Investment-Specific Technological Change, Investment Sectoral Allocation and Human Capital Accumulation in a Model of Export-Led Growth

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Abstract: This paper contributes to the literature on economic growth by seeking to join several lines of research on structural factors in a more fully specified framework, on the one hand, and by making this more inclusive supply side to interact with demand factors in a model of export-led growth. Balance-of-payments constraints influence the adoption of investment-specific technological change which requires the import of capital goods, while the sectoral allocation of physical and human capital is likewise revealead to be crucial for growth, both results having important policy implications.

Keywords: embodied technological change; sectoral allocation of investment; human capital accumulation; export-led growth.

Resumo: O artigo contribui para a literatura sobre crescimento econômico por meio da combinação de várias linhas de pesquisa sobre fatores estruturais em um arcabouço mais plenamente especificado, por um lado, e da análise da interação dessa especificação mais inclusiva do lado da oferta com fatores de demanda em um modelo de crescimento liderado pelas exportações. Restrições de balanço de pagamentos influenciam a adoção de mudança técnica investimento-específica que requerem importação de bens de capital, enquanto a alocação setorial dos estoques de capital físico e humano igualmente se revela crucial para o crescimento, resultados que têm importantes implicações em termos de política.

Palavras-chave: mudança técnica embutida; alocação setorial do investimento; acumulação de capital humano; crescimento liderado pelas exportações.

Classificação JEL: O11; O33; O41.

Classificação Anpec: Área 5 - Crescimento, Desenvolvimento Econômico e Instituições.

1. Introduction

There has been considerable empirical and theoretical research devoted to the study of models that seek to enhance our understanding of the mechanisms that influence economic growth, though not many of them explore how demand and supply forces interact to determine growth performance. There is also plenty of empirical evidence that technological change comes largely in the form of advances in the manner that capital is produced. Arguably, technological innovation leads to some development of new types or vintages of capital, and this development is actually an important engine of growth. This technological change embodied in the form of new equipment represents phenomena such as advances in computer technology, robotization of assembly lines, faster and more efficient means of telecommunications, and so on. Meanwhile, investment allocation plays quite crucial a role in harvesting the benefits of investment-specific, capital-embodied, technical change, with human capital allocation in turn mattering for technological adoption and diffusion as well. Indeed, the adoption of embodied technical change is likely to require specific human capital in addition to physical capital, and an increase in skilled labor facilitates the adoption of new technologies (Greenwood & Yorukoglu 1997).

This paper makes an innovative contribution to the literature on growth dynamics in two distinct respects. First, it seeks to join these lines of theoretical and empirical research on structural factors (to wit, investment-specific technological change and accumulation and allocation of both physical and human capital) in a model framework which is more inclusive and fully specified as far as the supply side is concerned. In this sense, this paper is an innovative step in the direction of uniting the literatures on physical and human capital allocation with the original findings of Greenwood, Hercowitz & Krusell (1997), as well as of a number of subsequent contributions reported in the following section, that investment-specific technological change is a considerable force in explaining the observed growth rates. Second, this more fully specified supply side is made to interact with demand factors in a dynamic model of export-led growth, so that this paper is also an innovative step in the direction of furthering the understanding of the supply constraints to such a demand-driven growth strategy. Intended primarily as it is to gain further analytical understanding of the several constraints on growth, the underlying presumption of this paper is that there are sizeable increasing returns, on both theoretical and empirical grounds, to greater cross-fertilization among these lines of research on investment-specific technological change, accumulation and allocation of physical and human capital and export-led growth.

Indeed, recent advances in the theory of endogenous technological progress have led to renewed interest in the relation between international trade, technical change, human capital and economic growth. Grossman & Helpman (1991) developed an early theoretical articulation of the view that technological progress is the main engine of growth and that international trade is a vehicle for technological diffusion. Similarly, in the structural economic dynamics approach developed by Pasinetti (1993), which nonetheless has a distinctively classical pedigree, the primary source of international gains is mobility of knowledge, it being international learning – of outside methods of production – that can therefore be claimed to represent the primary source of international gains.

Several empirical studies have identified channels through which national productivity levels are interrelated, emphasizing the role of international trade. Coe & Helpman (1995) and Keller (1998), for example, consider foreign trade as a carrier of knowledge and assess the importance of imports in introducing foreign technology into domestic production and spurring total factor productivity. The claim is that a country that is more open to machinery and equipment imports derives a larger benefit from foreign research and development, it being show empirically that countries that have experienced faster growth in total factor productivity have imported more from the world's technology leaders.

Meanwhile, a similar reasoning underlies Benhabib & Spiegel (1994), who focus on the role of human capital in economic development and interpret cross-country differences in the level of human capital as differences in technology. The results of their growth-accounting exercise suggest that the role of human capital in economic growth is one of facilitating the adoption of technology from abroad and the creation of appropriate domestic technology. This clearly contrasts with studies based on the human-capital-augmented Solow model (such as in Mankiw, Romer & Weil 1992), which treat human capital as a separate factor of production. Mayer (2001) combines these two strands of the literature (to wit, foreign trade as a carrier of knowledge and role of human capital in economic growth as one of facilitating the adoption of technology) to investigate empirically technology transfer to developing countries and its contribution to economic growth. In this sense, the paper highlights the importance of trade as a vehicle for technological spillovers and attempts to trace the combined role of human capital and technology diffusion in growth. The results of the growth-accounting exercise for a sample of 53 developing countries relating productivity differences to differences in the stock of human capital and machinery imports suggest a positive and statistically strongly significant impact of the combination of machinery imports and the stock of human capital on growth during the transition to the steady state. This impact is most significant when general-purpose machinery imports are combined with that part of the labor force which has a high level of education. An important implication of this finding is therefore that the role of human capital in economic growth is best described as affecting the speed of technological adoption from abroad and hence productivity, rather than as being an independent factor of production.

