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Complexity, Specialization, and Growth

Benno Ferrarini and Pasquale Scaramozzino

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Benno Ferrarini is Senior Economist at the Economics and Research Department of the Asian Development Bank. Pasquale Scaramozzino is Professor of Economics in the Department of Financial and Management Studies, SOAS, University of London, and in Dipartimento di Economia Diritto e Istituzioni, Università di Roma Tor Vergata.

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ABSTRACT

This paper analyzes the role of complexity in production on the level of output and on its rate of growth. We develop an endogenous growth model with human capital accumulation, where increased complexity could exert either a positive or a negative effect on the level of output but always a positive effect on its rate of growth. Our empirical measure of complexity is derived from net trade flows, and is based on the product space description of production sectors in the global economy. The evidence from a broad cross-section of countries is consistent with the main theoretical predictions of the model, and supports the view that production complexity is important in order to account for differences in economic performance. An indicator of the intensity of vertical trade among countries is also shown to be relevant to explain output performance.

Keywords: international trade flows, vertical trade, economic growth, complexity

JEL classification: F43, O11, O14, O15, O33

I. INTRODUCTION

A complex production structure requires the development of appropriate skills and the ability to adapt to changing technological needs. However, the role of complexity in production and its consequences on economic performance are still underexplored, despite being among the very motivations for the emergence of economics as a discipline. Indeed, the importance of an efficient division of labor was a key factor in Adam Smith's (1776) argument in support of the gains from specialization. The recent literature does not appear to have built on Smith's analysis, and technological complexity does not occupy center stage in the debate on the differences in economic performance across countries.

At the same time, the literature on development economics has long acknowledged the importance of the underlying capabilities as a condition for long-term growth. For example, Hirschman (1958) related capabilities to the existence of backward and forward linkages across sectors. Lewis (1955), Rostow (1959) and Kaldor (1967), among others, portrayed economic development as a process of structural transformation and gains in productivity through the transfer of resources and the acquisition of higher productive capabilities. More recently, contributions such as Lall (1992) or Kremer (1993) emphasized the crucial role of capabilities in the context of innovation, economic growth, and development. At the firm level, Sutton (2001) showed that the ability to exploit scarce capabilities is at the root of the success of modern economies.

Production complexity and capabilities are difficult to observe or to measure directly. Hausmann and Klinger (2006) and Hidalgo, Klinger, Barabási and Hausmann (2007) have thus developed the notion of *product space*, in which production sectors are located on the basis of their global specialization profile across countries. The proximity of sectors in the product space is thought of as relating to the similarities in their underlying capability requirements. Proximity is important, because it denotes a country's ability to adapt to and venture into neighboring production sectors. Economic development thus involves a process in which countries continuously strive to upgrade their complex set of capabilities in order to be able to move into higher productivity sectors, thus further refining and expanding their capabilities until the next proximate sector will become achievable (Hidalgo and Hausmann 2009).

Hausmann and Hidalgo (2011) explore the relationship between production diversification and the ubiquity of products across countries. Increased capabilities tend to be associated with greater product diversification. At the same time, only countries with more capabilities will be able to manufacture products which require a wide range of capabilities in their production process. These products will therefore be less ubiquitous in the product space, since only a relatively limited number of countries will be able to produce them. Hausmann and Hidalgo (2011) indeed observe a negative relationship between the product diversification of countries and the ubiquity of products that they trade in world markets.

Building on these insights, the present paper analyzes the role of complexity in the context of an endogenous growth model and offers empirical evidence for a cross-section of countries. Complexity is based on the notion of density, as in Hausmann and Klinger (2006), where it measures a good's distance in the product space from the sectors associated with a country's export basket. The average density of a country is a measure of the adaptability of that country's production structure across sectors, which relates to the fungibility of its resource endowments and of its available technology.

Our endogenous growth model is driven by human capital accumulation augmented by trade specialization and complexity, along the lines of Costinot (2009). Higher production complexity plays a dual role: on the one hand it enhances human capital accumulation through the advancement of skills and the promotion of learning (Lucas 1988, 1993), while on the other it increases the risk of production failure when it heightens the number of tasks that need be executed correctly. Consistent with Kremer's (1993) O-ring theory, a more complex technology entails a higher risk of failure because it lowers the probability that all of the required tasks are performed correctly. Our theoretical framework thus predicts a potentially different impact of complexity on the level of output and its rate of growth. While increased complexity is always associated with a higher long-run rate of growth, at any given time it may—other things being equal—either increase or decrease the level of output, depending on whether or not the gains from specialization outweigh the costs associated with production failures.

The model predictions are put to the test and validated for a broad cross-section of countries, with data spanning from 1990 to 2009. We find that complexity does influence the level of output either positively or negatively, varying across income categories and geographic regions. Controlling for human capital as well as other determinants of output, we also find that complexity exerts a positive influence on the rate of growth of output.

The structure of the paper is as follows. Section II sets out the endogenous growth model with human capital accumulation and complexity. Section III introduces our trade-based measure of complexity. Section IV discusses the empirical evidence. Section V examines the role of network trade and complexity on economic performance. Section VI concludes.

II. COMPLEXITY, HUMAN CAPITAL, AND GROWTH

The interactions between technological complexity, capabilities, and economic performance can be explored with the aid of an endogenous growth model with human capital accumulation and heterogeneous industries. Technological complexity plays a key role in enhancing the development of new skills and human capital formation, and is thus critical for the growth rate of the economy. We examine a very flexible specification, which enables us to consider the multiple potential effects of complexity on both the level and the rate of growth of output.

Accumulation of human capital is modeled following Lucas (1998, 1993). Workers decide how much of their time should be allocated to current production and to the formation of human capital, which would increase their future productivity. Industries are not identical, but each of them is characterized by a different level of complexity in its production technology. Greater complexity could be associated with a reduction in industry output, because of the difficulty of correctly performing all the required tasks (Kremer 1993). On the other hand, it could have a positive effect on output because it is associated with a more advanced region in the product space (Hidalgo, Klinger, Barabási, and Hausmann 2007). A higher average level of complexity would always have a beneficial effect on the rate of growth of the economy, because it enhances the accumulation of human capital. Hence, while the impact of greater complexity on the level of output could be ambiguous, its effect on the rate of growth of the economy is always positive.

