Empirical analysis of human capital development and economic growth in European regions

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Impact of education and training

Preface

The impact of human capital on economic growth: a review *Rob A. Wilson, Geoff Briscoe*

Empirical analysis of human capital development and economic growth in European regions *Hiro Izushi, Robert Huggins*

Non-material benefits of education, training and skills at a macro level Andy Green, John Preston, Lars-Erik Malmberg

Macroeconometric evaluation of active labour-market policy – a case study for Germany *Reinhard Hujer, Marco Caliendo, Christopher Zeiss*

Active policies and measures: impact on integration and reintegration in the labour market and social life *Kenneth Walsh and David J. Parsons*

The impact of human capital and human capital investments on company performance Evidence from literature and European survey results *Bo Hansson, Ulf Johanson, Karl-Heinz Leitner*

The benefits of education, training and skills from an individual life-course perspective with a particular focus on life-course and biographical research *Maren Heise, Wolfgang Meyer*

The foundations of evaluation and impact research

Preface

Philosophies and types of evaluation research *Elliot Stern*

Developing standards to evaluate vocational education and training programmes *Wolfgang Beywl; Sandra Speer*

Methods and limitations of evaluation and impact research *Reinhard Hujer, Marco Caliendo, Dubravko Radic* From project to policy evaluation in vocational education and training – possible concepts and tools. Evidence from countries in transition. Evelyn Viertel, Søren P. Nielsen, David L. Parkes, Søren Poulsen

Look, listen and learn: an international evaluation of adult learning *Beatriz Pont and Patrick Werquin*

Measurement and evaluation of competence *Gerald A. Straka*

An overarching conceptual framework for assessing key competences. Lessons from an interdisciplinary and policy-oriented approach *Dominique Simone Rychen*

Evaluation of systems and programmes

Preface

Evaluating the impact of reforms of vocational education and training: examples of practice *Mike Coles*

Evaluating systems' reform in vocational education and training. Learning from Danish and Dutch cases *Loek Nieuwenhuis, Hanne Shapiro*

Evaluation of EU and international programmes and initiatives promoting mobility – selected case studies *Wolfgang Hellwig, Uwe Lauterbach, Hermann-Günter Hesse, Sabine Fabriz*

Consultancy for free? Evaluation practice in the European Union and central and eastern Europe Findings from selected EU programmes Bernd Baumgartl, Olga Strietska-Ilina, Gerhard Schaumberger

Quasi-market reforms in employment and training services: first experiences and evaluation results *Ludo Struyven, Geert Steurs*

Evaluation activities in the European Commission *Josep Molsosa*

Empirical analysis of human capital development and economic growth in European regions Hiro Izushi, Robert Huggins

Abstract

Recent discussion of the knowledge-based economy draws increasingly attention to the role that the creation and management of knowledge plays in economic development. Development of human capital, the principal mechanism for knowledge creation and management, becomes a central issue for policy-makers and practitioners at the regional, as well as national, level. Facing competition both within and across nations, regional policy-makers view human capital development as a key to strengthening the positions of their economies in the global market. Against this background, the aim of this study is to go some way towards answering the question of whether, and how, investment in education and vocational training at regional level provides these territorial units with comparative advantages.

The study reviews literature in economics and economic geography on economic growth (Chapter 2). In growth model literature, human capital has gained increased recognition as a key production factor along with physical capital and labour. Although leaving technical progress as an exogenous factor, neoclassical Solow-Swan models have improved their estimates through the inclusion of human capital. In contrast, endogenous growth models place investment in research at centre stage in accounting for technical progress. As a result, they often focus upon research workers, who embody high-order human capital, as a key variable in their framework. An issue of discussion is how human capital facilitates economic growth: is it the level of its stock or its accumulation that influences the rate of growth? In addition, these economic models are criticised in economic geography literature for their failure to consider spatial aspects of economic development, and particularly for their lack of attention to tacit knowledge and urban environments that facilitate the exchange of such knowledge.

Our empirical analysis of European regions (Chapter 3) shows that investment by individuals in human capital formation has distinct patterns. Those regions with a higher level of investment in tertiary education tend to have a larger concentration of information and communication technology (ICT) sectors (including provision of ICT services and manufacture of ICT devices and equipment) and research functions. Not surprisingly, regions with major metropolitan areas where higher education institutions are located show a high enrolment rate for tertiary education, suggesting a possible link to the demand from high-order corporate functions located there. Furthermore, the rate of human capital development (at the level of vocational type of upper secondary education) appears to have significant association with the level of entrepreneurship in emerging industries such as ICT-related services and ICT manufacturing, whereas such association is not found with traditional manufacturing industries.

In general, a high level of investment by individuals in tertiary education is found in those regions that accommodate high-tech industries and high-order corporate functions such as research and development (R&D). These functions are supported through the urban infrastructure and public science base, facilitating exchange of tacit knowledge. They also enjoy a low unemployment rate.

However, the existing stock of human and physical capital in those regions with a high level of urban infrastructure does not lead to a high rate of economic growth. Our empirical analysis demonstrates that the rate of economic growth is determined by the accumulation of human and physical capital, not by level of their existing stocks. We found no significant effects of scale that would favour those regions with a larger stock of human capital.

The primary policy implication of our study is that, in order to facilitate economic growth, education and training need to supply human capital at a faster pace than simply replenishing it as it disappears from the labour market. Given the significant impact of high-order human capital (such as business R&D staff in our case study) as well as the increasingly fast pace of technological change that makes human capital obsolete, a concerted effort needs to be made to facilitate its continuous development.