However, balance-of-payments constraints also influence the adoption of investment-specific technological change: if technological progress is embodied in capital goods, the ability of underdeveloped countries to absorb foreign technological innovation relies on the possibility of import capital goods that are not domestically produced. As a result, the paramount importance of exports as a component of demand is that it happens to be the only component that can generate the foreign exchange to pay for the import content of other components of demand such as investment (Thirlwall 1997). This is therefore yet another reason for net exports to feature prominently in the demand side of the model developed in this paper.

Meanwhile, findings such as that by Collechia & Schreyer (2002) show that not only the investment but also its allocation play an important role in harvesting the benefits of technological change (especially information and communication technologies) embodied in capital goods. That investment allocation plays a central role in the development process is not a novelty, though. Several authors such as Bose (1968), Weitzman (1971), Araujo and Teixeira (2002) and Araujo (2004), drawing upon the seminal contribution of Feldman (1928), have shown that decisions regarding investment allocation determines the growth rate of output in a closed economy. In this sense, Feldman's approach may be useful to shed light on the contemporary process of economic growth of developing countries. This model is widely used as a benchmark to study the effects of the investment allocation on economic growth but one of its limitations is not take into account technological progress.[1] For this reason it may not be considered to properly deal with the contemporary process of economic growth that relies heavily on technological progress.

In this paper we extend Feldman's contribution by incorporating investment specific technological change and human capital into a four sector model in which supply and demand interact to endogenously determine growth. As it turns out, the model developed here is a step in the direction of furthering the understanding of the role played by both the allocation and accumulation of physical and human capital in a growth dynamics whose main engine is technological change.

The remainder of the paper is organized as follows. Section 2 provides a review of the theoretical and empirical literature on investment-specific technological change, while Section 3 describes the workings of the supply side of the model. The export demand side is described in Section 4, followed then by a discussion of a variety of theoretical, empirical and policy implications that can be drawn from the growth dynamics implied by model. The closing section summarizes the main conclusions derived along the way.

2. Related literature on investment-specific technological change

Technical change embodied in the form of new equipment represents phenomena such as advances in computer technology, robotization of assembly lines, faster and more efficient means of telecommunications, and so on. Given the sector-specific nature of this type of technological change, the relative price of new equipment can be used to identify the stochastic process driving the technological change. This type of technological innovation is different from the usual changes in total factor productivity in which capital of different generations is thought of as being the same type of good, or having the same cost as previous vintages of capital (i.e. as measured in units of the consumption good). In case it is found that investment-specific technological change accounts for a considerable fraction of total growth in total factor productivity, it is suggested an important role for investment in spurring productivity growth above and beyond its traditional role of capital deepening.

Greenwood, Hercowitz & Krusell (1997) investigate the role that investment-specific (or capital-embodied) technological change played in generating postwar U.S. growth, the premise being that the introduction of new, more efficient capital goods is an important source of productivity change. The authors claim that the traditional growth accounting is conceptually flawed and severely understates the importance of technological progress embodied in new capital goods for explaining growth, and develop an alternative framework centred round the concepts of ''neutral technological change'' and ''investment-specific technological change''. Revealingly, their empirical exercise suggests that it is falling real prices for new investment goods associated with investment-specific technical change that accounts for most of the observed postwar U.S. growth, with relatively little being left over to be explained by other factors, such as total factor productivity. More precisely, capital-embodied technical change explains close to 60% of

[1] As pointed out by Araujo (2004), "[o]ne of the characteristics of this [Feldman's] model is that it does not take into account neither exogenous nor endogenous technical progress. For this reason, it might be possible to think that this model is not appropriate to explain properly the contemporary process of economic growth, which relies heavily on technical progress".

the growth in output per hours worked, with residual, neutral productivity change then accounting for the remaining 40%. Besides, the authors decompose this 60% figure into a direct effect (the increasing quality of given flows of investment in consumption units) and an indirect effect (the stimulus for further investment in consumption units). They obtain that the direct effect can be accounted responsible for 38% of labor productivity growth in the 1947-1994 period, while the remaining 22% (adding up to 60%) can be explained by the indirect effect.

Hercowitz (1998), meanwhile, reviews the so-called ‘embodiment’ controversy between Jorgenson and Solow in the 1960s centered on the importance of capital-embodied (or, in more recent parlance, investment-specific) technological change. While disembodied technological change affects output growth independently of capital accumulation, embodied technological change requires investment to do so. Solow (1960) claims that the latter is dominant, which implies that investment is the key transmission mechanism of technological change to output growth, while Jorgenson (1966) replies that from the data available then, one could not obtain an answer regarding the relative importance of both forms of technological change. In this context, the main conclusion obtained in Greenwood, Hercowitz & Krusell (1997) is that embodiment is the main transmission mechanism of technological progress to economic growth.

Earlier on, and from a keynesian perspective, Kaldor (1957) had introduced the idea of a technical progress function relating the rate of growth of output per worker to the rate of growth of capital per worker. Kaldor claimed that it is not possible to distinguish, at least empirically, between movements along a production function (the substitution of capital for labor) and movements in the whole function due to technical progress, as the one implies the other. In other words, there cannot be capital deepening without some technical progress embodied in the new capital, and most new ideas need capital accumulation for their embodiment. Hence the shape of the technical progress function depends on the degree to which capital accumulation embodies new techniques which improve labor productivity.

Greenwood, Hercowitz & Krusell (2000), meanwhile, investigate the role that investment-specific technical change plays in generating business-cycle fluctuations. As in Greenwood, Hercowitz & Krusell (1997), the analysis is motivated by the negative comovement between the relative price of new equipment and equipment investment, an evidence that suggests that capital-embodied technological change, by triggering equipment investment, may be a source not only of long-term growth, but also of economic fluctuations. However, the quantitative exercise carried out in Greenwood, Hercowitz & Krusell (2000) for the U.S. economy in the 1954-1990 period reveals that investment-specific technological change contributed relatively less to the business cycle than to long-term growth (about 30% as compared to 60%).