In each country c = 1, 2, …, N, the size of the labor force is fixed at L_c. The average level of human capital is h_c. For the sake of simplicity, this is assumed to be constant across all industries in the economy. The share of non-leisure time allocated to current production is

denoted by $\lambda_c \in [0,1]$, and the corresponding share allocated to human capital formation is $1-\lambda_c$.

There is a continuum of industries *i*, which are uniformly distributed over the unit interval: $i \sim U[0,1]$. Each industry is characterized by a parameter $z^i \geq 0$ which captures the technological complexity of the industry. The complexity of an industry determines its location in the product space and is associated with a more advanced production technology. Higher complexity is related to the division of labor and hence to the number of tasks that are involved in the production process. In this respect, an increased number of tasks could result in gains from the specialization of labor, but at the same time could be associated with a lower probability that they are all jointly executed correctly. The degree of complexity of an industry is taken to be a technological characteristic of that industry, and is assumed to be constant across countries. The economies will therefore differ in terms of the moments of the statistical distribution of industries in the complexity space.

Output per worker of industry *i* in country *c* can be expressed as:

$$Q_c^i = \lambda_c h_c e^{\alpha_c z^i} \tag{1}$$

The level of output is an increasing function of the share of time allocated to current production λ_c and of human capital h_c. It is also a function of the complexity of industry *i*, z^i, through the parameter $\alpha_c \equiv \theta_c - \delta_c$, where $\theta_c \geq 0$ captures the potential positive product–space effect of complexity on output and where $\delta_c \geq 0$ expresses the possible negative influence from the O-ring complementarities in production. In principle, $\alpha_c \gtreqless 0$: the net effect of complexity on the level of output depends on whether the product-space or the O-ring effect dominates. The multiplicative/exponential functional form is chosen for its analytical convenience.

Let $\varphi_c(z^i)$ be the density function of complexity in country *c*. The total output of country *c* is thus:

$$Q_c = L_c \int_0^\infty Q_c^i \varphi_c(z^i) dz^i \tag{2}$$

For analytical tractability, we assume that industry complexity z^i in country *c* has a gamma distribution with shape parameter $k_c > 0$ and scale parameter $\beta_c > 0$: $z^i \sim Gamma(k_c, \beta_c)$, or:

$$\varphi_c(z^i) = \frac{1}{\beta_c^{k_c}\Gamma(k_c)}(z^i)^{k_c-1}e^{-z^i/\beta_c}, z^i \geq 0 \tag{3}$$

From the properties of the gamma distribution, the average complexity in country *c* is given by $z_c = E_c(z^i) = k_c\beta_c$ and its variance by $V_c(z^i) = k_c\beta_c^2$. In the density function (3), k_c can be interpreted as the shape parameter and β_c as the scale parameter of the gamma distribution. In what follows the shape parameter k_c plays the role of a technological parameter and is associated with the production characteristics of the industry. It is thus constant across countries: $k_c = k$, *c* = 1, 2, … The scale parameter β_c is instead associated with the specific distribution of complexity in each individual country and is country specific. Average complexity in country *c* is thus given by $z_c = k\beta_c$.

Replacing (1) and (3) into (2), the level of output of country *c* can be expressed as[1]:

$$Q_c = L_c \lambda_c h_c \cdot \frac{1}{(1-\alpha_c \beta_c)^k} \tag{4}$$

From (4), the effect on output of the country-specific complexity parameter β_c is in principle ambiguous, and depends on the sign of the parameter α_c. If the positive product-space effect of complexity dominates, then $\alpha_c > 0$ and greater complexity is associated with increased output. By contrast, if the negative O-ring effect from complexity is predominant then $\alpha_c < 0$ and greater complexity is associated with a lower level of output.

The human capital formation equation is based on Lucas (1988, 1993):

$$\dot{h}_c = \delta_c (1 - \lambda_c) z_c h_c \tag{5}$$

where the parameter $\delta_c > 0$ measures the effectiveness of the training system in country *c*. Relative to the original formulation by Lucas, human capital formation now includes average complexity z_c as one of the arguments of the accumulation equation, alongside the initial level of human capital.

Output growth is given by:

$$\frac{dQ_c}{dt} = L_c \lambda_c \cdot \frac{1}{(1-\alpha_c \beta_c)^k} \cdot \frac{dh_c}{dt} = L_c \lambda_c \cdot \frac{1}{(1-\alpha_c \beta_c)^k} \cdot \delta_c (1 - \lambda_c) z_c h_c \tag{6}$$

and thus the instantaneous output growth rate must coincide with the rate of growth of human capital:

$$g_c \equiv \frac{dQ_c}{dt} \cdot \frac{1}{Q_c} = \delta_c (1 - \lambda_c) z_c = \delta_c (1 - \lambda_c) k \beta_c = \frac{\dot{h}_c}{h_c} \tag{7}$$

From equation (4), the level of output Q_c is an increasing function of the size of the labor force L_c, of the time allocated to current production λ_c, and of average human capital h_c. The role of complexity z_c depends on the interaction of the scale parameter of the gamma distribution, β_c (since $z_c = k\beta_c$), and the parameter $\alpha_c = \theta_c - \delta_c$ in the production function (1). In particular, increased complexity could exert a negative effect on the level of output if α_c is negative, *i.e.* if $\delta_c > \theta_c$ and the O-ring effect dominates over the gains from specialization.

From equation (7), the dynamic effects on the growth rate of output, g_c, are an increasing function of the time allocated to human capital formation, $(1 - \lambda_c)$, of the quality of the educational system, δ_c, and of the average degree of complexity of the economy, measured by β_c.

