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Variety, Competition, and Population in Economic Growth: Theory and Empirics

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Abstract

We provide aggregate macroeconomic evidence on how, in the long-run, a diverse degree of complexity in production may affect not only the rate of economic growth, but also the correlation between the latter, population growth and the monopolistic (intermediate) markups. For a sample of OECD countries, we find that the impact of population change on economic growth is slightly positive. According to our theoretical model, this implies that the losses due to more complexity in production are lower than the corresponding specialization gains. Using a Finite Mixture Model, we also classify the countries in the sample and verify for each cluster the impact that the population growth rate and the intermediate sector's markups exert on the 5-year average real GDP growth rate.

Keywords: Economic growth; Population growth; Variety-expansion; Specialization; Complexity; Product market competition.
JEL codes: O3; O4; J1.

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"The productivity-enhancing effects of horizontal innovations are not... obvious... For while having more products definitely opens up more possibilities for specialization, and of having instruments more closely matched with a variety of needs, it also makes life more complicated and creates greater chance of error...."

(Aghion and Howitt [3], p. 407.)

1 Introduction

Economic theory has long ago made clear that the degree of product market competition (PMC, henceforth) and the rate of population growth have a strong impact on economic growth. This occurs because they affect, respectively, the path of future profits accruing to the successful innovator and the availability of researchers in an economy.

In order to analyze, both theoretically and empirically, how population growth and the extent of the monopolistic markups rewarding prospective innovators may simultaneously affect economic growth, we employ a simple extension of the canonical *semi-endogenous growth* model by Jones [30]. The main reason for using this framework resides in the fact that in two companion contributions Jones [29]-[30] provided convincing evidence against two broad categories of *fully endogenous growth* models (the AK-type and the R&D-based, respectively). In particular, the evidence against the first generation of R&D-based fully endogenous growth models (i.e., Romer [52]; Grossman and Helpman [23]; Aghion and Howitt [2]) is especially persuasive. These models predict that economic growth is proportional to the amount of resources invested in R&D (the number of researchers allocated to this activity). Nonetheless, in the last few decades R&D investments have increased remarkably in most of advanced countries, with the long-run growth rates of per capita output and total factor productivity of these countries not showing a comparable upward trend.

The aim of the present paper is twofold. The first goal is to re-examine the long-run relationships between PMC and economic growth, and between population growth and economic growth. Re-assessing these much debated connections is still important especially because we are now aware that the introduction of new varieties of horizontally-differentiated intermediate inputs (i.e., an improvement in the rate of technological change) determines a trade-off between productivity gains (due to more specialization) and productivity losses (due to more complexity). Our modelling strategy differs from the traditional *semi-endogenous growth* theory (Jones [30]) because it accounts explicitly for this trade-off.[1]

The second goal is to reach a quantitative understanding of the *complexity effect* associated to technological progress (intermediate inputs proliferation), in comparison to the more standard *specialization effect* of variety-expansion.

To have an immediate picture of the mechanisms described in our paper, consider an R&D-based growth model à la Romer [52] and suppose, as in Jones [30], that there

[1] In the canonical *semi-endogenous growth* model, the *complexity effect* is either non-existent or very small, and as such totally negligible. Furthermore, in Jones [30] the equilibrium markup of any intermediate-input's price over its marginal cost of production is not disentangled from the factor-inputs shares in GDP. By explicitly disentangling the two measures, our analysis also allows an in-depth examination of the long-run nexus between the rate of economic growth and the intermediate local monopolists' market power.

are diminishing technological opportunities in the sector that produces new ideas for new varieties of differentiated intermediates. Diminishing technological opportunities means that a researcher becomes less and less productive as the number of existing ideas grows up, so that in the long-run it is possible to keep on innovating at a constant pace only if the aggregate stock of researchers increases. In turn, if this stock is proportional to population size, the number of available researchers could ultimately be expanded only through an increase of population. A larger population generates therefore three different effects in our setting: one is direct, while the other two are indirect. The first effect is unambiguously positive and operates directly on the aggregate production function: with a rising population, more people can be employed to produce final output, and this clearly increases aggregate GDP. The two remaining effects are instead indirect, operate on the aggregate production function through the availability of new ideas, and are opposing in sign. With a larger population, more people can in principle be employed also in the R&D sector, which in turn leads to an increase in the number of existing ideas (i.e., intermediate goods varieties in our economy). If this number goes up, then two contrasting outcomes can simultaneously be observed on the aggregate GDP. On the one hand, due to the higher number of ideas, the productivity of all the other inputs (namely, labor and intermediates) can increase, so facilitating an increase of total GDP, as well (this is the positive and indirect *specialization effect*). On the other hand, however, having more varieties of intermediate inputs to be assembled in the same aggregate production function can also cause a rise of the degree of complexity of the technology in use, which ultimately determines a loss of the economy's GDP. Unlike the standard *semi-endogenous growth* theory, our model suggests that in the long run a fully positive effect of population growth on per capita income growth is possible only if the productivity losses, arising from more complexity, are sufficiently small and, in any case, lower than the related productivity gains resulting from more specialization. In contrast, when the (productivity) losses arising from complexity are greater than the corresponding (productivity) gains coming from specialization, the effect of population growth on the growth rate of per capita GDP is definitely negative. In this case, our model also suggests that it is possible to increase the economy's growth rate by reducing the incentives to produce new ideas (i.e., by lowering, *ceteris paribus*, the degree of monopoly power rewarded to the potential innovator). Finally, the population growth has a negative impact while the monopolistic markup has a positive influence on the long-run economic growth rate (at most, both impacts are equal to zero) in the intermediate case in which the productivity losses due to production complexity are moderately large, but still lower than (or at most equal to) the productivity gains resulting from specialization.[2]

[2]In this paper, we do not aim at capturing the mutual evolution of population growth, technological incentives, and per capita GDP along an economic and demographic transition toward a long-run equilibrium characterized by low fertility and mortality rates, high levels of R&D investments and persistent growth in per capita income (as in Galor [21] and Jones and Vollrath [34].) Hence, we choose a variant of the basic *semi-endogenous growth* model in which population growth and the intermediate sector monopolistic markup are both exogenous variables, and focus on the long-run nexus between population change and economic growth and between markups and economic growth. It is also out of the scope of this paper to illustrate any new mechanism able to command an economy's take-off from a "stagnant-equilibrium

The main advantage of our model, therefore, is that it is able to account simultaneously for a non-monotonous, non-uniform relationship not only between population growth and economic growth but also, and concurrently, between the degree of the monopolistic markup and economic growth. This is the most important difference between our theoretical results and those of the basic *semi-endogenous growth* model (Jones [30]), which does not allow any analysis of the long-run connection between PMC and economic growth while predicting, at the same time, an always-positive impact of the exogenous population growth rate on economic growth.

In the econometric part of the paper, we explicitly deal with this non-monotonicity. Using a semi-parametric approach, we find that the population growth rate produces a (slightly) positive influence on real per capita GDP growth, for a sample of OECD countries. Furthermore, when statistically significant, the impact of the monopolistic markup on growth is found to be barely negative or positive. Despite the magnitudes of these effects being sensitive to the estimation procedure, the quantitative analysis shows that (on average) countries in our sample behave consistently with the theoretical case in which the *specialization effect* prevails on the *complexity effect*.

This paper is structured as follows. Section 2 presents the relevant literature on the topic and explains the differences with our contribution. Section 3 provides the theoretical model and illustrates the differential impact that population growth and markups may have on long-run economic growth depending on the relative degree of complexity in production. In section 4, we present our econometric strategy, describe the employed dataset, discuss the econometric results, and provide some robustness checks. Section 5 summarizes, concludes and proposes new possible directions for future research.

2 Related literature

Recent theoretical research (both industrial organization- and macro- based) finds mixed results in the correlation between PMC and economic growth. The existing empirical evidence confirms the non-monotonicity of this relation.[3] Similarly, a complete agreement on the sign of the long-run correlation between population and economic growth rates has not emerged yet, both theoretically and empirically.[4]

steady state"into a self-sustaining "growth-equilibrium steady state", during which the GDP's share spent on R&D activities and population aging ultimately increase, while fertility and mortality fall. Instead, we develop a simple model in which, however, R&D activity plays a significant and explicit role.

[3]While Nickell [48] and Blundell et al. [10]-[11] find that competitive pressures encourage innovation and, therefore, have a positive effect on productivity growth in a long-run perspective, Aghion and Griffith's [1] review of the empirical literature on the topic points out that the relationship between competition and growth is, in general, non-monotonous and, in particular, inverted U-shaped.

