-0.048	(.015)	-0.032	(.013)
DEU	-0.058	(.016)	-0.050	(.015)	-0.031	(.013)
MLT	-0.046	(.021)	-0.021	(.017)	-0.057	(.015)
NLD	-0.039	(.016)	-0.040	(.015)	-0.026	(.013)
AUT	-0.045	(.016)	-0.028	(.015)	-0.018	(.013)
SVK	0.027	(.017)	-0.031	(.015)	-0.053	(.014)
HUN	0.028	(.016)	-0.026	(.015)	-0.032	(.013)
CZE	0.020	(.016)	-0.036	(.015)	-0.015	(.013)
SVN	0.017	(.017)	-0.003	(.015)	-0.029	(.013)
BEL	-0.013	(.016)	-0.001	(.015)	0.026	(.013)
CYP	0.036	(.019)	0.007	(.016)	-0.029	(.014)
GRC	0.040	(.017)	0.019	(.015)	0.018	(.013)
ESP	-0.008	(.016)	0.036	(.015)	0.068	(.013)
POL	0.012	(.016)	0.044	(.015)	0.043	(.013)
DNK	0.026	(.016)	0.034	(.015)	0.044	(.013)
ITA	0.014	(.016)	0.043	(.015)	0.058	(.013)
HRV	0.021	(.018)	0.039	(.015)	0.063	(.014)
EST	0.080	(.018)	0.051	(.015)	0.021	(.014)
BGR	0.047	(.017)	0.064	(.015)	0.073	(.013)
LVA	0.085	(.019)	0.100	(.015)	0.038	(.014)
PRT	0.091	(.017)	0.085	(.015)	0.086	(.014)
LTU	0.112	(.018)	0.123	(.015)	0.077	(.013)
ROM	0.118	(.017)	0.109	(.015)	0.089	(.014)
No. of obs.	48,988		54,561		56,556	

Note: Dependent variable is the log of bilateral exports at the industry level. Explanatory variables are the interactions between country dummies and the routineness indicator, normalized by the sample average (SWE is the excluded country). Control variables (not reported) are four interactions between country-endowments and industry-intensities, as well as destination-industry and origin-destination fixed effects. The indicator and dependent variable are standardized Z-variables such that the effects are measures in standard deviations. Countries are sorted by the average of the estimates over the four years.

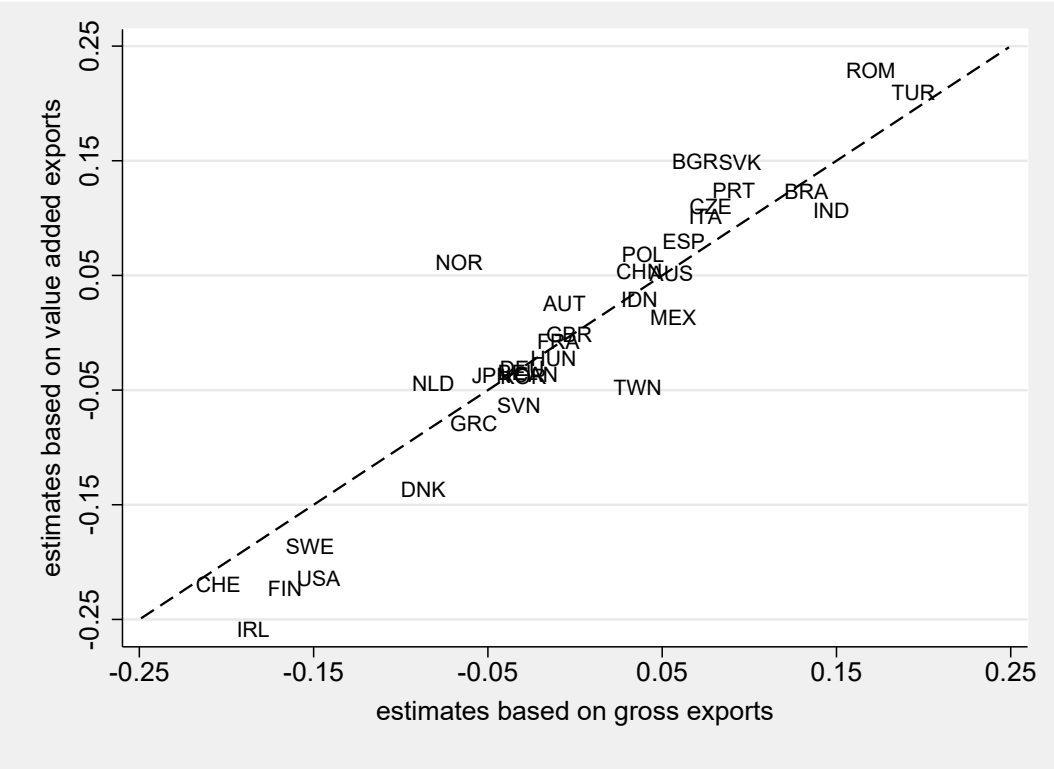
Table F.2: (Non-)Routine export specialization in sample of 50 largest exporters