[1] The specification in equation (4) implies positive scale effects. In general, when the elasticity of substitution between production factors is different from one, it is possible to have negative scale effects for poor economies (Zuleta 2004). The substitutability between production inputs is not one of the main concern of our analysis, so we do not incorporate it directly into our model, but we shall refer to it in our discussion of the empirical results in sections IV and V.

Thus, while increased complexity is always associated with an increase in the rate of growth of the economy, its role on the level of output is in principle ambiguous and depends on whether the gains from specialization or the O-ring effects are predominant.

III. COMPLEXITY AND TRADE

Our measure of complexity in production is based on net flows in international trade. The pioneering work by Hausmann and Klinger (2006) shows that trade specialization is closely associated to the extant capabilities in a country. This is in line with a classical view in trade theory that emphasizes resource endowments and the available technology as key determinants of trade specialization. A country's profile of specialization in turn relates to its position in the product space, which represents the production sectors in terms of the pattern of revealed comparative advantage observed across all the trading nations. In Hausmann and Klinger's (2006) analogy, the product space can be thought of as a forest, with sectors as trees and countries or their firms as monkeys. A large distance between any two trees indicates that the monkeys cannot easily jump from one to the other. Put differently, the corresponding sectors are very different in terms of their global specialization patterns as, for most countries, a revealed comparative advantage in one sector is not associated with a comparative advantage in the other sector. A country's firms will find it generally difficult to venture from one into the other. By contrast, whenever two trees stand close to each other, they put similar prerequisites to the country for it to achieve a situation of comparative advantage in those industries or sectors. Therefore, specialization in either of the two sectors typically leads to specialization in the other sector as well.

This is particularly the case for those parts of the product space where a relatively large number of sectors are tightly clustered. Countries with a strong industrial presence in that region will find it generally easier to adapt to the manufacture of a whole range of products within that same region. The degree to which sectors are close to each other in the product space is related to similarities in their production structure. Thus, the *density* of sectors in the product space is associated with the adaptability of a country's productive structure.

In our empirical analysis, we use a measure of the average density of sectors in the product space as an indicator of the degree of complexity of the production structure. A country with a high average sector density must possess the capabilities to adapt with greater ease to adjacent areas of the product space.

An important feature of our analysis is the use of *net trade flows* in the computation of the density index. In the original work by Hausmann and Klinger (2006), the construction of the product space is based on the revealed comparative advantage indicator proposed by Balassa (1965), which relies on export performance alone. However, for the purpose of measuring a country's production capabilities, net trade flows can be a more appropriate statistics. Intra-industry trade is a significant component of world trade flows, even at a high level of sectoral disaggregation. We therefore make use of Lafay's (1992) specialization index, which is based on net export flows[2].

The starting point for the construction of the index is the normalized trade balance, defined as follows:

[2] Our definition of the indicator is based on the version of Lafay's index set out in Bugamelli (2001): see also Zaghini (2005), Alessandrini *et al.* (2011), and Ferrarini and Scaramozzino (2011).

$$z(c,i) = \frac{x(c,i) - m(c,i)}{x(c,i) + m(c,i)} \tag{8}$$

where $x(c,i)$ are exports of industry *i*, in country *c*, and $m(c,i)$ are imports. A trade specialization index for each sector can then be computed as the difference between the normalized trade balance of the sector and the distribution of trade balances of a country across its products:

$$TS(c,i) = z(c,i) - \sum_i z(c,i) \tag{9}$$

The Lafay index, $LF(c,i)$, is obtained by weighing the trade specialization index $TS(c,i)$ by the sectoral contribution to trade:

$$LF(c,i) = TS(c,i) \cdot \frac{[x(c,i) + m(c,i)]}{X(c) + M(c)} \tag{10}$$

where $X(c) \equiv \sum_i x(c,i)$ and $M(c) \equiv \sum_i m(c,i)$. A positive value of the Lafay index, $LF(c,i) > 0$, indicates that country *c* enjoys specialization in the production of sector *i*.

An indicator of trade specialization can then be defined for sector *i* of country *c*, as a binary variable that takes the value 1 if country *c* is specialized in sector *i* and the value 0 otherwise:

$$q(c,i) = I(LF(c,i) \geq 0) = \begin{cases} 1 & if \quad LF(c,i) \geq 0 \\ 0 & if \quad LF(c,i) < 0 \end{cases} \tag{11}$$

The degree of closeness of any two production sectors *i* and *j* in the global product space is measured by the index of proximity $\theta(i,j)$:

$$\theta(i,j) = \min\{P(q(c,i) = 1 | q(c,j) = 1), P(q(c,j) = 1 | q(c,i) = 1)\} \tag{12}$$

The index of proximity between sectors *i* and *j* is inversely related to the distance between the sectors, and is defined in terms of the conditional probabilities of trade specialization in the global product space.[3]

Finally, we can compute the density index for sector *i* in country *c* as a weighted average of the trade specialization indicators, where the weights are the proximities of sector *i* with all the other sectors:

$$\omega(c,i) = \frac{\sum_j \theta(i,j) q(c,j)}{\sum_j \theta(i,j)} \tag{13}$$

The average density of country *c* is obtained as an average of the density indexes across all sectors:

$$\bar{\omega}(c) = \sum_i \omega(c,i). \tag{14}$$

[3] See Hausmann and Klinger (2006) for a motivation of the index of proximity (12) and for a discussion of its properties.

While density $\omega(c,i)$ measures a good's distance in the product space from the sectors associated with a country's export basket, the average density of a country $\overline{\omega}(c)$ is related to the adaptability of that country's production structure across all its sectors. Put differently, it is a measure of the number of paths out of all total possible paths within the product space that lead to the products that are already in a country's export basket. Average density measures how fungible a country's capabilities are, which in turn represent its resource endowments and available technology.

Density and its related measures have found broad application in growth diagnostic studies, where the focus is mainly on the existence in a country of the necessary capabilities or impediments for it to diversify its exports basket or to move up the value-added ladder (ADB 2009).