Table of contents

1.	Introduction	75
	1.1. Human capital theory	75
	1.2. Regions, states and skills: structure of the report	75
2.	Models of economic growth and human capital	77
	2.1. Early neoclassical perspectives	77
	2.2. Limitations of the Solow-Swan model	78
	2.3. Frankel-Romer model: AK approach to endogenous growth	79
	2.4. The second Romer model	80
	2.5. Schumpeterian growth model	81
	2.6. Accumulation or stock? Source of economic growth due to human capital	83
	2.7. Regional perspectives	85
	2.8. Summary of literature review	88
3.	Empirical analysis of regions in Europe	90
	3.1. Relationship between investment in education/training and demand for human capital	90
	3.1.1. Human capital development and employment patterns	90
	3.1.2. Human capital development and public science base	92
	3.1.3. Urban/rural settings and human capital development	92
	3.1.4. Relationship between human capital development and entrepreneurship	92
	3.1.5. Human capital development and unemployment rate	95
	3.1.6. Human capital development and economic growth	101
	3.2. Formal analysis of the relationship between human capital and economic growth at regional	
	and national level	101
	3.2.1. Estimates at the augmented Solow-Swan model: accumulation of human capital	101
	3.2.2. Estimates at the Nelson-Phelps framework: level of human capital stock	104
	3.2.3. Human capital and growth: cross-country estimates	106
4.	Summary and conclusions	110
	4.1. Significance of economic growth models	110
	4.2. The regional dimension	110
	4.3. Policy implications	111
	List of abbreviations	113
	Annex 1: Technical difficulty of incorporating increasing returns to a neoclassical model	114
	Annex 2: Growth rate of consumption in Romer (1986) model	115
	References	116

List of tables and figures

Tables

	Table 1:	Estimation of the augmented Solow-Swan model with the assumption of a steady state	102
	Table 2:	Estimation of the augmented Solow-Swan model	103
	Table 3:	Cross-regional growth accounting results: Human capital in log levels	105
	Table 4:	Cross-regional growth accounting results: Human capital in levels and in product of levels	
		and differences from the leading-edge region in labour productivity	107
	Table 5:	Cross-country growth accounting results, 1992-2000	108
Fig	ures		
	Figure 1:	A schematic representation of economic activities in the multisector model	
		(Aghion and Howitt, 1998, p. 86)	82
	Figure 2:	Interaction between the local education and training system and the locality's stock	
		of highly-skilled workers (adopted from Bradley and Taylor, 1996, p. 3)	87
	Figure 3:	Schematic model of knowledge and production	88
	Figure 4:	Students in tertiary education as a percentage of working age population	
		and employment in ICT sectors	91
	Figure 5:	Students in tertiary education as a percentage of working age population and R&D staff	91
	Figure 6:	Students in tertiary education as a percentage of population aged 20 to 24 years	
		and public R&D expenditures	93
	Figure 7:	Students in tertiary education as a percentage of working age population and population density	93
	Figure 8:	Students in upper secondary education as a percentage of working age population	
		and population density	94
	Figure 9:	Change in students in tertiary education as a percentage of population aged 16 to 19 years	
		and population density	94
	Figure 10:	Students in general type of upper secondary education as a percentage	
		of population aged 16 to 19 years and average firm size in ICT-related services	96
	Figure 11:	Students in vocational type of upper secondary education as a percentage	
		of population aged 16 to 19 years and average firm size in ICT-related services	96
	Figure 12:	Students in general type of upper secondary education as a percentage	
		of population aged 16 to 19 years and average firm size in ICT manufacturing	97
	Figure 13:	Students in vocational type of upper secondary education as a percentage	
		of population aged 16 to 19 years and average firm size in ICT manufacturing	97
	Figure 14:	Students in tertiary education as a percentage of working age population	
		and unemployment rate	98
	Figure 15:	Students in upper secondary education as a percentage of working age population	
		and unemployment rate	98
	Figure 16:	Unemployment rate and business R&D staff	99
	Figure 17:	Per worker GDP growth rate and students in tertiary education as a percentage	
		of working age population	99
	Figure 18:	Per worker GDP growth rate and students in general type	
		of upper secondary education as a percentage of working age population	100
	Figure 19:	Per worker GDP growth rate and students in vocational type	
		of upper secondary education as a percentage of working age population	100

1. Introduction

1.1. Human capital theory

As the global economy shifts towards more knowledge-based sectors (e.g. the manufacture of ICT devices, pharmaceuticals, telecommunications and other ICT-based services, R&D), skills and human capital development becomes a central issue for policy-makers and practitioners engaged in economic development both at the national and regional level (OECD, 1996). Yet, the impact education and vocational training activities exert upon changing national and regional economies remains less than thoroughly explained and analysed. Since the introduction of human capital theory in the 1960s, a number of studies have attempted to address this and related issues.

Human capital theory views schooling and training as an investment in skills and competences (Schultz, 1960 and 1961) (Becker, 1964). It is argued that, based on rational expectations of returns on investment, individuals make decisions on the education and training they receive as a way of augmenting their productivity. A similar strand of studies focuses on the interaction between the educational/skill levels of the workforce and measurements of technological activity (Nelson and Phelps, 1966). According to this theory, a more educated/skilled workforce makes it easier for a firm to adopt and implement new technologies, thus reinforcing returns on education and training. Empirical studies provide evidence supporting the aggregate effects of education and training. For example, Griliches (1970) estimated that one third of the Solow (1957) residual (i.e. the portion of the output growth in the US economy that could not be attributed to the growth in labour hours or capital stock) could be accounted for by the increase in the labour force's educational attainments. In the same vein, Denison (1979) reported the effect upon per capita income in the US, while others including Baumol et al. (1989), Barro (1991) and Mankiw et al. (1992) - have confirmed these positive relationships through a cross-section of countries covering all levels of development.