	1995		2005		2015	
	Coef.	**St.Dev.**	**Coef.**	**St.Dev.**	**Coef.**	**St.Dev.**
JPN	-0.205	(.012)	-0.181	(.011)	-0.172	(.010)
SGP	-0.174	(.012)	-0.163	(.011)	-0.136	(.010)
FIN	-0.144	(.012)	-0.145	(.011)	-0.122	(.010)
SWE	-0.150	(.012)	-0.132	(.011)	-0.109	(.010)
ISR	-0.120	(.013)	-0.121	(.011)	-0.123	(.010)
IRL	-0.111	(.012)	-0.118	(.011)	-0.112	(.010)
MEX	-0.085	(.013)	-0.115	(.011)	-0.114	(.010)
CHE	-0.126	(.012)	-0.096	(.011)	-0.084	(.010)
USA	-0.112	(.012)	-0.086	(.011)	-0.078	(.010)
TWN	-0.070	(.012)	-0.083	(.011)	-0.091	(.010)
MYS	-0.049	(.012)	-0.062	(.011)	-0.069	(.010)
FRA	-0.083	(.012)	-0.057	(.011)	-0.038	(.010)
DEU	-0.078	(.012)	-0.062	(.011)	-0.038	(.010)
GBR	-0.082	(.012)	-0.057	(.011)	-0.033	(.010)
NOR	-0.047	(.012)	-0.059	(.011)	-0.050	(.010)
RUS	-0.044	(.013)	-0.044	(.011)	-0.061	(.010)
NLD	-0.057	(.012)	-0.049	(.011)	-0.028	(.010)
CAN	-0.058	(.012)	-0.032	(.011)	-0.023	(.010)
AUT	-0.040	(.012)	-0.025	(.011)	-0.022	(.010)
SAU	-0.036	(.014)	-0.017	(.012)	-0.031	(.011)
CHN	-0.034	(.012)	-0.023	(.011)	-0.023	(.010)
BEL	-0.043	(.012)	-0.024	(.011)	-0.010	(.010)
HUN	0.014	(.013)	-0.048	(.011)	-0.031	(.010)
KOR	0.019	(.012)	-0.024	(.011)	-0.032	(.010)
ARE	-0.009	(.014)	0.010	(.011)	-0.026	(.010)
ZAF	0.002	-	0.006	-	0.018	-
ESP	-0.017	(.012)	0.016	(.011)	0.037	(.010)
SVN	0.034	(.014)	0.023	(.011)	-0.006	(.010)
PHL	0.054	(.013)	0.011	(.011)	-0.012	(.010)
CZE	0.080	(.013)	-0.003	(.011)	-0.004	(.010)
ITA	0.002	(.012)	0.031	(.011)	0.049	(.010)
DNK	0.014	(.012)	0.035	(.011)	0.049	(.010)
GRC	0.044	(.013)	0.036	(.011)	0.022	(.010)
POL	0.036	(.013)	0.043	(.011)	0.026	(.010)
SVK	0.059	(.014)	0.036	(.011)	0.017	(.010)
IDN	0.066	(.013)	0.035	(.011)	0.049	(.010)
BGR	0.039	(.014)	0.057	(.011)	0.054	(.010)
UKR	0.034	(.014)	0.058	(.011)	0.066	(.010)
IND	0.077	(.012)	0.049	(.011)	0.041	(.010)
PRT	0.069	(.013)	0.060	(.011)	0.051	(.010)
AUS	0.091	(.012)	0.067	(.011)	0.061	(.010)
BRA	0.065	(.012)	0.086	(.011)	0.086	(.010)
THA	0.101	(.012)	0.072	(.011)	0.075	(.010)
ROM	0.119	(.014)	0.111	(.011)	0.085	(.010)
TUR	0.122	(.013)	0.134	(.011)	0.111	(.010)
CHL	0.119	(.014)	0.156	(.012)	0.148	(.011)
NZL	0.159	(.013)	0.147	(.011)	0.140	(.010)
ARG	0.144	(.013)	0.156	(.011)	0.163	(.010)
VNM	0.236	(.016)	0.189	(.011)	0.113	(.010)
PER	0.179	(.016)	0.200	(.012)	0.209	(.011)
No. of obs.	219,894		253,409		265,276	