IV. EMPIRICAL FINDINGS

The theoretical model set out in Section II yields clear predictions for the effects of increased complexity in the production process. A greater degree of complexity could in principle have either a positive or a negative effect on the level of output, because of the potential trade-off between the gains from specialization and the O-ring effects. On the other hand, greater complexity should have a positive effect on output growth because it enhances the process of accumulation of human capital.

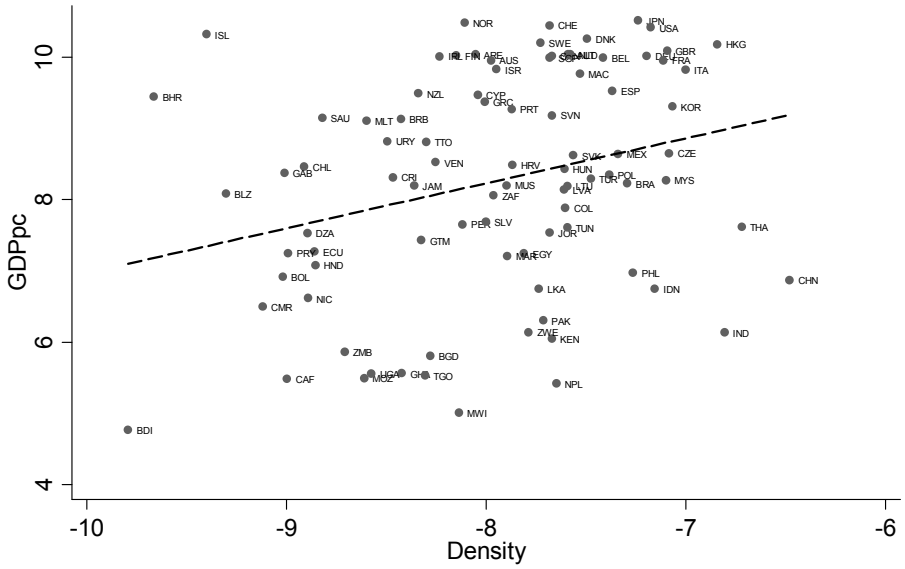
We test the predictions of the theoretical model for a cross-section of 89 countries over the period 1990–2009 (see the Appendix A1 for a full list of the countries included in the sample and Appendix A2 for a description of the data sources). We estimate both level and growth equations for gross domestic product (GDP) per capita over periods of five years each: 1990–1994, 1995–1999, 2000–2004, and 2005–2009. As discussed in Section III, the measure of complexity used in the analysis is the average product density by country according to the Lafay product space, defined in equation (14).[4] The size of the labor force is measured by total active population aged 15 or over. The share of time allotted to current production is proxied by the labor force participation rate, and average human capital by the number of years of schooling (Barro and Lee 2010).[5]

Figure 1 illustrates the relationship between density in the product space and GDP per capita. There is a positive correlation between the two variables, higher density being associated on average with larger values of GDP per capital. A number of Asian countries, such as the People's Republic of China, India, and Thailand, are characterized both by high density and by low levels of GDP per capita.

[4] We also performed the statistical analysis using the Balassa definition of the product space, which leaves the main results unchanged. Additional regression results are available from the authors upon request.

[5] See the data appendix for a description of all the variables used in the analysis.

Figure 1: GDP per Capita and Density
(logarithmic scale, averages across periods)



Note: International Standards Organization (ISO) 3-digit alphabetic codes (http://wits.worldbank.org/WITS/wits/WITSHELP/Content/Codes/Country_Codes.htm). The paper used the World Bank's ISO alpha-codes.

Sources: Please refer to Appendix A2.

Table 1 presents the estimates of regressions on the logarithm of GDP per capita as the dependent variable. The model has been estimated by panel data GLS, which allows for a flexible covariance structure for the disturbances and for random effects, and which can be interpreted as a matrix-weighted average of the within- and the between-units estimators. Explanatory variables are the average density for the country in the product space (*ldensity*), total active population (*llabf*), labor force participation rate (*llabfpr*), and years of schooling (*lschool*). All the variables are expressed in logarithmic form. The regressions were estimated over the four sub-periods 1990–1994, 1995–1999, 2000–2004, and 2005–2009.

Column (1) of Table 1 gives the estimated coefficients for the regression on all 89 countries in the sample. Density has a positive and significant coefficient on GDP per capita, which is consistent with the product space effect of the complexity variable. That is, countries occupying the denser areas of the product space are on average associated with higher GDP per capita, with causality running from the former to the latter. Schooling also has a positive coefficient, which is consistent with this variable's interpretation as a proxy for the human capital available in an economy. Interestingly, both the coefficients on the total active population and on the participation rate attract a negative sign. This could be related to a negative scale effect, and could be explained by low substitutability between production factors in poorer economies (Zuleta 2004).

Table 1: Complexity and Output Level

		By income Groups		By Regions					
Dependent Variable: GDP per Capita	**All Sample (1)**	**High Income (2)**	**Middle and Low Income (3)**	**Europe and North America (4)**	**East Asia and Pacific (5)**	**South Asia (6)**	**Latin America and Caribbean (7)**	**Middle East and North Africa (8)**	**Sub-Saharan Africa (9)**
ldens	0.075***	–0.076***	0.0522***	–0.327***	0.307***	–0.123**	0.202***	–0.122**	0.017
llabf	–0.0856***	0.1889***	–0.0889***	0.119***	–0.386***	0.043*	0.0317	–0.215***	–0.193**
llabfpr	–0.799***	2.284***	–2.062***	2.040***	–1.407**	–2.011***	–0.058	4.139***	–4.234***
lschool	2.197***	0.103	1.225***	1.151***	2.511***	0.866***	1.297***	1.419***	0.342***
cons	9.225***	–3.458***	15.420***	–5.685***	17.912***	11.410***	6.916***	–8.516***	26.893***
No. observations	355	156	199	116	48	20	76	40	55
No. countries	89	39	50	29	12	5	19	10	14

Notes:Sample periods: 1990–1994, 1995–1999, 2000–2004, 2005–2009.
(2) Estimation method: panel data GLS.
(3) * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Source: Authors' estimates.