Bartel and Lichtenberg (1987) and Wolff (1996, 2001) found that education/skill levels are positively related with technological change in the sectors concerned. Also Crouch et al. (1999) provide a degree of evidence that highly educated workers are more likely to be employed in sectors exposed to international competition in a recent period, suggesting close association between education/skill levels of workers and technological activity undertaken. Looking at these impacts upon society as a whole, Abramovitz (1986) argues that education and vocational training is part of a set of key ingredients sustaining society's growth, which he terms 'social capability'.

1.2. Regions, states and skills: structure of the report

When these impacts of education and vocational training are disaggregated, and their distributions among different segments of the society are considered, their effects are mixed and hence effective modes for policy intervention are not adequately developed. Unequal effects of skills and human capital development are very noticeable among regions, as well as among nations. A range of literature provides empirical evidence concerning inter-regional inequality in labour productivity. For example, Dunford (1997) demonstrates persistent disparities among the UK regions in productivity and economic participation. A recent study we have undertaken (Huggins and Izushi, 2002) confirms a significant variation in productivity among advanced regional economies around the globe. This is a source of great concern, since many regions are increasing their independence as political and economic units, and are competing against one another. At the same time, powerful multinational corporations are becoming evermore footloose, increasingly escaping from the controls of nation states (Ohmae, 1995).

Hence an important question is whether the infrastructure and provision of education and

vocational training at the regional level provides these territorial units with comparative advantages. In order to answer this question satisfactorily, it is necessary to understand the manner in which skills and human capital development exerts its influence on regional and national economies, as well as the links between the two geographic layers. The structure of the report is as follows.

Chapter 2 provides an overview of literature on economic growth and human capital. As human capital development and technological progress are inextricably linked, much attention is paid to the impact of technological progress on economic growth. Chapter 2 starts with a review of key models of economic growth. This covers an early neoclassical model employed by Solow and Swan, subsequent attempts to account for the contribution of technological progress to productivity growth, an endogenous growth model developed by Romer, and a Schumpeterian approach that places innovation at the centre of economic growth. It then looks into an issue raised by Benhabib and Spiegel (1994): how human capital affects economic growth. This is

followed by a review of studies that apply national models to regional economies. The chapter also reviews other models that fall outside the neoclassical framework.

Chapter 3 presents the results of our empirical analysis of regions in Europe. The first part looks into relationships between the supply and demand of human capital, and between human capital supply and other economic indicators at regional level. The results show that supply and demand of human capital development have distinct patterns relating to educational level as well as types of regions. The second part of Chapter 3 focuses on the question of which affects the economic growth of regions, the rate of accumulation of human capital or the level of stock of human capital. The empirical analysis demonstrates that the rate of accumulation of human capital has a clear impact upon economic growth at the regional level, while we find no significant impact from the level of human capital stock. This finding provides evidence that refutes Benhabib and Spiegel's thesis (1994).

Finally, Chapter 4 summarises key findings of the study and provides policy recommendations.

2. Models of economic growth and human capital (1)

2.1. Early neoclassical perspectives

Although economists have studied economic growth for generations, there is still disagreement about how it is accounted for in a formal model. While some researchers take a Keynesian route and stress the role of demand factors, other researchers follow the neoclassical route, or more recently a Schumpeterian approach, emphasising the role of factor supplies in growth. In general, supply-side models are designed to uncover production factors for economic growth and are hence considered more appropriate for the purpose of investigating the impact of human capital formation.

Neoclassical growth theory seeks to understand the determinant of long-term economic growth rate through accumulation of factor inputs such as physical capital and labour. Studies reveal a significant contribution from technical progress, which is defined as an exogenous factor. Solow (1957) and Swan (1956) are among those who first demonstrated this.

At the heart of the neoclassical model lies an aggregate production function exhibiting constant returns to scale in labour and reproducible capital. This can be written in general form as follows:

Y = F(K, L)

where Y is output (or income), K is the stock of capital, and L is the labour force. The function expresses the output Y under a given state of knowledge, with a given range of available tech-

niques, and a given array of different capital, intermediate goods and consumption goods. With constant returns to scale, output per worker (i.e. labour productivity) $y \equiv Y / L$ will depend on the capital stock per worker (i.e. capital intensity) $k \equiv K / L$. Under the assumption of constant returns to scale, the relationship each unit of labour has with capital in production does not change with the quantity of capital or labour in the economy.

A crucial property of the aggregate production function is that there are diminishing returns on the accumulation of capital. In other words, each additional unit of capital used by a worker produces a decreasing amount of output (²). A form called the Cobb-Douglas function usually expresses the relationship:

$$Y = L^{1-\alpha} K^{\alpha}, 0 < \alpha < 1$$

Alternatively the per worker production function can be written as:

$$y = f(k) = k^{\alpha}$$

In other words, labour productivity can increase only if there is capital deepening (i.e. if capital intensity increases) (³).

The crucial tenet of the neoclassical model is that, under decreasing returns on capital, output per worker does not increase indefinitely. Assuming:

- (a) people save a constant fraction s of their gross income y (⁴);
- (b) the constant fraction δ of the capital stock disappears each year as a result of depreciation;

(3) The idea is also expressed in mathematical terms as follows: $\frac{dy}{y} = \frac{dY}{Y} - \frac{dL}{L} = \alpha \left(\frac{dK}{dt} - \frac{dL}{dt}\right) = \alpha \frac{dk}{dt}$.

^{(&}lt;sup>1</sup>) This literature review section owes much to Aghion and Howitt (1998), Armstrong and Taylor (2000), and Richardson (1979) as well as Harris (2001) and Romer (1986 and 1990).

⁽²⁾ This is expressed in mathematical terms, F'(K) > 0 and F''(K) < 0 for all K.

⁽⁴⁾ While the assumption of a fixed saving rate is not a bad approximation to long-term data, many argue that people save at a rate that varies over their life. The permanent-income and lifecycle hypothesis presumes that people save with a view to smoothing their consumption over their lifetimes, taking into account their preferences for consumption at different dates and the rate of return that they can anticipate if they sacrifice current consumption in order to save for the future (Aghion and Howitt, 1998, p. 17-18). A model based on this assumption is the Cass-Koopmans-Ramsey model.