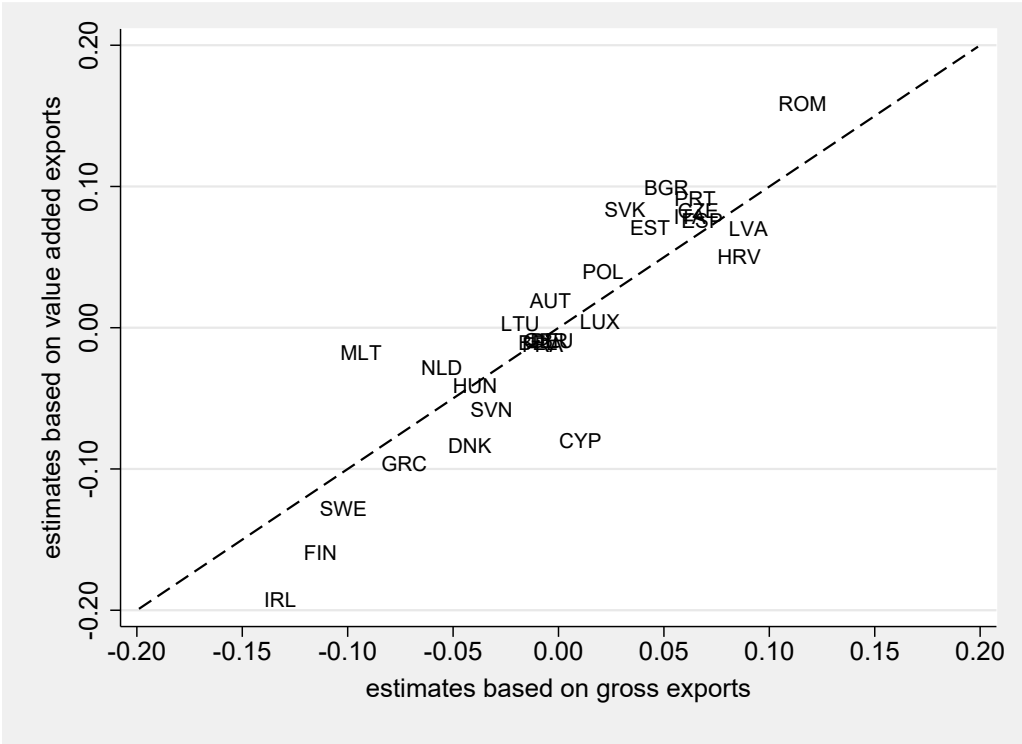
Note: Dependent variable is the log of bilateral exports at the industry level. Explanatory variables are the interactions between country dummies and the routineness indicator, normalized by the sample average (ZAF is the excluded country). Control variables (not reported) are four interactions between country-endowments and industry-intensities, as well as destination-industry and origin-destination fixed effects. The indicator and dependent variable are standardized Z-variables such that the effects are measures in standard deviations. Countries are sorted by the average of the estimates over years.

F.2 First-stage estimates based on value added trade

Figure F.1: (Non-)Routine export specialization based on value added trade



(a) Large exporters (36 countries)



(b) EU member states