In columns (2) and (3) of Table 1**,** the sample is split in two, between countries with high income and countries with middle or low income. Density and the labor market variables have an opposite impact on these two income groups. Density negatively influences GDP per capita for high-income countries, and positively influence middle- and low-income countries. By contrast, total active population and the labor participation rate take positive sign for the case high-income group of countries, whereas these coefficients are negative for the group of developing countries. Put differently, the product space effect of production complexity appears to matter mostly for middle- and low-income countries, where it increases per capita income and where there is also a negative scale effect from the size of the labor force. By contrast, product density dampens per capita income for the group of high-income countries. A possible explanation for this is that the negative O-ring effect of increased complexity dominates over the product space effect for these countries. Furthermore, a positive scale effect is observed in relation to the labor market variables, whereas schooling is positive but not statistically significant.

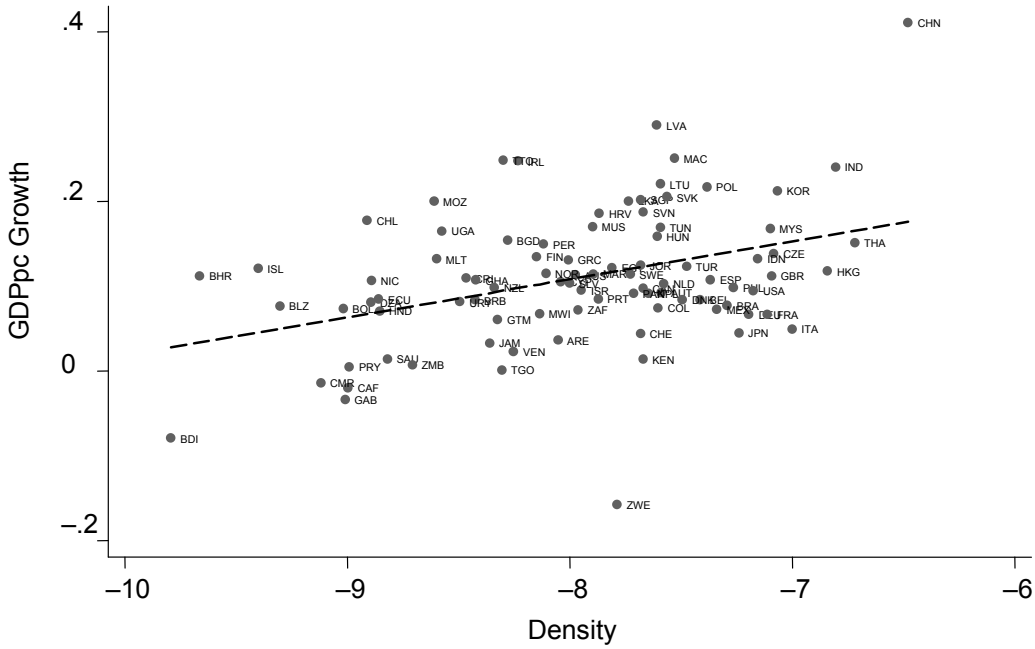
Columns (4)–(9) of Table 1 show the estimates for six geographic subsamples. The density variable is statistically significant for each of these regions, expect for Sub-Saharan Africa in the last column. The coefficient on density is negative for Europe and North America, South Asia, and Middle East and North Africa. It is positive for East Asia and Pacific, and for Latin American and Caribbean. It is notable that the labor market variables tend to attract an opposite sign to the density variable. This indicates that the role of complexity relates to the size effect on the level of output, and therefore possibly to the degree of substitutability of the factors entering production.

The growth model laid out in Section II allows for the case that greater complexity may affect the level of output negatively, but in general both its level and growth effect are expected to be positive. This is borne out in Figures 1 and 2, plotting GDP per capita and its growth rate against density for the sample of countries included in the regressions. On average, countries associated with a more dense occupation of the product space experienced faster growth during 1990–2009. As would be expected, Asian countries' sustained growth makes them cluster mostly about the upper right side of Figure 2, whereas a number of developed countries experienced growth slower than average, such as did the France, Germany, Italy, Spain, the United Kingdom, and the United States.

To control for other potential determinants of economic growth, the growth regressions examine the relationship between complexity and growth by inclusion of the initial level of GDP per capita. In relation to the whole sample of countries, the first column of Table 2 shows that the coefficient on density is positive and significant, in line with the predictions of our growth model. Indeed, a higher value of product density is expected to be associated with a more effective accumulation of human capital. Also consistent with the model is the coefficient on schooling, which is positive. The initial level of GDP per capita has a negative sign, which is consistent with the income-convergence hypothesis. Also the labor market variables have a negative sign, which suggests the presence of a negative scale effect on the growth rate.

The foregoing results are confirmed when the sample of countries is split according to income groups, shown in the second and third columns of Table 2. Notably, the coefficient on density remains positive and statistically significant, pointing to a potentially direct impact which complexity exerts on growth.

Figure 2: Growth of GDP per Capita and Density
(logarithmic scale, averages across periods)



Note: International Standards Organization (ISO) 3-digit alphabetic codes (http://wits.worldbank.org/WITS/wits/WITSHELP/Content/Codes/Country_Codes.htm).

Sources: Please refer to Appendix A2.

The remaining columns of Table 2 report the results for the geographical subsamples. The coefficient on the density variable is positive and highly significant, with the only exception of Europe and North America. For these two regions, the results may be driven by a relatively poor growth performance which was below average during 1990–2009, as already noted in relation to Figure 2. Also of interest is the coefficient on the level of initial income, which is positive and statistically significant for both the South Asia and for Sub-Saharan Africa aggregates. Conditional convergence would appear not to be in progress within these two regions.

In sum, the empirical evidence corroborates the model's prediction with respect to production complexity, which is found to be a significant factor explaining both the level of output and its rate of growth.