On the theoretical front, while Greenwood, Hercowitz & Krusell (1997, 2000) do not explicitly model the mechanism by which the real price of capital falls, Krusell (1998) develops an early model in which the price of capital falls due to some endogenous R&D. In the same vein, Huffman (2007) develops an alternative model in which the changing real price of capital is driven by endogenous research spending. The paper examines a model in which growth takes place through investment-specific technical change, which in turn is determined endogenously through research spending. It is shown that the degree of substitutability between research spending and new capital construction is explored plays an important role in conditioning the main results of the model. Hendricks (2000), meanwhile, develops a model of growth through technology adoption featuring the complementarity between technologies, which are embodied in capital goods, and skills that are in turn embodied in workers. Learning by workers and technological adoption by firms are complementary in the sense that the level of available labor experience limits the sophistication of capital goods firms can use in production, while the capital vintages in use determine the rate of learning. The model successfully accounts for the major emprical relationships between growth rates, equipment investment shares and relative equipment prices detected in postwar U.S. data by the literature on investment-specific technological change. Boucekkine, del Río & Licandro (2003), in turn, develop a model in which investment-specific technical change is endogenous, relying on Arrowian learning-by-doing in both the consumption and the investment goods sectors. The relative efficiency of the learning process in both sectors determines the relative importance of embodied and disembodied technical change, so that the growth rate is a function of the composition of technological change.

Collechia & Schreyder (2002), meanwhile, aim at quantifying the contribution of information and communication technologies to output growth in the past two decades in the U.S. and in eight other OECD countries. They find that, despite differences between countries, the U.S. has not been alone in benefiting from the positive effects of capital investment in the form of information and communication technologies on economic growth. Besides, they find that diffusion and usage of information and communication technologies play a key role which depends on the right framework conditions, not necessarily on the existence of a large sector producing information and communication technologies. As it turns out, allocation of this kind of capital-embodied technological change matters. Generally, there is no discernible systematic relationship between the size of the industry producing information and communication technologies and the contribution of this kind of technical change to output growth. Indeed, although technical advances in information and communication technologies are available almost universally, the degree of uptake and use of them in production has varied across OECD countries. With broadly similar changes in relative prices, a question that arises is what explains this variation, and allocational differences emerge as a plausible explanation. Although it is likely that there are other reasons, differences in economic structure (for instance, different shares of industries producing, and intensive in, information and communication technologies) can arguably be seen as playing a role as explanatory factors behind differences in the uptake and diffusion of new technologies between OECD countries.

In the same vein, Cummins & Violante (2002) measure technical change at the asset, industry and aggregate level in the U.S. from 1947 to 2000 and find that technological improvement in equipment and software accounts for an important fraction of output growth and plays a key role in the productivity resurgence of the 1990s. More precisely, improvement in the quality of equipment and software explains about 20% of growth in the U.S. in the postwar period and about 30% of growth in the 1990s. Besides, they find that 60% of labor productivity growth in the postwar period comes from technological advances in equipment and software. The authors also measure for the aggregate economy and different sectors the ‘technological gap’, which is how much more productive new machines are compared to the average machine, and find that it has more than doubled in the last 20 years – from around 15% in 1975 to about 40% in 2000. What is revealing for the purpose of the model developed in this paper is that the technolical gap explains the dynamics investment in new technologies and the returns to human capital in a way which is consistent with the Nelson-Phelps conjecture. According to Nelson & Phelps (1966), the improvement of the average productivity of capital depends on the technological gap and on the ‘adaptable’ labor which defines human capital. Cummins & Violante (2002) estimate an adoption equation based on the Nelson-Phelps conjecture and find that the growth rate of average practice moves nearly one for one with the technological gap and is correlated with measures of adaptable labor such as the shares in the labor force of college graduates and of young workers.

Meanwhile, Sakellaris & Wilson (2004) estimate the rate of embodied technological change directly from plant-level manufacturing data on production, input and investment decisions along with histories on their vintages of equipment investiment, with the preferred estimate being 12% for the typical U.S. manufacturing plant during the years 1972-1996, with the contribution of embodied technological change to total technological change being about two thirds. This number is higher than what is conventionally accepted in the literature, and implies that the role of capital-embodied technological change as an engine of growth is likely even larger than previously estimated. Indeed, most of the empirical literature on embodiment, including the papers by Hulten (1992) and Greenwood, Hercowitz & Krusell (1997), has relied on an estimate of the rate of technological change that is embodied in equipment capital of about 3% for the years 1954 to 1990. Meanwhile, it is also far greater than the rate of 4% that Cummins & Violante (2002) estimate for U.S. from 1948 to 2000.

Bakhshi & Larsen (2005), in turn, use an adaptation of Greenwood, Hercowitz & Krusell (1997) and find that technological progress specific to the information and communication technology sector accounts for around 20-30% of long-run labor productivity growth in the United Kingdom. Besides, they also find that shocks to specific technical change in the form of information and communication technologies may contribute significantly to business cycle fluctuations, a result similar to that obtained in Greenwood, Hercowitz & Krusell (2000) for investment-specific technical change more generally.

Fisher (2006) develops a model to identify the short-run effects of neutral technological shocks, which affect the production of all goods homogeneously, and investment-specific shocks, which affect only investment goods. On the basis of the preferred specification, these two technology shocks account for 73% of hours’ and 44% of output’s business cycle variation in US from mid-1950s to 1982, and 38% and 80% from then to around 2000, with the majority of these effects being driven by investment shocks.

Nonetheless, Oulton (2007) argues that the concept of investment-specific technological change elaborated by Greenwood, Hercowitz & Krusell (1997, 2000) is rather closely related to the more familiar concept of total factor productivity. The authors disputes the claim by Greenwood, Hercowitz & Krusell (1997, 2000) to the effect that traditional growth accounting is conceptually flawed and severely understates the importance of technological progress embodied in new capital goods for explaining growth. To the contrary, Oulton (2007) intends to shows that in its technology aspects the basic model developed by Greenwood, Hercowitz & Krusell (1997) is a special case of the traditional growth accounting model. As it turns out, the contribution of investment-specific technological change to growth is about 1.5 larger in Greenwood, Hercowitz & Krusell (1997) than in Oulton (2007).