(c) the rate of population growth is *n*, and population growth will cause the capital stock per worker *k* to fall at the annual rate *nk*;

then the net rate of increase in k can be written by the following equation as:

$$\frac{dk}{dt} = sf(k) - (n+\delta)k = sk^{\alpha} - (n+\delta)k$$

While the decline in the capital stock per worker due to depreciation and population growth is proportional to the capital stock, the growth of per worker capital through saving is constrained by decreasing returns on capital in production. When the marginal product of capital per worker falls to a sufficiently low level, gross investment will be just sufficient to maintain the existing stock of capital. Hence, the capital stock per worker will, in the long term, converge asymptotically to k^* that is defined by:

$$sk^{\alpha} - (n+\delta)k^* = 0$$
.

In this steady-state equilibrium, output and the capital stock will both continue to grow, but only at the rate of population growth.

The model's implication does not account for empirical evidence of long-term growth. Using this framework, Solow (1957) demonstrated that an attempt to account for decades of US economic growth produced an astonishing residual of approximately 85 %. Solow attributed most of the residual to technological change (⁵). Accordingly, we can modify the neoclassical model by supposing that there is a productivity (or technology) parameter *A* in the aggregate function that reflects the current state of technological knowledge.

$$Y = F (A, K, L).$$

Assuming that productivity increases smoothly over time at a constant growth rate g (⁶),

$$Y = A_0 e^{gt} K^{\alpha} L^{1-\alpha}$$

From this, it follows that growth in income is determined by productivity growth g and the growth of capital per worker (⁷). Hence, even if the capital stock and the labour force grow at the same rate, output per worker will increase provided that the rate of technical progress is higher than zero.

2.2. Limitations of the Solow-Swan model

An obvious limitation of the Solow-Swan model is its failure in accounting for the causes of technological progress. Although the model shows that technological progress contributes to economic growth, it does not spell out why technological progress takes place. The rate of technological progress is set at *g* without any theoretical relationships with other variables within the model (i.e. the rate is set exogenously). The justification normally given is that technological change originates from knowledge produced by the public science base (e.g. universities, public research institutes) outside the domain of the economic system the model expresses (Solow, 1957) (Shell, 1966 and 1967).

However, there is every reason to believe that technological progress itself depends on economic decisions, to much the same degree as capital accumulation. Entrepreneurs look for ways to make a profit and one way of doing this is to produce new ideas. Since there is a profit incentive to produce new knowledge and to innovate, knowledge creation and innovation need to be incorporated into a model of economic growth in such a way that, while they spur economic growth, they are in turn further advanced by economic growth. In other words, technological progress needs to be endogenised.

Another issue of the Solow-Swan model is its assumption of constant returns to scale. There is some evidence that suggests increasing returns in

- (6) Namely, $A = A_0 e^{gt}$.
- (7) In mathematical terms, this is expressed as, $\frac{\frac{dy}{dt}}{y} = \frac{\frac{dY}{dt}}{Y} \frac{\frac{dL}{dt}}{L} = g + \alpha \left(\frac{\frac{dK}{dt}}{K} \frac{\frac{dL}{dt}}{L}\right) = g + \alpha \frac{\frac{dK}{dt}}{k}$.

⁽⁵⁾ It is worth noting that neither capital stock *K* nor labour force *L* included human capital in Solow's calculation. The model assumes that labour is homogeneous.

long-term economic growth. For example, Kendrick (1976) attempted to explain US economic growth by adding intangible investments, such as human capital (e.g. R&D and education and training), to the capital stock that normally consists of tangible components (i.e. physical capital and labour). Such intangible investments can be counted as capital stock because they must have a lifetime of more than one year, that is, they improve the quality of the tangible factor over two or more annual accounting periods. However, he found that, between 1929 and 1969, an annual growth rate in real total capital (2.4 %) represented only 70 % of the 3.4 % average annual growth of real product in the private domestic business economy (Kendrick, 1976, p. 131). Romer (1986, p. 1013) suggests that, given the repeated failure of this kind of growth accounting exercise, there is no basis in the data for excluding the possibility that aggregate production functions are best described as exhibiting increasing returns.

The idea that increasing returns are central to the explanation of long-term growth is at least as old as Adam Smith's story of the pin factory (Smith, 1776). Alfred Marshall (1890) introduced the concept of increasing returns that are external to a firm but internal to an industry. Allyn Young furthered the idea with his competitive equilibrium interpretation, though no formal dynamic model embodying that insight was developed. Kenneth Arrow (1962) assumed that the productivity of a given firm is an increasing function of cumulative aggregate investment for the industry. Avoiding issues of specialisation and divisions of labour, Arrow argued that increasing returns arise because new knowledge is discovered as investment and production take place (Romer, 1986, p. 1005).

The failure of neoclassical models to introduce technological progress in such a way to account for its causes (i.e. endogenise technological progress) is, in large part, due to technical difficulty dealing with increasing returns in a dynamic general equilibrium framework. Attempts to understand increasing returns have sought their source in technological progress. However, the approach entails technical difficulty if it is to maintain the Walrasian framework of marginal product (⁸).

Arrow (1962) avoided the problem by assuming that the growth of productivity A is an unintended consequence of the experience of producing new capital goods, a phenomenon he called 'learning by doing'. He assumed that an increase in Knecessarily leads to an equiproportionate increase in knowledge through 'learning by doing'. In his model, K and L are paid their marginal products as those firms that produce capital goods are not compensated for their learning by doing (i.e. contribution to a growth in A). Yet, the growth of A became endogenous in the sense that it would increase saving propensity, which would in turn affect output up to an equilibrium point. The Arrow model is fully operational in the case of a fixed capital/labour ratio. This implies that the model does not have enough increasing returns to sustain output growth in the long term without growth in labour, as in the Solow-Swan model (Aghion and Howitt, 1998, p. 23).