Table 2: Complexity and Output Growth

Dependent Variable: Difference in log of GDP per capita	All Sample (1)	By Income Groups: High income (2)	By Income Groups: Middle and low income (3)	By Regions: Europe and North America (4)	By Regions: East Asia and Pacific (5)	By Regions: SouthAsia (6)	By Regions: Latin America and Caribbean (7)	By Regions: Middle East and North Africa (8)	By Regions: Sub-Saharan Africa (9)
ldens	0.0436***	0.0481***	0.039***	–0.054***	0.112***	0.063***	–0.018	0.032*	0.063***
llabf	–0.006***	–0.031***	0.007	–0.004	–0.022***	0.015***	0.009	–0.010	0.032*
llabfpr	–0.098***	–0.100*	–0.070	–0.152***	1.237***	0.934***	–0.149	–0.000	0.128
lschool	0.047***	0.142***	0.057***	0.173***	0.073*	–0.208***	0.115***	0.228***	–0.098**
lpcgdp	–0.004*	0.003	0.012	–0.045***	0.018	0.388***	0.012	–0.067***	0.052**
cons	0.885***	1.030***	0.407*	0.438***	–4.137***	–5.567***	0.094	0.611	–0.649
No. observations	267	117	150	87	36	15	57	30	42
No. countries	89	39	50	29	12	5	19	10	14

Notes: See Table 1.

Source: Authors' estimates.

V. GLOBAL SUPPLY CHAINS, COMPLEXITY, AND ECONOMIC PERFORMANCE

The measure of complexity used in the foregoing analysis is based on net export flows or trade balances, which identify a country's position within the global product space. In contrast to the Hausmann and Klinger (2006) concept of product space, based on exports data alone, our revised concept of product space and the related density measure do account for intra-industry trade to the extent that it involves countries' trading in similar products (e.g., cars for cars). However, only the horizontal type of intra-industry trade is captured by coarse-grained sector balances, such as what typically dominates trade among countries within the European Union (EU). It is unreflective of so-called vertical trade (e.g., car engines) as a consequence of the international fragmentation of production and involving cross-border flows of parts and components and unfinished products as they pass sequential stages of production to undergo further processing or assembly in several different countries prior to meeting final demand.[6]

To account for vertical trade in our empirical investigation, we employ the network trade index (NTI), which is a newly developed measure capturing the intensity of trade among countries participating in the international production networks (Ferrarini 2013). The NTI is defined as the share of partner *j*'s components of industry *s* in reporter *i*'s total imports of parts and components, weighted by the share of industry *s* in country *i*'s total final good exports. Specifically, denote by c_s^j, the value of imports to country *i* of components of industry *s* from country *j*. The total imports of components from sector *s* to country *i* is therefore $\sum_j c_s^j$, and the share of country *j*'s components of industry *s* on total imports of *s* in *i* is $c_s^j / \sum_j c_s^j$. Let us further denote by p_s^i the exports of *s* from country *i*. The *NTI* for trade partner *j* of country *i* is defined as:

$$NTI^{j|i} = \sum_s \sum_{j \neq i} \frac{c_s^j}{\sum_j c_s^j} \cdot \frac{p_s^i}{\sum_s p_s^i} \tag{15}$$

where, $p_s^i / \sum_s p_s^i$ is the share of sector *s* on total exports from country *i*. A higher value of *NTI* indicates a greater importance of country *j* in the network of industrial relations of country *i*.

In its aggregate form, the index is derived as a geometric average across sectors, and is then normalized to vary between 0 and 1:

$$\widetilde{NTI} = \frac{NTI - NTI_{min}}{NTI_{max} - NTI_{min}} \tag{16}$$

[6] The literature unambiguously points to a rapid expansion of production networks and vertical trade in the global economy, particularly since the early 1990s. Nowhere has the expansion of vertical trade networks and supply chains been more pronounced than in Asia, particularly after the People's Republic of China's (PRC) rise as a global hub of manufacturing during the 2000s. By 2007, more than half of the PRC's exports value represented value-added imports from other countries (Koopman, Wang, and Wei 2008). Duernecker, Meyer, and Vega-Redondo (2012) provide evidence on the importance of the integration of an economy into the global trade network for its rate of growth.

The *NTI* in logarithmic form enters the regressions in both levels and growth as an additional explanatory variable. The estimates are shown in Tables 3 and 4, in relation to the level and growth equations respectively. The sample now comprises 58 countries, instead of 89, due to data limitations for the computation of *NTI*. Different sample size is the only difference between the estimates reported in the first column of Table 3 and the first column of Table 1. The estimates are very similar. In particular, the coefficient on density is positive and significant as in column (1) of Table 1. Column (2) of Table 3 includes the logarithm of *NTI* as an additional regressor. The coefficient is positive and significant, which is evidence that a country's integration in the vertical trade networks exerts a direct positive effect on the level of output. Indirectly, the introduction of the *NTI* among the explanatory variables causes the coefficient on density to become negative. One possible explanation for this is that this measure of vertical trade directly captures some of the positive effects of trade networks that were previously picked up by the density measure of the product space, the computation of which relies on product categories coarse enough for horizontal intra-industry trade to pick up substantial portions of vertical intra-industry trade.[7] Once *NTI* is included in the analysis, the effect of the density is dominated by the O-ring complexity effects, and its coefficient therefore becomes negative.

As in Table 1, the third and fourth columns of Table 3 report the estimation results for the sample split into high-income and middle- and low-income countries. The *NTI* variable remains positive and highly significant for both groups of countries. The density variable is negative, but is statistically significant only for high-income countries. The labor market variables are positive for high-income countries and negative for middle-and-low income countries, thus mirroring the results from Table 1.