Greenwood & Krusell (2007) reply to Oulton (2007) by claiming that the measures used in traditional growth accounting to gauge the importance of investment-specific technological progress have little economic content, unlike the measure obtained from their approach. They argue that their structural approach is the preferred route to take for measuring the contribution of investment-specific technological progress to growth, the reason being that the measure advanced by this approach to gauge such contribution has a well-defined economic interpretation. More precisely, such measure uncovers the fraction of economic growth that results from investment-specific technological progress; i.e., the fraction of growth that would remain if other forms of technological progress were shut down. Traditional growth accounting, which takes a more structure-free approach, cannot answer this simple question for the following simple reason. Output growth derives from both technological advance and capital accumulation, with the latter being partly driven by technological progress. Hence, Greenwood & Krusell (2007) claim, in order to estimate the contribution of a particular form of technological progress to economic growth one must be able to make an inference about how much of capital accumulation was induced by this form of technological advance. Making such an attribution requires a complete structural model, and in the absence of such a model, traditional growth accounting resorts to ad hoc measures with little economic content. For Greenwood & Krusell (2007), Oulton (2007) in fact illustrates how a measure of embodiment can be obtained in a more standard manner. In either case, though, the traditional growth approach still fails to answer the most apropos question of how much of growth is accounted for by investment-specific technological progress. As economic growth derives from two basic sources (to wit, technological change and capital accumulation, with the latter resulting from the former), it is impossible to allocate capital accumulation across the underlying causal sources of technological advance without an economic model.

More recently, Ho (2008) used panel data relative to a sample of 4-digit U.S. manufacturing industries from 1974 to 1994 to examine the impact of investment-specific technological change on labor composition in U.S. manufacturing industries from 1974 to 1994. The author shows that investment-specific technological change increases the relative demand of non-production (skilled) workers to production workers, while total factor productivity growth does not change labor composition. Marquis & Trehan (2008), in turn, disputes the identification by Greenwood, Hercowitz and Krusell (1997, 2000) of the relative price of (new) capital with capital-specific technological change by claiming that, in a two-sector growth model, the relative price of capital equals the ratio of the productivity processes in the two sectors, though. Restrictions from this model are then used with data on wages and prices by Marquis & Trehan (2008) to construct measures of productivity growth and test the identification made by Greenwood, Hercowitz and Krusell (1997, 2000), which turns out to be strongly rejected by the data. In case this result proves correct, it may imply that the relative price of capital cannot be used in isolation to draw inferences about the contribution of capital-specific technical change to either economic growth or to output fluctuations.

3. Production structure and aggregate supply

Let us assume that the economy is divided in two groups of sectors: the first is a traditional group and comprises sectors 1 and 2, while the second is a newly advanced group (a sort of New Economy, let us say) and comprises sectors 3 and 4. Sectors 1 and 2 are modeled according to Feldman’s (1928) contribution, with the capital goods sector being denoted by subscript 1, and the non-durable consumption goods sector being denoted by subscript 2. Capital goods are used by sectors 1 and 2, but once investment is made, capital goods cannot be transferred from one sector to the other (irreversibility assumption). A proportion λ of the current production of the capital goods sector is allocated to itself while the remaining, 1-λ, is allocated to sector 2, with 1 ≥ λ ≥ 0. The technology of production is Leontief in both sectors:

$$Y_1 = \min[A_1K_1, B_1L_1] \tag{1}$$
$$Y_2 = \min\left[A_2K_2, B_2L_2\right] \tag{2}$$

where Y_1 stands for the production of capital goods, A_1 is the corresponding output-capital ratio and K_1 refers to the stock of capital in the investment sector. L_1 stands for the unskilled labor force employed in sector 1 and B_1 is the corresponding output-labor ratio. Meanwhile, Y_2 refers to the production of the non-durable consumption good, A_2 is the corresponding output-capital ratio and K_2 is the capita stock in the non-durable consumption goods sector. The amount of unskilled labor force in this sector is denoted by L_2, while B_2 is the corresoponding output-labor ratio. Following Feldman's original contribution, unskilled labor is always in excess supply in both sectors. The production in these sectors is given by:

$$Y_1 = A_1K_1 \tag{3}$$
$$Y_2 = A_2K_2 \tag{4}$$

The law of motion of the stock of capital in sectors 1 and 2 is therefore given by:

$$\dot{K}_1 = \lambda(t)Y_1(t) - \delta K_1(t) \tag{5}$$
$$\dot{K}_2 = \left[1 - \lambda(t)\right]Y_1(t) - \delta K_2(t) \tag{6}$$

Sectors 1 and 2 are vertically integrated, and in case they were the only sectors of the economy, the growth rate of the consumption sector would depend on the growth rate of the investment sector and, in the long run, the former would converges to later, which would then be the growth rate of the economy as a whole (Araujo and Teixeira 2002, p. 253). In this paper there are two other newly advanced sectors, though, so that the growth rate of the capital goods sector is obtained by dividing both sides of equation (5) by K_1 and noting that $Y_1 = A_1K_1$. Hence $\frac{\dot{Y}_1}{Y_1} = \lambda A_1 - \delta$ and $\lim_{t\to\infty}\frac{\dot{Y}_2}{Y_2} = \lambda A_1 - \delta$.