[4]According to Sala-i-Martin et al. [53], the sign of the whole impact of population growth on economic growth is ambiguous. Using a sample of 78 countries between 1965 and 1990, Williamson ([57], pp. 113-115) shows that there is no significant relationship between population and economic growth rates. This result, however, is sensitive to the empirical specification employed. For example, when the log of life-expectancy in 1960 and two further controls for economic geography are added, population growth is shown to generate a positive and significant impact on GDP per capita growth. Bruce and Turnovsky [12] also assess the link

The state of the debate on the relation between demographic change and economic growth is very well summarized by the main argument of Kelley and Schmidt [36]. Using both cross-section and time-series data, the authors provide compelling evidence that the impact of population growth on per capita income growth has changed over time (it has been statistically not significant in the 1960s and the 1970s and statistically significant, large and negative in the 1980s), and varies with the level of economic development (it is generally negative in less developed countries and can be positive for some developed countries). The authors explain these results through the fact that the impact of population change on economic development may be drastically different in sign depending on which specific component of population growth is especially affected by a given demographic shock. An increase of population growth, attained through a rise of fertility, has a monotonically negative consequence on economic growth, whereas the same increase of population growth, achieved through a decline of mortality, has a monotonically positive influence on the growth rate of real per capita income. This has profound implications for the analysis, as it suggests that the composition of a simultaneous rise of fertility and decline of mortality, both leading to a higher population growth rate, is in theory an important explanation of the emergence of a non-monotonous relationship between population and economic growth rates. Following a similar line of reasoning, in a recent paper Prettner [49] proves that introducing a more realistic demographic structure within the canonical *fully-* and *semi-endogenous growth* models is desirable, as it allows to disentangle the growth effects of a changing population from those of a changing individuals' age-structure. He finds that decreasing mortality has a positive effect on long-run economic growth, while the converse holds true for decreasing fertility. The positive growth effects of decreases in mortality outweigh the negative growth effects of decreases in fertility in *fully-endogenous growth* models à la Romer [52], while these positive and negative growth effects exactly offset each other in *semi-endogenous growth* models à la Jones [30]. In our paper, we do not split the population growth rate into its birth- and death- rate components, and continue to postulate that the economy is populated by representative (identical) individuals/households living forever. This is done because we are indeed interested in uncovering (both theoretically and empirically) the long-run correlation between the overall rate of demographic change and the rate of real per capita GDP growth. This also explains why in our analysis the rate of population growth is an exogenous variable.

It is worth noting that our model can also account for the possibility of a negative long-run correlation between population and economic growth rates in R&D-based models. Despite we are not the first to obtain a similar result (in particular, see Prettner [50]), the way we attain it is new.[5] Specifically, in our model there is

between population growth and economic growth in a model with a two-parameter survivorship function. Their calibrations show that an increase in the population growth rate, caused either by higher fertility or reduced mortality, lowers the income growth rate.

[5]Using a Romer [52]-Jones [30]'s setup, Prettner [50] has already shown, indeed, that an increase in population growth, while positively influencing aggregate human capital accumulation, decreases simultaneously schooling intensity (defined as the productivity of teachers times the public resources spent on educating each child). The fall of schooling intensity has, in turn, a negative impact on the future evolution of aggregate human capital. If the negative effect dominates, the resulting slowdown of aggregate human

no human capital investment; the reason for this choice is twofold. First, from the empirical standpoint, including human capital in our regressions does not significantly alter our results.[6] Second, and more important, from the theoretical standpoint, we opt for a parsimonious framework which is, however, able to capture the interplay between productivity-increasing (due to specialization) and productivity-decreasing (due to complexity) generated by a variety expansion. To our knowledge, the analysis of the economic implications of this channel is novel within the rich literature studying the relation between population change and economic growth, and represents the main contribution of this article.

In our model, the balance between the *specialization effect* and the *complexity effect* crucially impacts on the sign of the long-run correlations between population and economic growth, and between markups and economic growth. This is in line with the Kremer [38]'s "O-Ring theory", according to which for some countries (especially those using particularly "complicated"production processes) the productivity-gains from more specialization might be overcome by the associated productivity-losses due to a more complex production organization. Our paper shows that when this happens we should observe not only a different level of the growth rate of per capita income but also, and perhaps more importantly, a change in the relation between economic growth, population growth and markups across countries.[7]

Our work is especially related to Bucci [13] [14], Bucci and Raurich [15], Ferrarini and Scaramozzino [20], and Maggioni et al. [42]. Unlike Bucci [13], it is not an objective of this article to emphasize the growth effects of the so-called *returns to specialization* (Benassy [9]) and their role in shaping the link between population growth-economic growth and between markups-economic growth. Moreover, contrary to Bucci [13], we pay no attention here to how the type of agents' intertemporal utility might additionally affect the relationship between population and economic growth rates. Differently from Bucci [14], instead, we analyze here the simplest possible *semi-endogenous growth* model without human capital accumulation. In this respect, the present paper formally demonstrates that having (either exogenous or endogenous accumulation of aggregate) human capital within a *semi-endogenous* growth framework is not essential in yielding the result of a non-uniform relation between population and economic growth rates. Unlike Bucci and Raurich [15], we do not aim at explaining the differential impact that in the long-run a given change in the population growth rate may have on economic growth through either: (i) the nature (*fully-* or *semi-endogenous*) of the process of economic growth, or (ii) the peculiar engine(s) driving economic growth (i.e., human capital, R&D, or both).

Following the methodology developed by Lafay [39], Hausmann and Klinger [25], Hidalgo et al. [28], Hausmann and Hidalgo [24], Ferrarini and Scaramozzino [20] use data on net trade flows to compute a measure for complexity in production, namely the production density index, for 89 countries along the period 1990-2009. For these countries, they separately estimate, through a panel data GLS model, the impact of a larger product density on the level and the growth rate of GDP per

capital accumulation eventually reduces technological progress and, therefore, economic growth.

[6]See sub-section 4.4.

[7]In a recent paper, Neves Sequeira et al. [47] apply the entropy to capture the *complexity effect* into an endogenous growth framework.

capita. For the whole sample, density has a positive and significant coefficient on the level of GDP per capita (countries occupying the denser areas of the product space have on average higher GDP per capita, with causality going from the former to the latter). However, when the sample is split by income levels, it is observed that density positively affects GDP per capita in middle/low income countries, while it dampens per capita income for the group of high-income countries. Concerning the growth regressions (that examine the relationship between product density and economic growth by including the initial level of GDP per capita as a regressor), the authors find that, for the whole sample of countries, the coefficient on density is still positive and significant. This result is confirmed when the sample is split by aggregated income groups (high vs. middle/low income countries). However, by considering six different geographical regions separately, it is observed that only for Europe and North America the parameter on the density variable is significantly negative. In line with the "O-Ring theory", the evidence presented by Ferrarini and Scaramozzino [20] supports the idea that, especially for advanced countries, it can be the case that the productivity-gains from more specialization are smaller than the associated productivity-losses due to increased complexity in production. Unlike Ferrarini and Scaramozzino [20], we focus solely on advanced (OECD) countries, employ a different econometric technique, and analyze how the balance between complexity and specialization (induced by input proliferation) contributes to affect not only the rate of economic growth, but also the joint long-run relation between population growth, economic growth, and markups.

Finally, by using a sample of Turkish manufacturing firms between 2003 and 2008, Maggioni et al. [42] study the link between complexity and volatility at the firm-level. Their main conclusion is that firms producing more complex goods (i.e., goods requiring a wider set of diverse and exclusive capabilities) enjoy higher output stability. Differently from Maggioni et al. [42], we employ here a macro-level perspective and focus on the role of product/country complexity on aggregate economic growth, rather than firms' output volatility. In this sense, our analysis offers a nice complement to Maggioni et al. [42]'s contribution.

3 The Model

3.1 Production and R&D technology

In this section, we present a version of Romer [52], with four relevant departures, concerning respectively: i) the shape of the aggregate production function; ii) the technology for producing intermediate inputs; iii) the production function of "ideas"; iv) the presence of a positive population growth rate. In what follows, we comment in more detail on these four differences.