2.3. Frankel-Romer model: AK approach to endogenous growth

More recent attempts to endogenise technological progress were spurred by Paul Romer's two seminal papers (1986 and 1990). Of these, the first 1986 paper has its theoretical origin in Frankel's (1962) AK model (⁹). Frankel assumed that each firm *j* in the economy has a production function expressed as:

$$Y_{j} = \overline{A}K_{j}^{\alpha}L_{j}^{1-\alpha}$$

where K_j and L_j are the firm's own employment of capital and labour. He then extended this produc-

See Annex 1 for technical explanation of this.

(9) Aghion and Howitt, 1998, p. 25. Apparently Romer himself did not realise the theoretical lineage since he did not cite Frankel's work in his 1986 paper.

⁽⁸⁾ Aghion and Howitt (1998) put this as follows:

^{...} if A is to be endogenized, then the decisions that make A grow must be rewarded, just as K and L must be rewarded. But because F exhibits constant returns in K and L when A is held constant, it must exhibit increasing returns in three 'factors' K, L, and A. Euler's theorem tells us that with increasing returns not all factors can be paid their marginal products. Thus something other than the usual Walrasian theory of competitive equilibrium, in which all factors are paid their marginal products, must be found to underlie the neoclassical model (p. 23).

tion function to the whole economy, assuming that all firms face the same technology and the same factor prices, and will hire factors in the same proportions, which obtains:

$$Y = \overline{A}K^{\alpha}L^{1-\alpha}$$
 (1)

To endogenise the productivity parameter \bar{A} , Frankel assumed that it is a function of the overall capital/labour ratio:

$$\overline{A} = A(K/L)^{\beta}$$

because in many respects the stock of knowledge depends on the amount of capital per worker in the economy. This is based on the idea that technological knowledge is itself a kind of disembodied capital good (¹⁰).

Another assumption made in Frankel's model is that although \overline{A} is endogenous to the economy (i.e. related to changes in *K* and *L*), it was taken as given by each firm, because the firm would only internalise a negligible amount of the effect that its own investment decisions have on the aggregate stock of capital.

When $\alpha + \beta = 1$, equation (1) becomes Y = AK. This form of model is referred to as the AK model. Diminishing returns on the accumulation of capital play a crucial role in limiting growth in neoclassical models like the Solow-Swan model. However, in the Frankel model, output grows in proportion to capital because of the effect of knowledge creation activities that counteract diminishing returns.

In his 1986 paper, Romer in effect extended the Frankel model by introducing a lifetime utility function $W = \int_0^\infty e^{-\rho t} u(c(t)) dt$, where c(t) is the time path of consumption per person, u(.) is an instantaneous utility function exhibiting positive but diminishing marginal utility, and ρ is a positive rate of time preference. Romer assumed a production function with externalities of the same sort as considered by Frankel, and examined the case in which labour supply per firm was equal to

unity (i.e. *L*=1) and the rate of depreciation δ was zero. If it is supposed that the productivity parameter \bar{A} reflects the total stock of accumulated capital *NK* where *N* is the number of firms, $\bar{A} = A(NK)^{\beta}$.

In a steady-state growth, consumption $(^{11})$ and output grow at the same rate g, which is expressed as:

$$g = \frac{N^{1-\alpha} A\alpha - \rho}{\varepsilon}$$

if $\alpha + \beta$. This indicates that the larger the number of firms *N*, the more externalities there will be in producing new technological knowledge and therefore the faster the representative firm and the economy will grow (¹²).

As shown above, the AK approach introduces a specific relationship between technological progress and capital accumulation by assuming that knowledge is a sort of capital good and productivity increases with capital per labour. However, accumulation of knowledge is still external in the relationship since the approach does not explicitly express how knowledge creation is remunerated.

2.4. The second Romer model

Romer takes a different approach to accounting for technological progress in his article published in 1990. While he saw knowledge as part of the aggregate capital *K* and related technological progress to an increase in capital/labour ratio in his 1986 article, Romer focused this time on the production of knowledge by research workers. This model assumes that technological knowledge is labour-augmented, enhancing their productivity. The production function is expressed as:

$$Y = K^{\alpha} \left(AL \right)^{1-\alpha} \tag{2}$$

so that AL denotes a knowledge-adjusted workforce. Further, the model assumes that research

^{(&}lt;sup>10</sup>) Aghion and Howitt (1998) explains this:

It [technological knowledge] can be used in combination with other factors of production to produce final output, it can be stored over time because it does not get completely used up wherever it is put into a production process, and it can be accumulated through R&D and other knowledge-creation activities, a process that involves the sacrifice of current resources in exchange for future benefits (p. 25-26).

^{(&}lt;sup>11</sup>) The growth rate of consumption under the model is given in Annex 2.

^{(&}lt;sup>12</sup>) In his 1986 article, Romer in fact assumed $\alpha + \beta > 1$, that is, increasing social returns on capital.

workers create technological knowledge. In a simple form, this is expressed as:

$$\frac{dA}{dt} = \delta H_A A \tag{3}$$

where H_A is human capital of research workers, and δ is a parameter. It is plain to see that the more researchers, the more new ideas are created, and the larger the existing stock of knowledge *A*, the more new ideas are produced (i.e. effect of externalities).

Equation (3) shows that the rate of technical progress will be determined by the stock of human capital of research workers. In other words, an economy with a larger total stock of human capital will grow faster (Romer, 1990, p. S99).