As intimated earlier, the newly advanced economy is comprised by sectors 3 and 4, which produce, respectively, a durable consumption good and human capital. The two most common views associated with the so-called New Economy are that it is either limited to a few sectors or widespread throughout the economy. According to Gordon (2000, p. 72), who is referring to the American economy, "[t]he New Economy has created a dynamic explosion of productivity growth in the durable manufacturing sector (…). However the New Economy has meant little to the 88 percent of the economy outside durable manufacturing". Following this interpretation let us assume that even though information and communication technology, for instance, is a general purpose technology (Jorgenson & Stiroh 2000), it happens to be adopted only in sectors 3 and 4. Nonetheless, skilled labor force is required to the mastery of this technology, and several authors have argued that information and communication technologies and skills are complementary and not substitutes as traditional models have it. Acemoglu (2002), for instance, alongside with the other authors alluded to in the previous sections, points out that the bias of the technical change is mainly determined by the qualification of the available labor force. Consequently, a high proportion of skilled workers in the labor force implies a large market size for skill-complementary technologies, and hence encourages faster upgrading of the productivity of skilled workers. A possible way to incorporate this complementarity between skills and information and communication technologies is to assume that sector 3 produces durable consumption goods by using a Leontief technology:

$$Y_3 = \min[A_3 K_3^e, B_3 H_3] \tag{7}$$

where $H_3 = hL_3$ is the amount of human capital employed in this sector, which is given by the average per capita human capital of the skilled worker, *h*, multiplied by the number of worker in this sector L_3. Meanwhile, K_3^e stands for the stock of equipments installed in the durable consumption goods sector and A_3 and B_3 measure the efficiency, respectively, of equipments and human capital. Sector 4 increases the human capital of the economy and also uses a Leontief production function with both equipments and human capital as inputs. Assuming that H_4 refers to the stock of human capital in the educational sector, its production, denoted by Y_4, is given by:

$$Y_4 = \min[A_4 K_4^e, B_4 H_4] \tag{8}$$

where K_4^e is the stock of equipments in sector 4 and A_4 and B_4 measures the efficiency of equipments and human capital, respectively. As far as constraints are concerned, there are two possibilities here. The first one is that the production of sectors 3 and 4 is bounded by the existing stock of equipments. Although this case is possible it is not the most probable one since, following Solow (1957, 1962), the efficiency of equipments is assumed to have an exponential growth.[2] In this case small amounts of equipments may be compensated by increasing levels of embodied technological change. The possibility that the production in sectors 3 and 4 is bounded by the existing level of human capital in each of the sectors has greater support in the literature, in which the lack of skills has been pointed out as one of the main constraints to the adoption of new technologies, as reported in the preceding sections. Hence we assume that:

$$Y_3 = B_3 H_3 \tag{9}$$

$$Y_4 = B_4 H_4 \tag{10}$$

Note that $Y_4 = \dot{H}_3 + \dot{H}_4$, meaning that the production of sector 4 is equal to the total investment in human capital carried out in the economy, so that $B_4 H_4 = \dot{h} L_s + h\dot{L}_s$, with $L_s = L_3 + L_4$. Part of this investment, $h\dot{L}_s$, is allocated to endow the new skilled workers with the average level of existing human capital. The remaining part, $\dot{h}L_s$, meanwhile, raises the average level of human capital of the skilled labor force as a whole. Given that $\dot{H}_i = \dot{h}L_i + h\dot{L}_i$, with *i* = 3,4, we can write:

$$B_4 H_4 = \dot{h}(L_3 + L_4) + h(\dot{L}_3 + \dot{L}_4) \tag{11}$$

[2] This result is demonstrated in the next section.

Let us assume that the population, L, grows at a rate n and that the share of skilled population in sectors 3 and 4 remains constant through time. By dividing both sides of expression (7) by L_s and denoting by $\frac{L_4}{L_s} = \alpha$ the share of the skilled labor force that is employed in the educational sector we obtain after some algebraic manipulation the growth rate of human capital of the typical skilled worker:

$$\frac{\dot{h}}{h} = B_4\alpha - n \qquad (12)$$

It is then possible to show that the growth rate of the stock of human capital in sector 3 is given by $\dot{H}_3 = \dot{h}L_3 + h\dot{L}_3 = (B_4\alpha - n)hL_3 + hnL_3 = (B_4\alpha)H_3$. Hence $H_3(t) = H_3(0)e^{B_4\alpha t}$. By adopting the same procedure in relation to the stock of human capital in sector 4 we obtain that $H_4(t) = H_4(0)e^{B_4\alpha t}$. Hence the growth rate of the output in sectors 3 and 4 is given by $B_4\alpha$. Note that sectors 3 and 4 are vertically integrated since the output of sector 4 is an input for sector 3 and for itself. Following Feldman's tradition, therefore, it is intuitive that these sectors share the same growth rate in the long run.

4. Export demand side

Let us consider the following demand function for exports:

$$X = \left(\frac{P_d}{EP_f}\right)^{\eta} Z^{\phi} \qquad (13)$$

where X is the volume of exports, P_d is the domestic price of exports, E is the nominal exchange rate, P_f is the foreign price of imports, η is the price elasticity of the demand for exports, with $\eta < 0$, while ϕ is the income elasticity of demand for exports, $\phi > 0$. Assuming that relative prices measured in a common currency are constant, so that purchasing power parity holds, expression (13) yields:

$$\frac{\dot{X}}{X} = \phi\frac{\dot{Z}}{Z} \qquad (14)$$

4.1 First scenario

Let us first consider that the economy exports only the non-durable consumption good, which has a income elasticity of demand given by ϕ_2. Hence exports are a fraction of the production of the non durable consumption goods sector. Assuming that a constant fraction, γ, of the production of the non-durable consumption goods sector is exported, $X = \gamma Y_2$, while the remaining fraction, $1-\gamma$, is consumed internally, the growth rate of the production of the consumption goods sector has to be equal to:

$$\frac{\dot{Y}_2}{Y_2} = \frac{\dot{X}}{X} = \phi_2 \frac{\dot{Z}}{Z} \tag{15}$$