We consider the following aggregate production function:

$$Y_t = L_{Yt}^{1-\alpha} \left[\frac{1}{N_t^{\beta}} \int_0^{N_t} (x_{it})^{1/m} di \right]^{\alpha m} \quad \text{with} \quad 0 < \alpha < 1 \quad \text{and} \quad m > 1 \tag{1}$$

This production function formalizes the idea (Aghion and Howitt, [3], Chap. 12, equation 12.4, p. 407) that:

"*. . . The productivity-enhancing effects of horizontal innovations are not [. . .] obvious. . . For while having more products definitely opens up more possibilities for specialization, and of having instruments more closely matched with a variety of needs, it also makes life more complicated and creates greater chance of error . . .* "

In equation (1), L_Y is the labor input employed in the production of the homogeneous final good (Y), x_i, with $i = 0 \dots N$, is the quantity of the *i-th* variety of differentiated capital goods/intermediate inputs, and m is a technological parameter. The elasticity of substitution between any generic pair of varieties of differentiated capital goods is given by $m/(m-1)$. A decrease in m, by increasing the substitutability between durables, leads to tougher competition across capital-goods producers and to lower prices. Thus, m can be used as a (inverse) measure of the degree of competition in the intermediate product market. In a moment, we show that m is, indeed, the optimal markup on the production marginal cost in the durables sector (see equation (5)). As a whole, the aggregate production function (1) displays constant returns to scale to private and rival inputs (L_Y and x_i) and, following Ethier [18] and Benassy [7], [8] and [9], allows disentangling the measure of product market concentration (m) from the factor-shares in GDP (α and 1-α).[8]

Depending on its magnitude, parameter β summarizes the different effects that innovation may have on GDP. In particular, when positive, β is meant to capture the detrimental effect on Y of having a larger number of intermediate-input varieties to be assembled in the same manufacturing process. This is the *complexity effect*. This effect contrasts with the traditional and positive *specialization effect* that is reflected by the upper bound of the integral within the square bracket of equation (1). Under symmetry - when $x_i = x > 0 \; \forall i \in [0, N]$ - and with $L_Y > 0$ and $N \in [0, \infty)$, equation (1) suggests that an increase in N may have either a positive (if $\beta < 1$, i.e. the *specialization effect* is larger than the *complexity effect*), or a negative (if $\beta > 1$, i.e. the *specialization effect* is lower than the *complexity effect*), or else no impact at all on aggregate output (if $\beta = 1$, i.e. the *specialization effect* is offset by the *complexity effect*).[9]

Using equation (1), it is possible to compute the inverse demand function for the *i-th* intermediate:

$$p_{it} = \alpha L_{Yt}^{1-\alpha} \left[\frac{1}{N_t^{\beta}} \int_0^{N_t} (x_{it})^{1/m} di \right]^{\alpha m - 1} \frac{1}{N_t^{\beta}} x_{it}^{\frac{1-m}{m}} \tag{2}$$

[8]Since final output is produced competitively under constant returns to scale to rival inputs, at equilibrium L_Y and x_i are rewarded according to their marginal productivities. Hence, for given N, $(1-\alpha)$ is the share of Y going to labor and α is the share of total GDP going to intermediate inputs. A more exhaustive and formal discussion of the relations between Ethier [18] and Benassy [7], [8] and [9] and the specification used in equation (1) above can be found in Bucci ([13], pp. 2027-2028).

[9]In equation (1) we observe that if $\beta < 0$, then there is no *complexity effect*, since this parameter would amplify the positive effect of specialization emerging from the upper bound of the integral inside the square bracket. *A fortiori*, this is also true when $\beta = 0$ (again, in this case we would end up with the sole, traditional *specialization-effect* in the square bracket). Therefore, in order to model explicitly a *complexity effect* arising from an increase of N, some positive β is needed. However, in what follows we do not make any *ad hoc* assumption on the magnitude of the upper bound of β.

The second difference with respect to Romer [52] is related to the technology for producing intermediates. In this regard, we postulate that monopolistically competitive firms have access to the same one-to-one technology employing solely labor as an input (as in Grossman and Helpman [23] Chap. 3):[10]

$$x_{it} = l_{it} \qquad \forall i \in [0, N_t] \qquad N_t \in [0, \infty) \tag{3}$$

where l_i is the amount of labor required in the production of the *i-th* durable, whose output is x_i. Thus, the marginal cost of production is the wage. For given N_t, equation (3) implies that the total amount of labor employed in the intermediate sector at time t, L_{It}, is given by:

$$\int_0^{N_t} x_{it} di = \int_0^{N_t} l_{it} di = L_{It} \tag{4}$$

Under the assumption that there exists no strategic interaction across intermediate firms, maximization of the generic *i-th* firm's instantaneous profit leads to the traditional markup rule:[11]

$$p_{it} = m w_{It} = m w_t = p_t \qquad \forall i \in [0; N_t] \tag{5}$$

This expression says that the price is the same for all intermediate goods i and equal to a constant markup (m) on the marginal production cost (w_t) - in a moment we explain why we use $w_{It} = w_t$.

Because of symmetry across producers of intermediate inputs (see equation (5)), equation (4) implies:

$$x_{it} = x_t = \frac{L_{It}}{N_t} \qquad \forall i \in [0; N_t] \tag{4'}$$

and therefore:

$$\pi_{it} = \alpha \left(\frac{m-1}{m}\right) \left(\frac{L_{Yt}}{N_t}\right)^{1-\alpha} \left(\frac{L_{It}}{N_t}\right)^{\alpha} N_t^{\alpha[m(1-\beta)-1]} = \pi_t \qquad \forall i \in [0; N_t] \tag{6}$$

The third difference with respect to Romer [52] is related to the aggregate R&D technology:

$$\dot{N}_t = \frac{1}{\chi} L_{Nt}^{\lambda} N_t^{\phi} \qquad \text{with} \;\; N(0) > 0, \; \chi > 0, \; 0 < \lambda \leq 1, \; \phi < 1 \tag{7}$$

where χ is a technological parameter, N_t is the number of ideas already invented and L_{Nt} is the labor input employed in research. In this model, labor (L) is employed to

[10] In the on-line Appendix C (not intended for publication), we formally show that our results would not qualitatively change if physical capital (instead of labor), accumulated through households' savings, is assumed to be the only input in the one-to-one technology for producing intermediates.

[11] More precisely, we assume that each of these firms is so small that it takes $\left[\frac{1}{N_t^{\beta}} \int_0^{N_t} (x_{it})^{1/m} di\right]^{\alpha m-1}$ as given, hence:

$$\frac{\partial}{\partial x_{it}} \left[\frac{1}{N_t^{\beta}} \int_0^{N_t} (x_{it})^{1/m} di\right]^{\alpha m-1} = 0$$

produce, respectively, consumption goods (L_Y), durables (L_I), and ideas (L_N). Since it is assumed to be perfectly mobile, at equilibrium labor will be rewarded according to a unique wage rate, i.e. $w_{Yt} \equiv w_{It} \equiv w_{Nt} \equiv w_t$.

The fourth and last difference we introduce in this model with respect to Romer [52] is that population grows at a positive, constant and exogenous rate, $\frac{\dot{L}_t}{L_t} \equiv n > 0$.[12] Equation (7) stems from the criticism of strong scale effect one may find in the first-generation of *Schumpeterian growth* models (see Jones [30], equation (6), p. 765; Jones [33], equation (16), p. 1074). In equation (7), λ and ϕ denote, respectively, the returns to the labor input employed in research and the intertemporal spillover coming from the accumulated stock of (disembodied) knowledge. When $\phi < 1$, higher values of N imply that the same amount of R&D resources (research labor) generates a lower growth rate of ideas, i.e. there exist diminishing technological opportunities. The presence of diminishing technological opportunities is key to the removal of the strong scale effect in the first-generation of R&D-based growth models: since the marginal impact of an individual researcher on the growth rate of new ideas decreases with the stock of existing ideas, it is possible to maintain a constant rate of innovation only by increasing (at a constant rate, too) the number of researchers. This, in turn, is possible solely if the economy's population grows at a positive rate. Since the R&D sector is competitive, i.e. N_t is endogenously determined by the free entry condition, the wage rate of one unit of research labor-input is given by:

$$w_{Nt} = \frac{1}{\chi} \frac{N_t^{\phi}}{L_{Nt}^{1-\lambda}} V_{Nt} \tag{8}$$

where

$$V_{Nt} = \int_t^{\infty} \pi_\tau e^{-\int_t^\tau r(s)ds} d\tau \qquad \forall \tau > t \tag{9}$$

In equations (8) and (9), V_N is the market value of the generic *i-th* blueprint, π is the instantaneous profit of the *i-th* intermediate firm, and r denotes the real rate of return on households' asset holdings (to be introduced in a moment).

3.2 Households

The number of infinitely lived households of this economy is constant and normalized to one. Hence, the size of population/labor-force coincides with the size of the single dynastic family (L), which supplies labor inelastically. The representative household uses savings (forgone consumption) to accumulate assets, taking the form of ownership claims on firms. Thus,

$$\dot{A}_t = (r_t A_t + w_t L_t) - C_t \qquad \text{with } A(0) > 0 \tag{10}$$

In equation (10), A, C and L denote, respectively, household's asset holdings, consumption and labor-input, w is the real wage and r is the real rate of return on A.[13] According to this equation, household's investment in assets (the LHS) equals

[12] We simplify further the analysis by assuming that the aggregate labor-force equals the total population. Under this assumption per capita and per-worker variables do coincide.