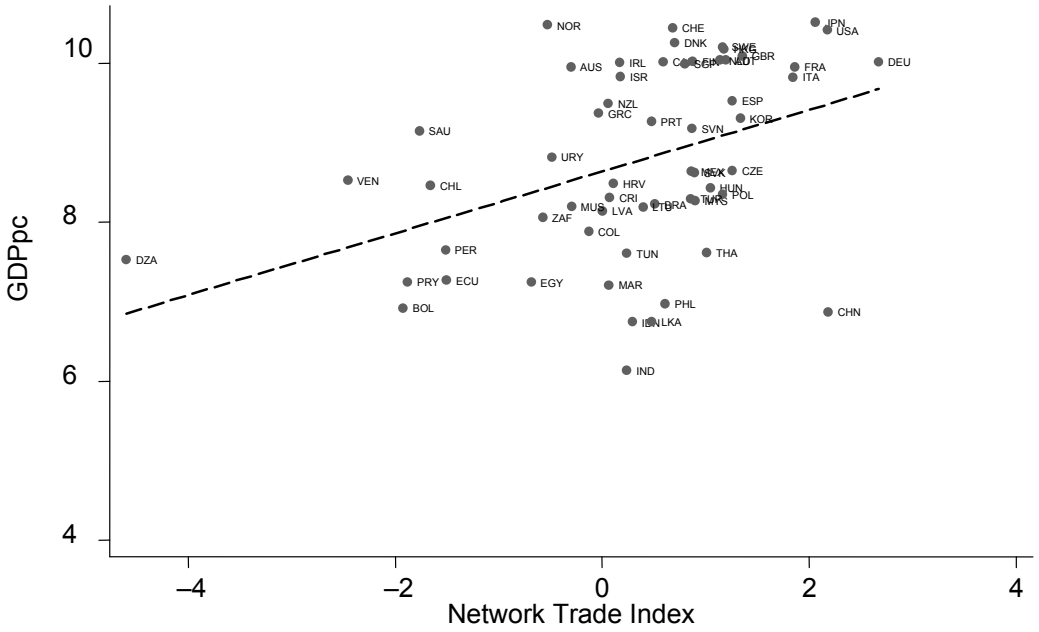
Columns (5)–(10) of Table 3 report results by geographical regions. The coefficient on *NTI* is positive for all regions, and is highly significant for Europe and North America, East Asia and Pacific, and Middle East and North Africa. Vertical integration into global production network and trade is therefore highly relevant to explain the level of output per capita. The coefficient on density offers a more nuanced picture across regions: it is negative for Europe and North America and for the Middle East and North Africa, but positive for South Asia. Although the effect of density in the product space is on average negative for the whole sample of observations (column (2)), the results indicate that complexity may well exert a positive influence on per capita GDP for specific countries or regions.

Finally, Table 4 reports the estimates obtained by including *NTI* in growth equations. The density variable remains positive for the sample as a whole, consistent with its role on human capital formation. It is only negative for specific regions, such as Europe and North America (see Table 2). The *NTI* variable is now however mostly insignificant.

The role of integration into the global production networks therefore appears to be important for the level of output, rather than for the growth performance of countries.

[7] The Spearman correlation coefficient between *ldens* and *lnti* is 0.7857.

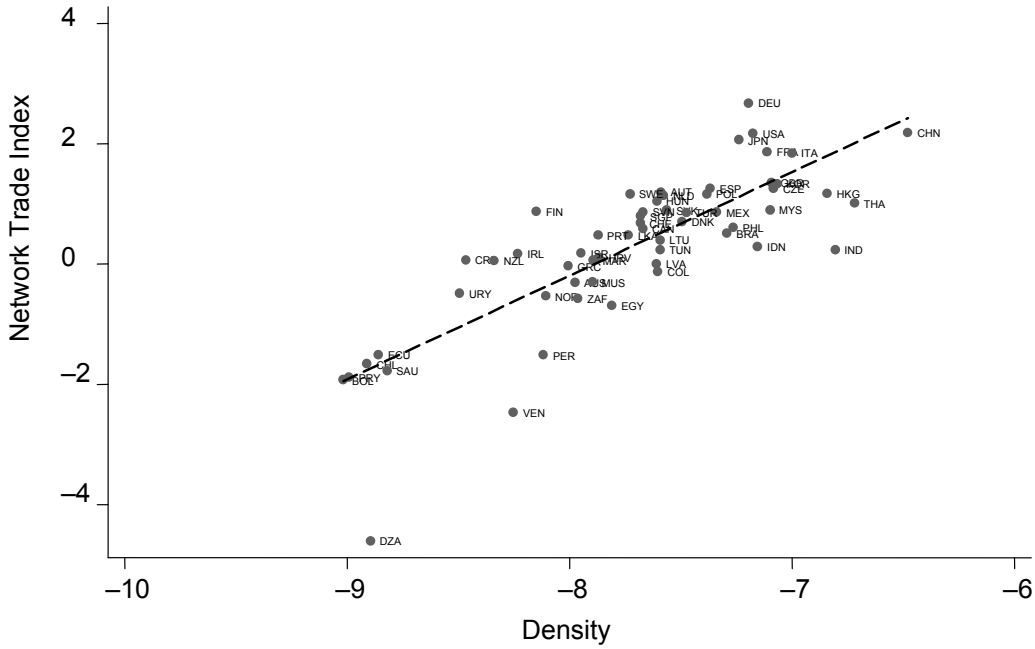
Figure 3: GDP per Capita and Network Trade
(logarithmic scale, averages across periods)



Note: International Standards Organization (ISO) 3-digit alphabetic codes (http://wits.worldbank.org/WITS/wits/WITSHELP/Content/Codes/Country_Codes.htm).

Sources: Please refer to Appendix A2.

Figure 4: Network Trade and Density
(logarithmic scale, averages across periods)



Note: International Standards Organization (ISO) 3-digit alphabetic codes (http://wits.worldbank.org/WITS/wits/WITSHELP/Content/Codes/Country_Codes.htm).

Source: Please refer to Appendix A2.