Let us assume that the growth rate of international income is exogenously given at $\frac{\dot{Z}}{Z} = r_e$. Equation (13) then implies that the growth rate of demand for the production of sector 2 is given by:

$$\frac{\dot{Y}_2}{Y_2} = r_e \phi_2 \tag{16}$$

However, equation (6) implies that, in the long run, the feasible growth rate of the production of consumption goods is given by :

$$\frac{\dot{Y}_2}{Y_2} = \lambda A_1 - \delta \tag{17}$$

Given the condition that the growth rates expressed by equations (16) and (17) have to be equal, we can obtain $\lambda*$, the fraction of the current production of capital goods that has to be used in the capital goods sector to meet the demand requirements, which is given by:

$$\lambda* = \frac{r_e \phi_2 + \delta}{A_1} \tag{18}$$

The share of capital goods allocated to the production of capital goods is thus positively related to the rates of growth of export demand and depreciation, and negatively related to the output-capital ratio in the investment sector. As in this scenario it is assumed that durable consumption goods are not exported, let us further assume that the growth rate of the demand for these goods is given by:

$$\frac{\dot{Y}_3}{Y_3} = r_i + n \tag{19}$$

Where *n* is the growth rate of per capita demand for durable consumption goods and *n* is the growth rate of population. Equation (19) is therefore a natural rate of growth of demand as defined by Pasinetti (1993). However, the feasible growth rate of the supply of durable consumption goods is given by:

$$\frac{\dot{H}_3}{H_3} = B_4 \alpha \tag{20}$$

Given the condition that the growth rates expressed by equations (19) and (20) have to be equal, we can obtain $\alpha*$, the share of the skilled labor force that has to be allocated to the educational sector, which is given by:

$$\alpha^* = \frac{r_i + n}{B_4} \tag{21}$$

The share of the skilled labor force that has to be allocated to the educational sector is therefore positively (negatively) related to the natural rate of growth of demand for durable consumption goods (efficiency of human capital in the educational sector).

Meanwhile, the intertemporal equilibrium in the balance of payments, which is given by $MP_f E = P_d X$, requires, under purchasing power parity, $\dot{M} = \dot{X}$. Given that $X = \gamma Y_2$, we obtain $\dot{M} = \gamma \dot{Y}_2$, though. In the long run, it follows that $\dot{Y}_2 = (\lambda^* A_1 - \delta)Y_2$ and hence $\dot{M} = \gamma(r_e\phi_2 + \delta)A_2 K_2$, so that imports are given by:

$$M = \gamma(r_e\phi_2 + \delta)A_2 \int K_2(t)dt \tag{22}$$

Since in the long run it follows that $K_2(t) = K_2(t^*)\exp(r_e\phi_2 + \delta)(t - t^*)$, substitution of this expression into equation (22) and calculation of the integral yields:

$$M = \gamma A_2 K_2(t^*)\left[\exp(r_e\phi_2 + \delta)(t - t^*) + c\right] \tag{23}$$

where c is a constant. By evaluating equation (23) at t^* we conclude that in case $M(t^*) = X(t^*)$, it then follows that c is equal to zero and equation (23) sums up to $M = \gamma A_2 K_2(t^*)\left\{e^{[\gamma r_e\phi_2 + (1-\gamma)g_2](t-t^*)}\right\}$. Therefore, it is being assumed that each vintage of capital goods is the result of investment – or imports – plus the production of the sector 3, which is specialized in producing equipments, in period v, having a rate of embodied technological change given by m and a rate of depreciation given by δ.[3] We then obtain:

$$K_e(v,t) = [M(v) + Y_3(v)]e^{mv + \delta(v-t)} \tag{24}$$

The stock of equipments in this economy is thus given by the integral over the ages of different vintages of capital goods that are installed in this sector, which is in turn given by:

$$K_e(t) = \int_0^t K_e(v,t)dv = \int_0^t [M(v) + Y_3(v)]e^{mv + \delta(v-t)}dv \tag{25}$$

By differentiating both sides of this expression and applying the Fundamental Theorem of Calculus we obtain that the variation in the stock of equipments in sector 1 is given by:

$$\dot{K}_e(t) = [M(t) + Y_3(t)]e^{mt} - \delta K_e(t) \tag{26}$$

from which it follows that the change in the stock of the equipments is given by:

$$\dot{K}_e = q(M + Y_3) - \delta K_e \tag{27}$$

[3] This formulation follows Solow (1957, 1962). An alternative approach would be to model investment-specific technological change as a Markov process, as in Greenwood, Hercowitz & Krusell (1997).

where $q(t)=e^{mt}$ conveys the investment specific nature of technological change. In order to provide a fully characterization of the dynamic path of the stock of equipments in this economy it is necessary to consider the demand side to determine the value of *M*. As it turns out, we obtain the following dynamic path to the stock of equipments:

$$K_e(t)=\frac{\gamma A_2 K_2(t^*)\left\{e^{[\gamma r_e\phi_2+(1-\gamma)g_2]-t^*}\right\}e^{[\gamma r_e\phi_2+(1-\gamma)g_2+m]t}+\left(1-\xi\right)B_3H_3(0)e^{g_3t}}{g_3+\delta} \qquad (28)$$