[13] Notice that, in this economy, all labor is employed and at equilibrium obtains the same wage, w.

household's savings (the RHS). In turn, household's savings are equal to the difference between household's income (the sum of interest income, rA, and labor income, wL) and household's consumption (C). Given the above expression, the law of motion of per capita assets is:

$$\dot{a}_t = (r_t - n)a_t + w_t - c_t \qquad \text{with } a(0) > 0 \tag{11}$$

with $a \equiv \frac{A}{L}$ and $c \equiv \frac{C}{L}$ representing per capita asset holdings and per capita consumption, respectively. With a constant inter-temporal elasticity of substitution (CIES) instantaneous utility function, the objective of the household is to maximize, under the usual budget constraint, the discounted utility of per capita consumption of all its members:

$$\begin{aligned} \max_{\{c_t, a_t\}_{t=0}^{t=\infty}} U \quad &\equiv \quad \int_0^\infty \left(\frac{c_t^{1-\theta} - 1}{1-\theta} \right) e^{-(\rho - n)t} dt \qquad (12) \\ \text{s.t.} \quad & \quad (11) \\ & \quad a(0) \text{ given} \end{aligned}$$

with $\theta > 0$. In equation (12) we have normalized population at time 0 to one, $L(0) = 1$. The representative dynastic family chooses the optimal path of per capita consumption and asset holdings $\{c_t, a_t\}_{t=0}^{t=\infty}$, taking the interest rate r_t and the wage rate w_t as given. As in Barro and Sala-i-Martin ([6], p. 207, footnote 1), the following assumption ensures that the attainable inter-temporal utility, U, is bounded and that the transversality condition holds.

Assumption 1 $\rho > n + (1 - \theta)\gamma$.

where ρ is the pure subjective discount rate, and $\gamma = \gamma_c$ is the per capita growth rate of the economy in a balanced growth path equilibrium (to be defined in a moment). The solution to this problem gives the usual Ramsey-Keynes rule:

$$\gamma_c \equiv \frac{\dot{c}_t}{c_t} = \frac{1}{\theta}(r_t - \rho) \tag{13}$$

3.3 The labor market

Since labor is fully employed and distributed across production of consumption goods, production of intermediates and invention of new ideas, at equilibrium the following equalities must hold:

$$L_{Yt} + L_{Nt} + L_{It} = L_t \tag{14}$$

$$w_{Yt} = w_{Nt} = w_{It} \equiv w_t \tag{15}$$

Equation (14) says that at equilibrium total supply (the RHS) and total demand (the LHS) of labor must be equal. In the model, labor is a homogeneous factor-input, i.e. it can be employed interchangeably in the three sectors of the economy. Thus, labor will continue to move across these sectors until wage equalization is attained (equation (15)). Moreover, in equilibrium, aggregate household's asset holdings (A) must equalize the aggregate value of firms:

$$A_t = N_t V_{Nt} \tag{16}$$

where V_{Nt} is given by equation (9), which can be differentiated to get the canonical no-arbitrage condition:

$$\dot{V}_{Nt} = r_t V_{Nt} - \pi_t \tag{17}$$

In the model, the *i-th* idea allows the *i-th* intermediate firm to produce the *i-th* variety of durables. This explains why in equation (16) total assets (A) amount to the number of profit-making intermediate firms (N) times the market value (V_N) of each of them (which, in turn, is equal to the market value of each corresponding idea). On the other hand, the no-arbitrage condition (17) suggests that the return on the value of the *i-th* intermediate firm $r_t V_{Nt}$ must equal to the sum of the instantaneous monopoly profit accruing to the *i-th* intermediate input producer (π) and the capital gain/loss matured on V_{Nt} during the small time interval dt (i.e., $\dot{V}_{Nt}$).

3.4 Equilibrium

In this economy, an *allocation* and an *equilibrium* are defined, respectively, as follows:

Definition 1 *An* allocation *is a time path for consumption levels and asset holdings* $\{c_t, a_t\}_{t=0}^{t=\infty}$*; a time path for the available number of intermediate input varieties* $\{N_t\}_{t=0}^{\infty}$*; a time path for prices and quantities of each intermediate good* $\{p_t, x_t\}_{t=0}^{\infty}$*; time paths for the real interest rate and wages* $\{r_t, w_t\}_{t=0}^{\infty}$.

Definition 2 *An* equilibrium *is an allocation in which:*

1. *the evolutions of consumption and asset holdings are consistent with the solutions of the households' problem (12);*
2. *the locally monopolistic firms maximize instantaneous profits (6);*
3. *the evolution of* $\{N_t\}_{t=0}^{\infty}$ *is determined by the free entry condition in the R&D sector;*
4. *the evolution of* $\{r_t, w_t\}_{t=0}^{\infty}$ *is consistent with market clearing.*

We can now move to a formal characterization of the *Balanced Growth Path* (BGP) of this model. In keeping with Barro and Sala-i-Martin ([6], p. 34, footnote 11) and Strulik ([55], p. 136), we define a BGP equilibrium as follows:

Definition 3 *A BGP equilibrium in this economy is an equilibrium-path along which:*

1. *all variables depending on time grow at constant exponential rates;*
2. *the sectoral shares of labor employment* ($s_j = \frac{L_{jt}}{L_t}$, *with* $j = Y, I, N$) *are constant.*

We can now state the following:

Proposition 1 *There exists a unique BGP equilibrium in which the per capita levels of output, consumption and asset holdings grow at the same constant rate.*
Proof. *See on-line Appendix A.*

Along the BGP equilibrium, the following results do hold:[14]

$$\frac{\dot{N}_t}{N_t} \equiv \gamma_N = \Psi n \tag{18}$$

$$\gamma_y \equiv \frac{\dot{y}_t}{y_t} = \gamma_c \equiv \frac{\dot{c}_t}{c_t} = \gamma_a \equiv \frac{\dot{a}_t}{a_t} = \Phi\Psi n \tag{19}$$

$$r = \theta\Phi\Psi n + \rho \tag{20}$$

where:

$$\Phi \equiv \alpha\left[m(1-\beta)-1\right] \gtreqless 0 \qquad \text{and} \qquad \Psi \equiv \left(\frac{\lambda}{1-\phi}\right) > 0$$

Equation (18) gives the BGP equilibrium growth rate of the economy's number of intermediate input varieties (N). According to equation (19), income (y), consumption (c) and asset holdings (a), all expressed in per capita terms, grow at the same constant rate in the BGP equilibrium. Equation (20) gives the BGP value of the real rate of return on asset holdings (r).

Notice that (as in any canonical R&D-based growth model) the BGP growth rate of per capita income is strictly related to the BGP innovation rate: $\gamma_y = \Phi\gamma_N$. In turn, as in the basic *semi-endogenous growth* model (Jones [30]), the innovation rate (γ_N) depends solely on the parameters of the innovation technology (λ and ϕ) and the population growth rate (n), and is independent of the markup (m) and the parameter measuring increasing complexity due to input proliferation (β).[15] However, through Φ, γ_y still depends on m and β. This implies that the degree of market power, the extent of complexity, and the interactions between the two do ultimately matter for the level of economic growth, and for the sign of the correlation between population growth and economic growth in the long-run. This is something that we do not find in the standard *semi-endogenous growth* model. In addition, from equations (18)-(20), it is evident that γ_N is always positive whereas r is positive, as long as Φ is sufficiently large, i.e. $\Phi > -\frac{\rho}{\theta\Psi n}$.

Instead, for γ_y to be positive, Φ needs to be strictly greater than zero, which implies that, in principle, we would restrict our attention to the case where $0 < \beta < \frac{m-1}{m} < 1$. In order to explain the economic rationale behind this condition, notice that an increase in the markup leads to a decrease in the elasticity of substitution

[14] In the on-line Appendix A (not intended for publication), we also compute the BGP allocations of labor across the final output, intermediate and research sectors and check for the respect of the transversality condition.

[15] While m and β do not affect γ_N in the BGP equilibrium, they still impact: (i) on the market value of any generic idea (V_N, equation (9)), through the instantaneous profit of intermediate firms (π_i, equation 6); (ii) on the wage (w_N, equation (8)) accruing to one unit of research labor-input, through V_N. As a consequence, m and β are able to influence the allocation, through wage-equalization, of the available labor-input across sectors (see equations (14) and (15)).

between any pair of varieties of differentiated intermediate inputs and, therefore, to weaker product market competition across capital-goods producers. This, in turn, and *ceteris paribus*, can command higher instantaneous profits in the intermediate sector (6),[16] higher market prices for new ideas (9), and ultimately greater incentives to expand further the set of available varieties of intermediate inputs (i.e., to increase N_t). It is possible to show that, along a BGP, the level of per capita GDP is:

$$y_t = \left(s_y^{1-\alpha} s_I^{\alpha}\right) N_t^{\alpha[m(1-\beta)-1]}$$

where s_Y and s_I are the constant shares of labor allocated in the long-run to the final output and intermediate sectors, respectively. It is apparent from the last expression that, following an increase in N_t, y_t can (all the rest remaining equal) also rise if $\beta < \frac{m-1}{m} < 1$. In other words, our theory suggests that along a BGP the economy's growth rate can be positive only if the *complexity effect* (as summarized by a positive value of β) is sufficiently low and, in any case, smaller than the corresponding *specialization effect*. This is compatible with the basic *semi-endogenous growth* model (see Jones [29]), where (intermediate-)input proliferation yields no *complexity* effect at all. However, since the main objective of the present paper is to study the macroeconomic (growth) effects of intermediate input-variety proliferation, in what follows we do not limit ourselves to the very restrictive case in which $0 < \beta < \frac{m-1}{m} < 1$. Instead we present the results of our model in their more general form without imposing any *ex ante* restriction on the magnitude of the upper bound of β.[17] These results are summarized in the following proposition.