Table 3: Complexity, Network Trade, and Output Level

			By Income Groups		By Regions					
Dependent Variable:	All Sample		High Income	Middle and Low Income	Europe and North America	East Asia and Pacific	South Asia	Latin America and Caribbean	Middle East and North Africa	Sub-Saharan Africa
GDP per Capita	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ldens	0.077*	–0.188***	–0.199***	–0.011	–0.580***	–0.170	1.948***	–0.025	–0.836***	0.135
llabf	–0.089***	–0.010	0.133***	–0.105***	0.078*	–0.548***	0.260	0.162	–0.207***	1.335***
llabfpr	–1.118***	–1.055***	2.606***	–1.435***	2.204***	–3.538***	–2.583***	–1.958***	3.965***	–2.586
lschool	2.102***	2.000***	0.125	1.128***	1.133***	2.171***	3.460***	0.544***	1.835***	1.649**
lnti	-	0.331***	0.147***	0.046***	0.508***	1.250***	4.170	0.0745	0.347***	18.977***
cons	8.086***	7.545***	–5.021***	13.013***	–7.999***	25.581***	18.974	11.976***	–14.167***	4.712
No. observations	232	232	120	112	104	44	8	44	24	8
No. countries	58	58	30	28	26	11	2	11	6	2

Notes: See Table 1.

Source: Authors' estimates.

Table 4: Complexity, Network Trade, and Output Growth

Dependent Variable: Difference in log of GDP per capita	All Sample		By Income Groups: High Income	By Income Groups: Middle and Low income	By Regions: Europe and North America	By Regions: East Asia and Pacific	By Regions: Latin America and Caribbean	By Regions: Middle East and North Africa
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ldens	0.0577***	0.048***	0.009	0.048***	–0.036***	0.043	–0.005	–0.046
llabf	–0.012***	–0.012***	–0.029***	0.008	–0.012***	–0.007	0.023***	–0.008
llabfpr	–0.056**	–0.056**	–0.044	–0.140***	–0.156***	0.703***	0.009	0.133
lschool	0.138***	0.131***	0.095***	0.235***	0.123***	0.049	0.358***	0.312***
lpcgdp	–0.032***	–0.033***	–0.012	–0.026**	–0.024***	0.009	0.0121	–0.135***
lnti	-	0.005	0.011	0.006	–0.015**	0.049*	–0.003	0.040*
cons	0.975***	0.925***	0.724***	0.688*	0.641***	–2.561***	–1.183***	–0.090
No. observations	174	174	90	84	78	33	33	18
No. countries	58	58	30	28	26	11	11	6

Notes: See Table 1.

Source: Authors' estimates.

VI. CONCLUSIONS

This paper analyzes the role of complexity in production on output growth. This is still an under-explored issue in the current debate on the cross-country differences in economic performance. In an endogenous growth model with human capital accumulation, increased complexity could have an ambiguous effect on the level of output, but would always exert a positive effect on its rate of growth by enhancing human capital formation. Our measure of complexity is derived from net trade flows and is based on the product space description of production sectors in the global economy. The average density of a country in the product space is a measure of the adaptability of that country's production structure across sectors, and can be interpreted as being related to the fungibility of its resource endowments and of its available technology. We also consider an indicator of network trade, which is a direct measure of the intensity of vertical trade among countries. Empirical evidence from a cross-section of countries is consistent with the theoretical predictions and supports the view that production complexity is important to explain differences in economic performance.

Appendix A1: Countries Included in the Analysis

High-income countries:

ARE, AUS, AUT, BEL, BHR, BRB, CAN, CHE, CYP, CZE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, HKG, HRV, HUN, IRL, ISL, ISR, ITA, JPN, KOR, MAC, MLT, NLD, NOR, NZL, PRT, SAU, SGP, SVK, SVN, SWE, TTO, USA.

Middle- and Low-income countries:

BDI, BGD, BLZ, BOL, BRA, CAF, CHL, CHN, CMR, COL, CRI, DZA, ECU, EGY, GAB, GHA, GTM, HND, IDN, IND, JAM, JOR, KEN, LKA, LTU, LVA, MAR, MEX, MOZ, MUS, MWI, MYS, NIC, NPL, PAK, PER, PHL, POL, PRY, SLV, TGO, THA, TUN, TUR, UGA, URY, VEN, ZAF, ZMB, ZWE.

Europe and North America:

AUT, BEL, CAN, CHE, CYP, CZE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, HRV, HUN, IRL, ISL, ITA, LTU, LVA, NLD, NOR, POL, PRT, SVK, SVN, SWE, TUR, USA.

East Asia and Pacific:

AUS, CHN, HKG, IDN, JPN, KOR, MAC, MYS, NZL, PHL, SGP, THA.

South Asia:

BGD, IND, LKA, NPL, PAK.

Latin America and Caribbean:

BLZ, BOL, BRA, BRB, CHL, COL, CRI, ECU, GTM, HND, JAM, MEX, NIC, PER, PRY, SLV, TTO, URY, VEN.

Middle East and North Africa:

ARE, BHR, DZA, EGY, ISR, JOR, MAR, MLT, SAU, TUN.

Sub-Saharan Africa:

BDI, CAF, CMR, GAB, GHA, KEN, MOZ, MUS, MWI, TGO, UGA, ZAF, ZMB, ZWE.

Note: International Standards Organization (ISO) 3-digit alphabetic codes (http://wits.worldbank.org/WITS/wits/WITSHELP/Content/Codes/Country_Codes.htm).

Appendix A2: Definitions and Sources of Variables

Variable Name	Description	Source
lpcgdp	Logarithm of GDP per capita, current US$	World Development Indicators, The World Bank Group
ldens	Logarithm of average product density by country, according to the Lafay product space definition	Ferrarini and Scaramozzino (2011)
llabf	Logarithm of total active population (15 years and older), thousands	Key Indicators of the Labor Market, International Labor Organization (ILO)
llabfpr	Logarithm of labor force participation rate, percent	Key Indicators of the Labor Market, International Labor Organization (ILO)
lschool	Logarithm of total years of schooling (15 years and older), units	Barro and Lee (2010)
lnti	Logarithm of Network Trade Index (NTI), units	Ferrarini (2013)

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Complexity, Specialization, and Growth

The authors devise an endogenous growth model with human capital accumulation to assess the impact of production complexity on economic output and its rate of growth. They test the model with an empirical measure of complexity based on a revised product space description of the global economy. They find that production complexity is a key factor accounting for differences in output performance across economies.

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