It is worth emphasising that unlike his previous model, the second Romer model explicitly recognises the role human capital plays in economic growth. Also the model differs from human capital models such as the one developed by Becker et al. (1990) that treats all forms of intangible knowledge as being analogous to human capital skills that are rival and excludable. The second Romer model includes two distinct ways in which knowledge enters production. One is the contribution of new ideas (or designs in Romer's term) to producing new goods. Research workers employed by firms undertake the production of new designs. New designs are nonrival but excludable as their property rights are protected by patents. At the same time, new designs also increase the total stock of knowledge shared by the community of research workers and thereby increase the productivity of human capital in the research sector as a whole. Knowledge spillovers imply externalities: knowledge is thus nonexcludable in this realm (Romer, 1990, p. S84).

2.5. Schumpeterian growth model

Introducing the rival property of knowledge protected by property rights, the second Romer model adopts a Schumpeterian view of innovation and explicitly assumes market power. The idea was furthered in the 1990s by those models that assumed imperfect competition and elaborated more on the process of innovation. Among those early attempts was that of Segerstrom et al. (1990), who modelled sustained growth as arising from a succession of product improvements in a fixed number of sectors. However, Segerstrom et al. did not integrate the uncertain nature of innovation in their model. The introduction of uncertainty had to wait for the model proposed by Aghion and Howitt (1992). Aghion and Howitt assumed the creation of innovations through research as a stochastic process in which the innovation quantity is expressed as flow probability. As a specific form of the stochastic process, a Poisson process is normally adopted (13).

Aghion and Howitt (1998) extended the model to include more than one economic sector and to consider technology spillovers across sectors (Figure 1). In the model, there is one final good that is produced from a continuum of intermediate goods. Each intermediate good can be used to produce the final good independently of the other intermediate goods, with no complementarities between them. Each intermediate sector is monopolised by the holder of a patent to the latest generation of that intermediate good. Also each intermediate sector has its own research sector in which firms compete to discover the next generation of that particular good. Innovations in research sectors all draw on the same pool of shared technological knowledge that exist beyond sectoral boundaries. The state of this knowledge is represented by leading-edge

(d) The probability that a particular number of these events occurs in a particular time interval must not depend on the number of these events that occurred prior to the beginning of this time interval.

(Mansfield, 1980).

^{(&}lt;sup>13</sup>) Suppose that events of a particular kind occur at random during a particular time. Poisson process has the probability distribution that meets the following four conditions:

⁽a) The probability that each event occurs in a very short time interval must be proportional to the length of this time interval.

⁽b) The probability that two or more events of the relevant kind occur in a very short time interval must be so small that it can be regarded as zero.

⁽c) The probability that a particular number of these events occurs in a particular time interval must not depend on when this time interval begins.

technology. Each innovation at date t in any sector adds an increment to the level of the leading-edge technology at date t - 1 and permits the innovator to start producing in his sector using the new level of the leading edge technology. The previous incumbent in sector *i*, whose technology is no longer leading-edge, will be displaced. Hence the leading-edge technology grows gradually, at a rate that depends on the aggregate flow of innovations in the economy as a whole.

Aghion and Howitt (1998) also incorporated in their model horizontal imitation as a source to restrict effects of increasing returns to scale. While the neoclassical theory of Solow and Swan assumes constant returns to scale, R&D models of growth no longer have constant returns in all the factors that are growing: capital, knowledge and labour. Growth models proposed by Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992), for example, predict that the steady-state growth rate depends on the level of resources devoted to R&D – if the level of R&D resources is doubled, then per capita growth in output should also double. Jones (1995) criticises this, showing the dramatic increase of scientists and engineers in the US during the last 40 years contradicting a constant mean of the growth rate of the economy over the same period. To counter this, Aghion and Howitt argue that a source that limits such scale effects is imitations and a resultant growth of intermediate goods in the economy without adding to overall productivity.

The steady-state growth rate of per-worker income g, which equals the growth rate of leading-edge technology, is expressed as:

$$g = \sigma \lambda \phi(n)$$

where σ is the size of an average increment of knowledge that is added to the level of leading-edge technology at each innovation, λ is the productivity of R&D, *n* is the amount of input in research which is adjusted by the level of the leading-edge technology (¹⁴), and $\phi(\cdot)$ is a function of the probability with which innovations take place (¹⁵). In other words, the steady-state growth rate *g* depends positively upon the productivity of R&D (λ). Also, the flow probability of innovations



Figure 1: A schematic representation of economic activities in the multisector model (Aghion and Howitt, 1998, p. 86)

(¹⁴) It is presumed that as technology advances, the resource cost of further advances increases proportionally.

(¹⁵) The function of innovation probability $\phi(\cdot)$ has the property that represents a decreasing marginal product of research input *n*. The function's property is due to research congestion within a product.

depends positively on technology-adjusted input in research (*n*). Given the same level of leading-edge technology, the growth rate depends positively upon research input. Further, as an effect of horizontal imitation, Aghion and Howitt argue that the steady-state growth rate of per-worker income also depends positively on population growth (16).

2.6. Accumulation or stock? Source of economic growth due to human capital

The above review shows that models of economic growth vary in the ways they predict production factors can cause an economy to grow. According to the Solow-Swan model, the growth of per capita income arises from accumulation of capital until the economy reaches a steady state. In the steady state, per capita income growth relies solely on technological progress that the model does not attempt to explain. In contrast, endogenous growth models set R&D at the centre of their framework. They predict that per capita income growth is determined by the amount of resources devoted to R&D. The neoclassical Solow-Swan model sees the change in the amount of capital (i.e. capital accumulation) as the source of economic growth (until the economy reaches a steady state), whereas endogenous growth models assume that the level of the stock of a particular capital (that is devoted to R&D) decides economic growth.