Proposition 2 *Along the BGP we observe that:*

1. *Sign*$(\gamma_y) =$ *Sign*(Φ)*;*
2. *Sign* $\left(\frac{\partial \gamma_y}{\partial n}\right) =$ *Sign*(Φ)*;*
3. *Real per capita income growth is equal to zero in the absence of any population change (i.e., when $n = 0$);*
4. *Sign* $\left(\frac{\partial \gamma_y}{\partial m}\right)$ *depends on whether β is greater, smaller, or else equal to one.*

Proof. *The proof of the first part of the proposition is immediate when one takes into account that in the model $\Psi > 0$ and $n > 0$. To prove the second part of the*

[16] From equation (6), it is immediate to see that:

$$\frac{\partial \pi_i}{\partial m} = \left(\frac{\alpha}{m}\right)\left(\frac{L_Y}{N}\right)^{1-\alpha}\left(\frac{L_I}{N}\right)^{\alpha} N^{\alpha[m(1-\beta)-1]}\left[\left(\frac{1}{m}\right) + \alpha(m-1)(1-\beta)\ln N\right]$$

For given $\alpha \in (0,1)$, $m > 1$, $L_Y > 0$, $L_I > 0$ and $N > 0$, this derivative is clearly positive if the following (sufficient) conditions do hold: $\beta < 1$, $N \in [0, \infty)$ sufficiently large.

[17] As a matter of fact, in our regressions we deal with negative GDP growth rates, as well (see Table 3). In terms of our model, this is explained by the fact that in certain circumstances/countries, following the proliferation of varieties of the same employed intermediate input, the resulting productivity-losses due to increased complexity in production are sufficiently large (see our discussion at the end of section 2).

proposition, notice that: $\frac{\partial\gamma_y}{\partial n} = \Psi\Phi$. *To prove the third result, we observe that in equation (19)* $\gamma_y = 0$ *if* $n = 0$. *Equation (19) also implies that:*

$$\frac{\partial\gamma_y}{\partial m} \equiv \begin{cases} \Psi n\left[\alpha(1-\beta)\right] > 0 & \textit{if} \quad \beta < 1 \\ \Psi n\left[\alpha(1-\beta)\right] = 0 & \textit{if} \quad \beta = 1 \\ \Psi n\left[\alpha(1-\beta)\right] < 0 & \textit{if} \quad \beta > 1 \end{cases}$$

■

Using the definition of Φ and equation (19), we finally observe that:

- if $0 < \beta < \frac{m-1}{m}$, then: $\Phi > 0$, $\gamma_y > 0$, $\frac{\partial\gamma_y}{\partial n} > 0$ and $\frac{\partial\gamma_y}{\partial m} > 0$;
- if $\beta = \frac{m-1}{m}$, then: $\Phi = 0$, $\gamma_y = 0$, $\frac{\partial\gamma_y}{\partial n} = 0$ and $\frac{\partial\gamma_y}{\partial m} = 0$;
- if $\frac{m-1}{m} < \beta < 1$, then: $\Phi < 0$, $\gamma_y < 0$, $\frac{\partial\gamma_y}{\partial n} < 0$ and $\frac{\partial\gamma_y}{\partial m} > 0$;
- if $\beta = 1$, then: $\Phi < 0$, $\gamma_y < 0$, $\frac{\partial\gamma_y}{\partial n} < 0$ and $\frac{\partial\gamma_y}{\partial m} = 0$;
- if $\beta > 1$, then: $\Phi < 0$, $\gamma_y < 0$, $\frac{\partial\gamma_y}{\partial n} < 0$ and $\frac{\partial\gamma_y}{\partial m} < 0$.

Proposition 2 suggest that the impact of the intermediate sector's markup on real per capita growth crucially depends on the sign of $(1-\beta)$. If $\beta < 1$, the specialization gains obtained from an expansion in input variety are larger than the possible losses due to more complexity in production and $\frac{\partial\gamma_y}{\partial m} > 0$. If $\beta > 1$, the specialization gains are smaller than the possible losses due to more complexity in production and $\frac{\partial\gamma_y}{\partial m} < 0$. Finally, when $\beta = 1$, the specialization gains are offset by the possible losses due to more complexity in production and $\frac{\partial\gamma_y}{\partial m} = 0$. Therefore, a decrease in m, by increasing the elasticity of substitution across intermediate inputs and, hence, the toughness of competition in this industry, can imply a lower, or a higher, or else no effect at all on per capita income growth (PMC and economic growth are ambiguously correlated in sign in the model).

The result that, in the absence of demographic change, growth in real per capita income is equal to zero is a distinctive characteristic of any basic *semi-endogenous growth* models (see Jones [30]). Our setting, however, includes additional features that cannot be found in canonical *semi-endogenous growth* theory. In particular, the relation between γ_N and γ_y is mediated by the term $\Phi \equiv \alpha\left[m(1-\beta)-1\right]$, unlike Jones [30] (p. 767, equation (8)) where $\gamma_N = \gamma_y = \Psi n$. Thus, while in Jones [30] (p.780, equation (A1)) $\beta = 0$, and hence $\Phi \equiv \alpha(m-1) > 0$, in our model Φ can also be negative. This occurs, for any given $m > 1$, when β is sufficiently large, $\beta > (m-1)/m \in (0,1)$, i.e. when the *complexity effect* is strong enough (which can ultimately lead to negative growth rates of per capita income when the innovation activity expands). Moreover, since n affects positively γ_N (as in Jones [30]), an increase in the rate of population growth can also imply (when $\Phi < 0$, or with a *complexity effect* particularly strong) a negative impact on per capita income growth.[18]

[18] There is another trait that makes our model different from Jones [30]: in equation (19) the growth rate of the economy depends not only on n and, among others, the parameters ϕ, λ and β, but also on m. This specific difference with respect to Jones [30] can be ascribed to the fact that in our model we have:

4 Quantitative analysis

From the theoretical analysis developed in the previous section, we obtain that an economy's real per capita GDP (RGDP, hereafter) growth rate can be related with population growth and intermediate sector's markup, in one of the three ways reported in Table 1:

Table 1: Summary of the theoretical predictions

Case I	$0 < \beta < \frac{m-1}{m}$	$\frac{\partial \gamma_y}{\partial n} > 0$	$\frac{\partial \gamma_y}{\partial m} > 0$
Case II	$\frac{m-1}{m} \leq \beta \leq 1$	$\frac{\partial \gamma_y}{\partial n} \leq 0$	$\frac{\partial \gamma_y}{\partial m} \geq 0$
Case III	$\beta > 1$	$\frac{\partial \gamma_y}{\partial n} < 0$	$\frac{\partial \gamma_y}{\partial m} < 0$

The rest of the paper will confront these predictions with the data. In particular, we will estimate several models for equation (19). In doing this, we will abstract from $\Psi \equiv \frac{\lambda}{1-\phi}$. In fact, since this term must be positive, this choice entails, at most, an attenuation bias in our estimates.[19] Using our theoretical model as a guidance, the parameter estimates for population growth and the interaction between the latter and the intermediate sector markup let us infer which effect is predominant, between *complexity* and *specialization*.

Our results indicate that, on average, for the countries included in our sample, the *specialization effect* is larger than the corresponding *complexity effect*. In particular, when unobserved heterogeneity is taken into account, we document a positive role for population growth in economic development, which, through the lens of our theory, is ultimately due to a particularly strong *specialization effect*.[20] We proceed now by discussing the econometric strategy, then we illustrate the dataset and the main findings of our empirical analysis.

(i) postulated that intermediate firms produce with labor (rather than forgone consumption) and, more importantly, (ii) disentangled the intermediate firms' gross markup of price over the marginal production cost from the factor-input shares in GDP. It can be easily demonstrated that, using the Jones' assumptions, our model can exactly reproduce the BGP growth rate of the Jones' economy. See on-line Appendix B for further details.