Meanwhile, the dynamic path of the stock of capital in sectors 1 and 2, respectively, is given by:

$$K_1(t)=K_1(0)e^{[\gamma r_e\phi_2+(1-\gamma)g_2]t} \qquad (29)$$

$$K_2(t)=K_2(0)e^{[\gamma r_e\phi_2+(1-\gamma)g_2](t-t^*)} \qquad (30)$$

In order to analyze the performance of the economy let us present the dynamic path of the production of each sector in the table below:

$$Y_1(t)=Y_1(0)e^{[\gamma r_e\phi_2+(1-\gamma)g_2]t}$$

$$Y_2(t)=Y_2(t-t^*)e^{[\gamma r_e\phi_2+(1-\gamma)g_2](t-t^*)}$$

$$Y_3(t)=Y_3(0)e^{g_3t}$$

$$Y_4(t)=Y_4(0)e^{g_3t}$$

As it turns out, the growth rates of sectors 1 and 2 depend on $\gamma r_e\phi_2+(1-\gamma)g_2$, which is nothing but a convex combination of the growth rate of external and internal demand. The growth path of the group of traditional sectors is therefore positively related to the growth rate of exports. Besides, the higher the fraction of the production of non-durable consumption goods that is exported, the stronger the impact of a change in the growth rate of exports on the growth rates of the production of both non-durable consumption and capital goods. Meanwhile, the rate of growth of the newly advanced sectors, which form the so-called New Economy, are both given by the growth rate of the production of durable consumption goods, which is exogenously given at a natural level. Though only these newly advanced sectors employ imported equipments in their production, their shared growth rate does not depend on the export performance of the economy, the reason being that production in these sectors is constrained ultimately by the existing stock of human capital rather than the existing stock of equipments and only non-durable consumption goods are exported. Meanwhile, the shared growth rate of the traditional sectors does depend on the growth rate of exports, even though they do not employ imported equipments in production.

4.2 Second scenario

Let us now suppose that the economy exports only durable consumption goods, whose income elasticity of export demand, ϕ_3, is higher than the income elasticity of export demand for non-durable consumption goods, so that $\phi_3>\phi_2$. Hence exports are now a fraction of the production of the durable consumption goods sector. Assuming that a fixed share, ξ, of the production of the durable consumption goods is exported, $X = \xi Y_3$, while the remaining share, $1-\xi$, is consumed internally, it follows that the growth rate of the production of the consumption goods sector has to be equal to:

$$\frac{\dot{Y}_2}{Y_2} = \frac{\dot{X}}{X} = \phi_3 \frac{\dot{Z}}{Z} \quad (31)$$

Let us assume again that the growth rate of international income is exogenously given at $\frac{\dot{Z}}{Z} = r_e$. Equation (13) then implies that the growth rate of demand for the production of sector 3 is given by:

$$\frac{\dot{Y}_3}{Y_3} = r_e \phi_3 \quad (32)$$

However, the long-run feasible growth rate of the production of durable consumption goods is given by :

$$\frac{\dot{Y}_3}{Y_3} = B_4 \alpha - n \quad (33)$$

Given the condition that the growth rates expressed by equations (32) and (33) have to be equal, we can obtain $\alpha *$, the share of the skilled labor force that has to be allocated to the educational sector, which is given by:

$$\alpha * = \frac{r_e \phi_3 + n}{B_4} \quad (34)$$

The share of the skilled labor force that has to be allocated to the educational sector is thus positively (negatively) related to the rate of growth of export demand (efficiency of human capital in the educational sector). As the production of non-durable consumption good is now consumed internally, the growth rate of the supply of capital goods adopted to produce non-durable consumption goods is given by equation (15), while the growth rate of the demand is given by the natural rate, $r_i + n$. Hence the value of $\lambda *$ that equilibrates supply and demand is given by:

$$\lambda * = \frac{r_i + n + \delta}{A_1} \quad (35)$$

The share of capital goods allocated to the production of capital goods is now positively related to the rates of natural growth of demand and depreciation, and negatively related to the output-capital ratio in the investment sector.

Meanwhile, the intertemporal equilibrium in the balance of payments, which is again given by $MP_f E = P_d X$, requires, under purchasing power parity, $\dot{M} = \dot{X}$. Since

$X = \xi Y_3$, we obtain $\dot{M} = \xi \dot{Y}_3$, though. In the long run, it follows that $\dot{Y}_3 = (\alpha * B_4 - n) Y_3$ and hence $\dot{M} = \xi r_e \phi_3 B_3 H_3$, so that imports are given by:

$$M = \xi r_e \phi_3 B_3 \int H_3(t) dt \tag{36}$$

Since in the long run it follows that $H_3(t) = H_3(0) \exp r_e \phi_3 t$, substituting this expression into equation (36) and calculating the integral we obtain:

$$M = \xi B_3 H_3(0) \left[\exp r_e \phi_3 t + c \right] \tag{37}$$

where c is a constant. By evaluating equation (37) at time zero we obtain that the value of this constant is given by $c = \frac{M(0)}{X(0)} - 1$. By assuming that $M(0) = X(0)$, in turn, we obtain c = 0 and equation (32) reduces to $M = \xi B_3 H_3(0) e^{r_e \phi_3 t}$. The dynamic path of the stock of equipments is therefore given by:

$$K_e(v,t) = [M(v) + (1-\xi) Y_3(v)] e^{mv + \delta(v-t)} \tag{38}$$

The stock of equipments in this economy is thus given by the integral over the ages of different vintages of capital goods that are installed in this sector, which is in turn given by:

$$K_e(t) = \int_0^t K_e(v,t) dv = \int_0^t [M(v) + (1-\xi) Y_3(v)] e^{mv + \delta(v-t)} dv \tag{39}$$

By differentiating both sides of this expression and applying the Fundamental Theorem of Calculus we obtain that the variation in the stock of equipments in sector 1 is given by:

$$\dot{K}_e(t) = [M(t) + (1-\xi) Y_3(t)] e^{mt} - \delta K_e(t) \tag{40}$$

from which it follows that the change in the stock of the equipments is now given by:

$$\dot{K}_e = q[M + (1-\xi) Y_3] - \delta K_e \tag{41}$$

Recalling that $M = \xi B_3 H_3(0) e^{r_e \phi_3 t}$ and $Y_3 = B_3 H_3(0) \exp(\alpha * B_4 - n)$, with $\alpha * = \frac{r_e \phi_3 + n}{B_4}$, we obtain $Y_3 = B_3 H_3(0) \exp(r_e \phi_3) t$. By replacing this expression into equation (41) we then obtain $\dot{K}_e = q[B_3 H_3(0) \exp(r_e \phi_3) t] - \delta K_e$. Evaluating this expression in steady state, we get:

$$K_e(t) = \frac{q B_3 H_3(0)}{\delta + r_e \phi_3 + m} e^{(r_e \phi_3 + m)t} \tag{42}$$