This disagreement about the source of economic growth is also found in discussions on human capital. Broadly, there are two basic frameworks with which to model and analyse the relationship between human capital formation and economic growth (Benhabib and Spiegel, 1994) (Aghion and Howitt, 1998). The first approach has its origin in Becker's (1964) theory of human capital and has attracted attention with the 1988 article by Lucas. It is based on the idea that growth is primarily driven by the accumulation of human capital. According to this approach, differences in growth rates of per capita income across economies are in large part accounted for by differences in the rates at which the economies accumulate human capital. The second approach dates back to the seminal paper of Nelson and Phelps (1966) and has recently been revived in Schumpeterian growth literature. It contends that the stock of human capital determines the economy's capacity to innovate or catch up with more advanced economies, which in turn drives economic growth. Hence, the level of human capital stock is, though indirectly, a determinant of per capita economic growth in this view.

In the economy assumed by Lucas (1988), individuals choose at each date how to allocate their time between current production and skills acquisition (or schooling), taking into account increases in productivity and wages in future periods that arise from current investment of time in education or training. If h denotes the current human capital stock of the representative person, and u denotes the fraction of the person's time currently allocated to production, the Lucas model can be summarised by:

$$y = k^{\beta} (uh)^{1-\beta}$$

where k denotes the per capita stock of physical capital, and:

$$\frac{dh}{dt} = \delta h(1-u), \ \delta > 0.$$

While the second equation expresses that the growth rate of human capital is determined by time spent in education or training, the first equation describes the way human capital affects current production. As the first equation's similarity to the Solow-Swan model suggests, per capita income growth comes from accumulation of human capital (as well as accumulation of physical capital). In other words, the growth rate of per capita income depends positively on the growth rate of human capital capital). Under the assumption of constant returns to the stock of human capital, the steady-state growth is expressed by:

$$g = \delta(1-u^*)$$

^{(&}lt;sup>16</sup>) Aghion and Howitt (1998, p. 108) note: This new effect [of imitation] shows that what used to be thought of as an embarrassing scale effect in Schumpeterian growth theory can be seen ... as a novel prediction that distinguishes it from the neoclassical theory of Solow and Swan. Instead of saying that growth goes up with the level of population, it goes up with the growth rate of population.

where u^* is the optimal allocation of individuals' time between production and education/training.

In contrast, Nelson and Phelps (1966) suggested that this standard view of human capital as an additional input would represent a gross misspecification of the production process. They argued that education and training facilitate the adoption and implementation of new technologies, which are continuously invented at an exogenous rate. In their view, the growth of productivity parameter *A* is expressed by:

$$\frac{\frac{dA}{dt}}{A} = c(H) \cdot \frac{T_t - A_t}{A_t}$$

where T_t denotes the level of theoretical knowledge at date *t*. It is evident in the specification that the growth rate of *A* depends on the gap between its level and the level of *T*, and the level of human capital *H* through the function c(H)

where
$$\frac{dc}{dH} > 0$$
 (17).

Extending the model, Benhabib and Spiegel (1994) substituted technology 'catch-up' across different economies for the closing of a gap between A and T in the Nelson and Phelps framework. According to Benhabib and Spiegel, the growth rate of productivity parameter A for an economy i is written as:

$$\frac{\frac{dA_{it}}{dt}}{A_{it}} = g(H_i) + c(H_i) \cdot \frac{\max_j A_{jt} - A_{it}}{A_{it}}$$
(4)

where the endogenous growth rate $g(H_i)$ and the catch-up coefficient $c(H_i)$ are non-decreasing functions of H_i . In other words, the level of human capital not only enhances the ability of an economy to develop its own technological innovations (as in R&D-based growth models), but also its capacity to adapt and implement technologies developed elsewhere.

There is disagreement in empirical evidence as to which influences economic growth – accumulation of human capital or level of human capital stock.

In a cross-country study of per capita GDP growth during two periods (from 1965 to 1975 with 87 countries and from 1975 to 1985 with 97 countries), Barro and Sala-i-Martín (1995) obtained the following findings:

- (a) educational attainment (measured by average years of schooling) is significantly correlated with subsequent growth (with a correlation coefficient at around 0.05), although if the aggregate measure of educational attainment is decomposed by level of education, the impact of primary education remains largely insignificant;
- (b) public spending on education also has a significantly positive effect on growth: a 1.5 % increase of the ratio of public education spending to GDP during the period 1965-75 would have raised the average growth rate during the same period by .3 % per year (¹⁸).

Mankiw et al. (1992) also tested the impact of human capital formation using the Solow-Swan model. In their test, they assumed a steady state (¹⁹) and used a proxy for the rate of human

 $(^{17})$ The growth rate of A settles down to the growth rate of T in the long-term.

(18) Barro and Sala-i-Martín assume that a function for a country's per capita growth rate in period t, Dy, as

$$Dy_t = F(y_{t-1}, h_{t-1}; ...),$$

where y_{t-1} is initial per capita GDP and h_{t-1} is initial human capital per person (based on measures of educational attainment and health). The omitted variables, denoted by ..., comprise an array of control and environmental influences.

⁽¹⁹⁾ Mankiw et al. use an augmented Solow-Swan model that is expressed as:

$$Y_t = K_t^{\alpha} H_t^{\beta} \left(A_t L_t \right)^{1-\alpha-\beta}$$

where *H* is the stock of human capital. When the fraction of income invested in physical capital is s_k , and the fraction of income invested in human capital is s_n , the evolution of the economy is determined by:

$$\frac{dk_t}{dt} = s_k y_t - (n+g+\delta)k_t$$
$$\frac{dh_t}{dt} = s_h y_t - (n+g+\delta)k_h$$

where y = Y/AL, k = K/AL, h = H/AL, n is growth rate of *L*, *g* is growth rate of *A*, and δ is depreciation rate. In the steady state, the following equation holds:

$$\log(Y_t/L_t) = \log A_0 + gt - \frac{\alpha + \beta}{1 - \alpha - \beta} \log(n + g + \delta) + \frac{\alpha}{1 - \alpha - \beta} \log s_k + \frac{\beta}{1 - \alpha - \beta} \log s_h$$

capital accumulation that measures approximately the percentage of the working age population that is in secondary school. In the test that examined GDP per working age person in 1985 for 98 non-oil countries, Mankiw et al. found that the coefficient on human capital accumulation is significant, that is, human capital accumulation, along with physical capital accumulation, accounts for the growth of per capita GDP.