[19]Omitting this multiplicative factor implies also that the coefficient associated to n, in the empirical counterpart of equation (19), is not expected to be lower than 1.

[20]This result substantially departs from that portion of the empirical literature on the topic, which finds either a general lack of or a negative correlation between population and economic growth rates (see Herzer et al. [27] and Li and Zhang [41] and Kelley and Schmidt [36] among others).

4.1 Econometric strategy

In this section, we estimate different models that are consistent with our theory. The econometric approach we follow allows to test the behavior of per capita GDP growth dynamics, under the assumption that unobserved heterogeneity affects parameters estimation. In particular, we employ a finite mixture model (FMM), relaxing the hypothesis of i.i.d. residuals (see Aitkin [4] and Alfò et al. [5], among others), and allowing for correlated random terms.[21] In such a model, the random component captures the impact of unobserved country-specific variables, limiting the effects of the omitted variable bias. FMM allows to deal with the unobserved heterogeneity due to the non-monotonic, non-uniform relationship between regressors and response, as predicted by our theory. Moreover, through this estimation procedure we are able to perform a cluster analysis: we sort countries into groups based on the homogeneity of the conditional distribution of their long-run growth rates with respect to the estimated unobservable factors.

According to the Generalized Linear Models framework (see McCullagh and Nelder [43]), the empirical counterpart of equation (19) can be written as:[22]

$$E(\gamma_{it}|n_{it}, m_{it}) = \mathbf{m_i}^\mathsf{T}\omega_{1i} + \mathbf{n_i}^\mathsf{T}\omega_{2i} \tag{21}$$

where $\gamma_{i,t}$ is the per worker GDP growth rate, $\mathbf{m_i}^\mathsf{T}$ is the vector of the annual products between intermediate sector's markup and population growth rate, $\mathbf{n_i}^\mathsf{T}$ is the vector of the annual population growth rates, for country i.[23] The parameters ω_{2i} and ω_{1i} capture the country-specific unobserved factors that affect per worker GDP growth, through population change and its interaction with the intermediate sector's markup.

Equation (21) entails a data generation process for per worker GDP growth that can be affected by some hidden factors, underlying the relationship between m_{it} and n_{it}. Conditionally to the regression parameters $\eta_i = [\omega_{1i}, \omega_{2i}, \sigma_i^2]^\mathsf{T}$, the probability density function of γ_{it} is given by:

$$f_{\gamma_i} = f(\gamma_{it}|\eta_i) = \prod_{t=1}^{T} \left\{ \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left[-\frac{1}{2\sigma_i^2} \left(\gamma_{it} - \omega_{1i}m_{it} - \omega_{2i}n_{it}\right)^2 \right] \right\} \tag{22}$$

We assume that parameters in η_i can be empirically described by random variables, with unspecified probability function, and cluster-specific variances σ_i. In this way, equation (22) takes explicitly into account the between countries random terms correlation.

[21] Assuming that some of the fundamental covariates were not included into the model specification, and that their joint effects can be accounted for by adding latent variables to the linear predictor, it is possible to relax the assumption of i.i.d. residuals (Aitkin [4], McLachlan and Peel [45]).

[22] It is worth noting that, in the FMM presented in this paragraph, we consider only two random components: population growth and its interaction with the intermediate sector's markup. The set of unobserved differences between countries is, however, potentially larger and multi-dimensional. Our approach, then, has the limit of representing a multi-dimensional phenomenon on a reduced dimensional scale. In order to tackle this issue, in section 4.4, we allow for a third random component.

[23] In this section, for notational simplicity, we omit the subscript y on the per worker GDP growth rate γ.

The nonparametric maximum likelihood estimator (NPMLE) of the distribution is discrete (Laird [40], Heckman and Singer [26]), with a finite number of locations and masses. This implies that the country-specific latent variables are modeled as measures of the difference between country *i-th*'s covariates and their sample mean. We assume that γ_{it} is a conditionally independent realization of the potential per worker GDP growth, given the set of random factors, which varies over countries and accounts for both individual variation and dependence among country-specific rates of growth.

Let now $\mathbf{u}_i$ denote the set of the country-specific unobservable factors that affect m_{it} and n_{it}, i.e. $\mathbf{u}_i = [u_{\omega 1}^{\mathsf{T}}, u_{\omega 2}^{\mathsf{T}}]$. Treating the latent effects as nuisance parameters, and integrating them out, we obtain the following likelihood function:

$$L(\cdot) = \prod_{i=1}^{n} \left\{ \int_{\mathcal{U}} f_{\gamma_i} \mathrm{d}G(\eta) \right\} \tag{23}$$

where $\mathcal{U}$ is the support for the latent variables space $G(\mathbf{u})$, i.e. $\mathcal{U}$ is the discrete probability measure on the space η_i, with $k = 1, \ldots, K$ support points, each of them with probability $\pi_k = \pi_1, \ldots, \pi_K$ with $\sum_{k=1}^{K} \pi_k = 1$. McLachlan and Peel [45] stress that the mixture reduces to a simple homogenous regression when $\mathcal{U}$ degenerates in a single support point with probability $\pi_k = 1$. To avoid unbounded likelihood, we assume a constant variance across mixture components, $\sigma_i = \sigma$. By introducing an undefined random distribution of parameters, this specification allows to estimate unbiased coefficients for population growth and its interaction with intermediate sector's markup, conditional to the effects of additional unobserved environmental variables. Our goal is to find the best discretization of the conditional log likelihood, given the data generating process of the response variable (Dempster et al. [17], McLachlan and Krishnan [44], among others).

Equation (23) can be approximated by the sum of finite number (K) locations:

$$L(\cdot) = \prod_{i=1}^{I} \left\{ \sum_{k=1}^{K} f\left(\gamma_i \left| \mathbf{m}_i, \mathbf{n}_i, \mathbf{u}_k \right.\right) \pi_k \right\} = \prod_{i=1}^{I} \left\{ \sum_{k=1}^{K} [f_{ik} \pi_k] \right\} \tag{24}$$

where $f\left(\gamma_i \left| \mathbf{m}_i, \mathbf{n}_i, \mathbf{u}_k \right.\right) = f_{ik}$ denotes the response distribution in the *k-th* component of the finite mixture. Locations u_k and corresponding masses π_k (prior probabilities) represent unknown parameters while the optimal number of cluster K is estimated via penalized likelihood criteria. This implies that:

$$\frac{\partial \log[L(\eta)]}{\partial \eta} = \frac{\partial \ell(\eta)}{\partial \eta} = \sum_{i=1}^{n} \sum_{k=1}^{K} \left(\frac{\pi_k f_{ik}}{\sum\limits_{k=1}^{K} \pi_k f_{ik}} \right) \frac{\partial \log f_{ik}}{\partial \eta} = \sum_{i=1}^{n} \sum_{k=1}^{K} w_{ik} \frac{\partial \log f_{ik}}{\partial \eta} \tag{25}$$

where w_{ik} represents the posterior probability that the *i-th* unit comes from the *k-th* component of the mixture. The corresponding likelihood equations are weighted sums of those of an ordinary log-linear regression model, with weights w_{ik}. Solving these equations for a given set of weights, and updating the weights from the current parameter estimates, we define an Expectation Maximization (EM) algorithm (see, for instance, McLachlan and Peel [45], and Alfò et al. [5] for the computation of EM in growth context).

4.2 The data

In this section, we provide a description of our data and discuss the procedures adopted to merge information from different sources in a single dataset.

First, we get data on real per worker GDP growth, population growth and exchange rate (to convert all the monetary values in constant 2005 US$) from the Penn World Table database (PWT, hereafter).[24]

Second, in order to construct a measure for the markup in the intermediate sector[25], we use the EUKLEMS database, which collects data on output, productivity, employment (skilled and unskilled), physical capital at industry level, for all European Union member states and for five of the high developed countries (US, Japan, Korea, Canada and Australia) from 1970 to 2007.[26] At the lowest level of aggregation, data are collected for 72 industries according to the European NACE revision 1 classification. We proxy the intermediate sector with the sum of the following industries: *basic metals and fabricated metal; electrical and optical equipment; electricity; gas and water supply; machinery; other non-metallic mineral; rubber and plastics; textile, leather and footwear; transport and storage; transport equipment; wood and cork.*

Following Griffith et al. [22], we compute the markup index for the intermediate sector, of country i at time t, as follows:[27]

$$m_{it} = \frac{Value\ Added_{it}}{Total\ Labor\ Costs_{it} + Total\ Capital\ Costs_{it}} \tag{26}$$

where all variables are in nominal prices and are provided by EUKLEMS.[28] In our baseline regressions, m is an index set equal to 1 in the base year 1995.[29]

Third, in order to identify a country's underlying complexity in production, we use: i) the *Network Trade Index* (NTI) and ii) two alternative density measures, based on *Lafay's index* ($\tilde{\omega}_{LI}$) and *Balassa index* ($\tilde{\omega}_{BI}$). All the indexes are provided by Ferrarini and Scaramozzino [20].[30]

Our final dataset consists of a sample that includes 23 OECD countries (Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, The Netherlands, Poland, Portugal, Slovak, Slovenia, Spain, Sweden, United Kingdom and USA), with a time span ranging from

[24]Time span: 1970-2007, 2005 as reference year. For more information on the PWT see: http://www.rug.nl/ggdc/productivity/pwt/.