The dynamic path of the stocks of capital goods in sectors 1 and 2 are given by:

$$K_1(t) = K_1(0) e^{(r_i + n)t} \tag{43}$$

$$K_2(t) = K_2(0)e^{(r_i+n)(t-t^*)} \tag{44}$$

In order to analyze the performance of the economy let us summarize the dynamic path of the production of each sector in the table below:

$$Y_1(t) = Y_1(0)e^{(r_i+n)t}$$
$$Y_2(t) = Y_2(t-t^*)e^{(r_i+n)(t-t^*)}$$
$$Y_3(t) = Y_3(0)e^{(r_e\phi_3)t}$$
$$Y_4(t) = Y_4(0)e^{(r_e\phi_3)t}$$

As it turns out, sectors 1 and 2 have a shared growth rate that is exogenously given at a natural level, while the newly advanced sectors that comprise the so-called New Economy have a shared growth rate which is equal to the rate of growth of exports. Intuitively, it is precisely because only durable consumption goods are exported and only the newly advanced sectors employ imported equipments in production that it is only the New Economy's growth rate which is influenced by the rate of growth of exports. Nonetheless, though only part of the production of the durable consumption goods sector is exported and only the newly advanced sectors use imported equipments in production, the shared growth rate of these sectors does not depend on either some income elasticity of imports or the fraction of the production of durables consumption goods which is exported, it being actually equal to the growth rate of exports. However, in this scenario the performance of the sector which produces human capital is directly linked to the export performance of the economy, with an increase in the growth rate of exports then requiring the allocation of a higher fraction of the skilled labor force to the human capital producing sector. Since there is an upper bound for the share of the skilled labor force which can be allocated to the production of itself, an export-led growth of the newly advanced sectors – and, by extension, of the economy – is likewise bounded.

5. Conclusion

There has been considerable research devoted to enhance our understanding of the mechanisms that influence economic growth, though not many of them explore carefully how demand and supply forces interact to determine growth dynamics. There is also plenty of evidence that technological change comes largely in the form of advances in the manner that capital is produced. Meanwhile, investment sectoral allocation plays quite crucial a role in harvesting the benefits of investment-specific technological change, with human capital sectoral allocation in turn mattering for technological adoption and diffusion as well.

This paper contributes to the literature on growth dynamics by seeking to join these lines of research on structural factors in a more fully specified framework, on the one hand, and by making this more inclusive supply side to interact with demand factors in a model of export-led growth. Arguably, balance-of-payments constraints also influence the adoption of investment-specific technological change which requires the import of capital goods, and this is yet another reason for net exports to feature prominently in the demand side of the model developed in this paper. As turns out, the sectoral allocation of physical and human capital is revealed to be crucial for the resulting growth dynamics.

The economy is divided in two groups of sectors. The first group is a traditional one and comprises two sectors which produce, respectively, a non-durable consumption good and a capital good. The second is a newly advanced group and comprises two sectors which produce, respectively, a durable consumption good (which can be used as information and communication technology) and human capital. Though information and communication technology is a general purpose technology, it is used only in the newly advanced sectors and skilled labor is required to the master it.

In a first scenario, in which only non-durable consumption goods are exported, the share of capital goods which has to be allocated to the production of capital goods varies positively with the rates of growth of export demand and depreciation, and negatively with the output-capital ratio in the investment sector. Meanwhile, the share of the skilled labor supply that has to be allocated to the human capital producing sector varies positively with the natural rate of growth of demand for durable consumption goods, and negatively with the efficiency of human capital in the educational sector. Besides, the traditional sectors share a growth rate which is a convex combination of the growth rate of external and internal demand, and the higher the fraction of the production of non-durable consumption goods that is exported, the stronger the impact of a change in the growth rate of exports on the shared growth rates of these traditional sectors. Though the traditional sectors do not employ imported equipments in their production, the shared growth rate of these sectors does depend on the growth rate of exports. The growth rates of the newly advanced sectors, in turn, are both given by the growth rate of the production of durable consumption goods, which is exogenously given at a natural level. Though only these newly advanced sectors employ imported equipments in their production, their shared growth rate does not depend on the export performance of the economy, since production in these sectors is constrained by the existing stock of human capital and exports include only non-durable consumption goods.

In a second scenario, in which only durable consumption goods are exported, the share of the skilled labor force that has to be allocated to the educational sector varies positively with the rate of growth of export demand, and negatively with the efficiency of human capital in this sector. As the production of non-durable consumption good is now entirely consumed internally, the share of capital goods which has to be allocated to the production of capital goods varies positively with the rates of natural growth of demand and depreciation, and negatively with the output-capital ratio in the capital goods producing sector. Meanwhile, traditional sectors have a shared growth rate that is exogenously given at a natural level, while the newly advanced sectors that form the so-called New Economy have a shared growth rate which is equal to the rate of growth of exports. Intuitively, it is precisely because exports include only durable consumption goods and newly advanced sectors are the only ones to employ imported equipments in their production that it is only the New Economy’s growth rate which happens to be influenced by the rate of growth of exports. Nonetheless, though exports include only part of the production of the durable consumption goods sector and newly advanced sectors are the only ones to emply imported equipments in production, the shared growth rate of these sectors does not depend on either some income elasticity of imports or the fraction of the production of durables consumption goods which is exported, it being actually equal to the growth rate of exports. However, in this scenario the performance of the sector which produces human capital is directly linked to the export performance of the economy, with an increase in the growth rate of exports then requiring the allocation of a higher fraction of the skilled labor force to the human capital producing sector. Since there is an upper bound for the share of the skilled labor force which can be allocated to the production of itself, an export-led growth of the newly advanced sectors – and, by extension, of the economy – is likewise bounded.

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