[25]There exist several methods to measure markups. See Nekarda and Ramey [46] for a review.

[26]For more information on the EUKLEMS database see: http://www.euklems.net/.

[27]Griffith et al. [22] point out that this approach is equivalent to that proposed by Roeger [51]. See Klette [37] for a discussion.

[28]For details see Timmer et al. [56].

[29]Results with alternative measures for sector profitability are discussed in section 4.4.

[30]See the on-line Appendix D.

1970 to 2007. Table 2 presents summary statistics. Table 3 shows that all countries in the sample experienced a positive average per capita RGDP growth rate along the period under observation. Since we are dealing with OECD countries, this is not surprising. It is worth noting, however, that, the sample contains also observations in which the 5-year average per capita RGDP growth rate is negative.

4.3 Results

Table 4 provides the estimation results for equation (21). Since the variation in growth rates at annual frequencies may give misleading insights about the longer-term growth process, we use the 5-year average per capita RGDP growth rate as dependent variable.[31]

Columns (1) and (2) report OLS fixed effects and Feasible GLS estimates, respectively. In the OLS fixed effects model, inference is biased because of the residuals' non-normality (i.e., the Shapiro-Wilk test rejects the normality hypothesis with a value 0.988 and a p-value=0.000) and the estimates are not statistically significant. The FGLS model allows for heterogeneous variance in the residuals and takes into account the possible correlation between the covariates. The estimated parameters are consistent with our theory; in particular, the marginal effects on per capita RGDP growth of population change (-0.4341) and intermediate sector's markup (0.0072) suggest that, on average, the *specialization effect* is slightly greater than the *complexity effect* (Case II).

Columns (3), (4), (5) and (6) report the Finite Mixture Model (FMM) estimates, in which we relax the assumption of global normality of the residuals. Using the AIC, we identify four clusters of countries, i.e. $K = 4$ in equations (24) and (25), listed along with summary statistics for n and m and complexity indexes in Table 5.[32] The Shapiro-Wilk normality test on the residuals had p-value=0.987 in cluster 1, 0.032 in cluster 2, 0.245 in cluster 3, and 0.750 in cluster 4. The marginal effect of the population growth rate is always tiny but positive and significant: an increase of 1% in the population growth rate is associated to an increase in the long-run per capita RGDP growth of 0.0176% in cluster 1, 0.0734% in cluster 2, 0.0214% in cluster 3 and 0.0420% in cluster 4. Instead, the impact of the intermediate sector's markup is found to be very close to zero for all the clusters, being tiny negative in the first two clusters, tiny positive in cluster 4 and non-significant in cluster 3. This suggests that countries in cluster 4 have performed in a way consistent with our theoretical Case I while countries in cluster 1 and cluster 2, in which $d\gamma_y/dn \approx 0$ and $d\gamma_y/dm \approx 0$, lay in between our theoretical Case I and II. Focusing on the average characteristics of the clusters, it emerges immediately that the positive impact of population dynamics on long-run growth decreases with the (average) population growth rate and increases with the complexity in production, proxied by Network Trade Index and the density indexes.

[31]Per capita RGDP is computed using the expenditure-side RGDP at chained PPP and population, provided by the PWT.

[32]Complexity indexes are reported to allow a full comprehension of our results. However, they are not used as a means of cluster characterization.

4.4 Robustness checks

This subsection checks the robustness of our empirical results.[33]

Alternative specifications. In order to improve the soundness of our econometric exercise, we estimate the FMM by adding a random intercept, which allows to capture country specific unobserved factors. This innovation strengthens the results of the baseline FMM. We obtain a better global fit: Figure 1 overlays the empirical density function of γ_y, obtained via FMM, with intercept (left graph) and without intercept (right graph), to that corresponding to observed data. We find again four clusters of countries which differ, in their composition, from those obtained in the previous model. Results are provided in Table 6. In two clusters, despite the presence of a third random component, both population change and intermediate sector's markup still exhibit a positive and significant impact on long-run growth. This is consistent with the theoretical Case I. In cluster 1, composed by Ireland and Poland, $d\gamma_y/dn$=0.512 and $d\gamma_y/dm$=0.010 while in cluster 2, composed by Greece, Portugal and Spain, $d\gamma_y/dn$=1.282 and $d\gamma_y/dm$=0.026. Similar effects are also found for countries in cluster 3 (Belgium, Canada, Czech Republic, Denmark, France, Germany, Netherlands, United States). In this case, however, only the intercept is significant, i.e. country variability is captured by country specific latent effect rather than n and its interaction with m.

RGDP growth rate. First, we examine whether our results are sensitive to different measures of RGDP growth rate. We run our regressions using the 5-year average real per worker GDP growth rate as dependent variable, computed using the expenditure-side RGDP at chained PPP ($\texttt{rgdp}^e$) and the number of persons engaged (`emp`), provided by the PWT. Alternatively, we employ the rate of change of the RGDP using national-accounts growth rates ($\texttt{rgdp}^{na}$) and the `GDP per worker growth` provided by the World Bank. Although some modifications occur in the composition of the clusters, our results do not change significantly. In particular, the FMM still identifies four clusters of countries in which the marginal effect of population growth on per capita RGDP growth is slightly positive.

Markups. Several robustness checks are carried out for the intermediate sector's markup. As usual, when dealing with index numbers, results can be dependent on the base year. We use an alternative base year, the 1985, and we don't find any significant change in our estimates.

We also apply the procedure proposed by Roeger [51] to tackle the issue of the empirical measurement of the markups. In particular, assuming the markup constant over the period under observation, for each country, we run the following regression:

$$SR_t - SRP_t = \left(1 - \frac{1}{\tilde{m}}\right)\left[(\Delta p_t + \Delta Q_t - u_t) + (\Delta r_t + \Delta K_t - v_t)\right] \tag{27}$$

where: $(SR_t - SRP_t)$ is the difference between the Solow residual and the price-based Solow residual, $\tilde{m}$ is the intermediate sector's markup, $(\Delta p_t + \Delta Q_t)$ is the nominal output growth, $(\Delta r_t + \Delta K_t)$ is the growth of capital cost. Both capital costs and nominal output are measured with error, with $v_t \sim i.i.d.(0, \sigma_v)$ and $u_t \sim$

[33] As our results are robust to the alternative specifications used, for the sake of brevity we do not present and discuss in detail all the parameters estimates. Of course, they are available upon request.

$i.i.d.(0, \sigma_u)$.[34] Estimates for $\tilde{m}$ are presented in Table 7 in the on-line Appendix E. Because of the lack of time variability of $\tilde{m}$, using this estimated markup, rather than the index computed using equation (26), implies less accurate estimates (with p-values<0.1). Parameters and marginal effects, however, are in line with those presented in the previous section. As a final exercise, we regress the sample mean of per capita RGDP growth rate on the sample mean of population growth rate and the interaction between the latter and the estimated markup $\tilde{m}$. In this case, we quantify the marginal effect of n on long-run growth as 3.928 (p-value=0.000).

Human capital. Following to Bucci [14], we estimate a version of the model in which the growth rate of the human capital (measured by the `hc` index provided by PWT) replaces the growth rate of population. Qualitatively, our results do not change. Estimates, however, are less accurate. Via FMM, we identify two (of four) clusters of countries for which the the marginal effects $d\gamma_y/dn$ and $d\gamma_y/dm$ are consistent with the theoretical Case I.

5 Concluding remarks

This paper has re-assessed how the changing degree of production complexity (i.e., the number of horizontally-differentiated intermediate inputs entering the same aggregate production function of a country) can ultimately affect not only the long-run growth rate of per worker income, but also the relation between the latter variable, population growth, and the degree of product market competition (PMC). Building upon Romer [52] and Jones [29] we developed a variant of the basic well-known *semi-endogenous growth* model capable of explaining why we may observe (as suggested by the already available empirical evidence) a non-uniform correlation between population growth/economic growth and between economic growth/markups. The theoretical explanation offered by our model is based on the idea that introducing new varieties of intermediate inputs generates a tension between productivity-gains due to more specialization and productivity-losses due to the presence of a more complex production process. The composition of these two differential effects of technological progress represents in the model the basis for the occurrence of a potentially non-monotonous correlation between population growth/economic growth and between PMC/economic growth.

The empirical analysis presented in the second part of the paper has suggested that a different degree of production complexity yields in the long-run a different growth rate of per worker output and, more importantly, a diverse impact of, respectively, population growth and product market competition on economic growth. In particular, using the 5-year average RGDP growth rate as a dependent variable, we have documented that the *specialization effect* is larger than the corresponding *complexity effect*. In the OLS and FGLS models, we obtain a slightly negative - but not statistically significant - impact of population growth on long-run growth. In the Finite Mixture Model with two random components, the marginal effect of population dynamics on long-run growth becomes slightly positive, ranging from 0.0176 to

[34] Christopoulou and Vermeulen [16] apply the same empirical strategy to estimate price-marginal cost ratios for 50 sectors in eight Euro area countries and the US over the period 1981-2004.

0.0734. The model allows to identify four clusters of countries and show that a higher complexity in production, here captured by a variety of indexes (the *Network Trade Index* and the density measure based on the *Layay Index* and the *Balassa Index*), is associated to a larger impact of the population growth rate on the 5-year average RGDP growth. Moreover, adding a third random component in the Finite Mixture Model strengthens the role of population dynamics in two clusters.

In conclusion, our results tell a very consistent story: on average, along the period 1970-2007, the countries included in our sample display specialization gains from innovation that more than compensate the losses due to more complexity in production.

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Table 2: Summary statistics

Variable	Description	Obs.	Mean	Std. dev.	Min	Max
m	intermediate sector's markup index (1995=1)	610	1.244	0.684	0.536	5.374
n	annual population growth rate	610	2.430	2.187	-1.291	8.918
γ_c	5-year avg. per capita RGDP growth rate	610	12.973	9.425	-20.258	46.830
γ_w	5-year avg. per worker RGDP growth rate	610	13.795	10.258	-9.836	76.160
NTI	Net Trade Index	432	0.214	0.224	0	1
$\tilde{\omega}_{BI}$	Balassa's index based product density	483	0.436	0.249	0	1
$\tilde{\omega}_{LI}$	Lafay's index based product density	483	0.456	0.203	0	1

Table 3: Descriptive statistic on 5-year average per capita RGDP growth rate

Country	Min	Mean	Max
Australia	1.005	10.669	18.647
Austria	0.965	13.650	27.136
Belgium	-13.283	11.172	26.152
Canada	-2.281	10.727	20.689
Czech Republic	-10.585	9.187	21.282
Denmark	-1.576	9.224	23.524
Finland	-11.393	11.676	33.294
France	-8.735	9.204	23.231
Germany	-3.247	12.021	25.554
Greece	12.619	18.116	23.081
Hungary	7.769	16.723	25.687
Ireland	13.528	27.762	46.830
Italy	-4.953	13.442	31.526
Japan	-3.337	13.726	37.062
Netherlands	-4.457	11.512	30.814
Poland	11.609	24.690	37.718
Portugal	-6.621	15.532	40.180
Slovak Republic	-20.258	11.600	32.167
Slovenia	-2.423	13.750	23.627
Spain	-15.644	14.560	34.722
Sweden	-1.808	10.994	24.456
United Kingdom	1.839	13.451	28.182
United States	1.652	10.354	17.671

Table 4: Results, country level data

	(1) **OLSFE**	(2) **FGLS**	(3) **FMM**$_{k=1}$	(4) **FMM**$_{k=2}$	(5) **FMM**$_{k=3}$	(6) **FMM**$_{k=4}$
	Dependent variable: 5-years per capita RGDP growth rate					
$m*n$	0.121	0.319	-0.005**	-0.023**	-0.012	0.005
n	-0.669	-0.846**	0.023***	0.100***	0.044***	0.035***
constant	0.142***	0.135***				
$\frac{\partial \gamma_y}{\partial n}$	-0.5125	-0.4341	0.0176***	0.0734***	0.0214***	0.0420***
$\frac{\partial \gamma_y}{\partial m}$	0.0027	0.0072	-0.0003***	-0.0002***	-0.0003	0.0001**
obs.	597	597	94	175	154	187

Significance levels: : 10% **: 5% ***: 1%.*

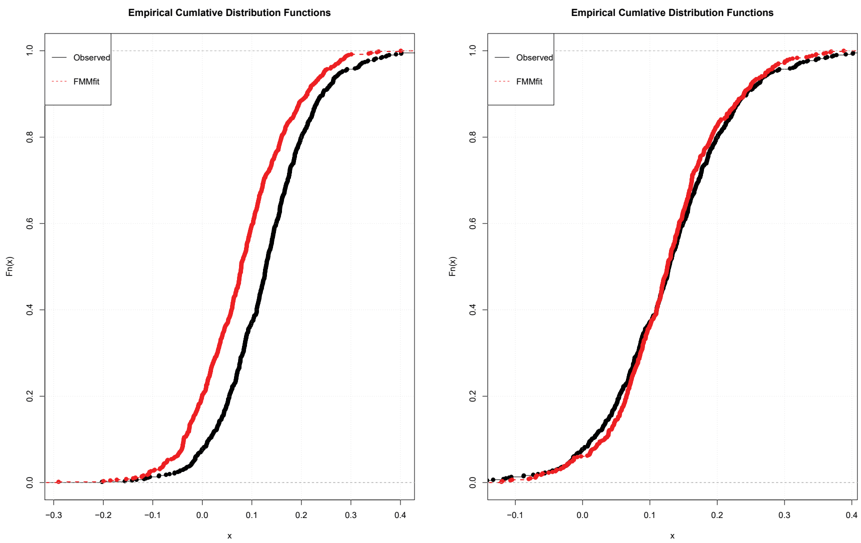

Figure 1: Empirical cumulative functions for FMM in Table 4 (left panel) and FMM in Table 6 (right panel)

Table 5: FMM, Clusters

Country	n	m	NTI	$\tilde{\omega}_{LI}$	$\tilde{\omega}_{BI}$
			Cluster 1		
Australia	6.602	1.359	0.051	0.255	0.166
Canada	5.595	0.920	0.077	0.384	0.336
United States	5.008	0.962	0.587	0.658	0.806
mean	5.735	1.081	0.239	0.432	0.436
std. dev.	0.658	0.198	0.247	0.168	0.270
			Cluster 2		
Austria	1.358	1.189	0.186	0.423	0.489
Belgium	1.089	1.443	.	0.508	0.366
Denmark	1.274	1.405	0.093	0.468	0.461
Germany	0.760	0.911	1.000	0.659	0.724
Slovenia	1.154	1.067	0.120	0.380	0.334
United Kingdom	1.119	0.918	0.228	0.739	0.852
mean	1.126	1.155	0.325	0.530	0.538
std. dev.	0.206	0.232	0.381	0.140	0.206
			Cluster 3		
Hungary	-0.454	2.059	0.153	0.408	0.259
Ireland	4.711	0.927	0.032	0.197	0.155
Italy	1.240	0.827	0.407	0.814	0.745
Poland	2.168	3.322	0.179	0.530	0.403
Portugal	2.651	1.114	0.063	0.281	0.224
Slovak Republic	1.576	3.488	0.124	0.431	0.243
Spain	3.434	1.448	0.202	0.543	0.554
mean	2.190	1.883	0.166	0.458	0.369
std. dev.	1.653	1.117	0.122	0.201	0.213
			Cluster 4		
Czech Republic	-0.110	1.392	0.203	0.747	0.804
Finland	1.843	0.922	0.120	0.196	0.163
France	2.648	1.623	0.415	0.715	0.802
Greece	3.502	2.197	0.017	0.242	0.242
Japan	2.579	0.903	0.518	0.653	0.833
Netherlands	3.165	1.513	0.173	0.415	0.429
Sweden	1.640	1.278	0.179	0.344	0.365
mean	2.181	1.404	0.232	0.473	0.520
std. dev.	1.207	0.445	0.174	0.230	0.287

Note: Model with 5-year avg. per capita RGDP growth rate as dependent variable.

Table 6: Robustness I: FMM with 3 random components

	(1) **FMM**$_{k=1}$	**(2)** **FMM**$_{k=2}$	**(3)** **FMM**$_{k=3}$	**(4)** **FMM**$_{k=4}$
	Dependent variable: 5-years per capita RGDP			
$m * n$	0.293***	0.829*	0.637	-0.709
n	-0.110***	-0.033***	-0.369	0.419
constant	0.293***	0.223***	0.099***	0.133***
$\frac{\partial \gamma_y}{\partial n}$	0.512***	1.282***	0.441	-0.574
$\frac{\partial \gamma_y}{\partial m}$	0.010***	0.026***	0.015	-0.013
obs.	192	88	268	31

Significance levels: : 10% **: 5% ***: 1%.*

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