In contrast, Benhabib and Spiegel (1994) estimated the stock of human capital and tested the augmented Solow-Swan model without the assumption of a steady state (²⁰). From the data of 78 countries during the period of 1965-85, Benhabib and Spiegel found that the log difference in human capital in their specification always enters insignificantly, and almost always with a negative coefficient. In other words, human capital accumulation is found to lead to a negative growth of the economy although this impact is statistically not significant.

Benhabib and Spiegel then undertook tests using different models that included the stock of human capital instead of the accumulation of human capital. In the model that includes an average of human capital stock over the period under study, human capital stock enters insignificantly with a negative sign (21). However, when initial income levels are introduced in the model, human capital stock enters significantly with the predicted positive sign. Benhabib and Spiegel suggest that catch-up remains a significant element in growth, and countries with higher education tend to close the technology gap faster than others. In the second model that incorporates both endogenous growth and catch-up terms as in equation (4) (22), the catch-up term enters positively and significantly for the entire sample of 78 countries. However, the coefficient estimate country-specific technological on

progress is negative and insignificant. Benhabib and Spiegel tested the same model for subgroups of their sample, assuming that the relatively strong impact of the catch-up term may change with the relative position of the country. They found:

- (a) for the poorest third of their sample, the catch-up term is positive and significant, whereas the endogenous growth term is negative and insignificant;
- (b) for the middle group, both terms are insignificant;
- (c) for the richest third of the sample, the endogenous growth term enters positively and significantly with a 6 % level of confidence while the catch-up term enters insignificantly with a coefficient estimate that is positive but close to zero.

From these results, they argue that human capital stocks in levels, rather than their growth rates, play a role in determining the growth of per capita income.

2.7. Regional perspectives

These models of economic growth are usually developed with respect to national-level economic growth and treat nations as spaceless units. The lack of attention to space attracted strong criticism from those who study regional economies. The determinants of growth over space carry certain implications that are not easy to reconcile with the central principles of growth models, and particularly neoclassical models. Richardson (1979, p. 142) summarises such neoclassical principles as:

- (a) reliance on the price mechanism as the spatial allocator of resources;
- (b) emphasis on marginal adjustments, whereas spatial functions are discontinuous and loca-
- (20) They assumed a production function, $Y_t = A_t K_t^{\alpha} L_t^{\beta} H_t^{\gamma}$, and used the following equation to examine the impact of human capital accumulation:
- $\log Y_{T} \log Y_{0} = \log A_{T} \log A_{0} + \alpha \left(\log K_{T} \log K_{0} \right) + \beta \left(\log L_{T} \log L_{0} \right) + \gamma \left(\log H_{T} \log H_{0} \right).$
- (²¹) The model's specification is as follows:

$$\log Y_T - \log Y_0 = \log A_T - \log A_0 + \alpha \left(\log K_T - \log K_0\right) + \beta \left(\log L_T - \log L_0\right) + \gamma \left(\frac{1}{T} \sum_{0}^{T} \log H_t\right).$$

(²²) The model's structural specification is as follows:

 $\log Y_{T} - \log Y_{0} = c + (g - m)H_{i} + mH_{i}(Y_{max}/Y_{i}) + \alpha (\log K_{T} - \log K_{0}) + \beta (\log L_{T} - \log L_{0}).$

tion changes usually mean inertia (i.e. no change) or a long-distance jump;

- (c) the assumption that growth can be constructively analysed with an aggregate production function and a homogenous capital stock;
- (d) the predilection for equilibrium solutions;
- (e) a greater facility with deterministic rather than probabilistic solutions.

A central weakness of neoclassical models lies in the assumption that all factors of production are completely mobile between regions within a country. The weakness is particularly acute when neoclassical models are employed to account for long-term regional disparities in economic development. The assumption of mobile factors within a country predicts that any differences in the capital/labour ratio, and thus labour productivity, between regions disappear in the long term as capital and labour move to the regions that yield the highest returns (²³).

As for short- or mid-term disparities, the assumption of nonexcludable knowledge poses another problem. This is because technological knowledge is assumed to be perfectly mobile between regions and always available to all regions simultaneously. For instance, the particular assumption limits the application of the Romer models to the world economy as a whole because technological progress diffuses across geographical space so that even small economies can benefit from it without having to rely on knowledge created within their own frontiers (Armstrong and Taylor, 2000, p. 79) (24). However, innovations do not diffuse instantaneously or at an even rate over the economy as a whole. They diffuse irregularly though predictably, reaching some areas very early in the adoption stage but not being adopted in other areas until very late. In some cases (e.g. when a threshold market is required), adoption at a particular location may never occur (Richardson, 1979, p. 125-126). The pioneering study in this area, Hägerstand (1966), focusing on agricultural innovations, demonstrated the importance of the communications network as a determinant of the diffusion path (25). He also showed that the diffusion process could be understood by a model of stochastic process (26).

Another aspect of nonexcludable knowledge is that some types of knowledge are embodied in individuals (i.e. tacit) and difficult to transfer through other means than interpersonal, often face-to-face communications. This needs to bring another class into the second Romer model: tacit knowledge embodied in individuals should be distinguished from patent-protected knowledge and shared, codified knowledge. Tacit knowledge also signifies the importance of human capital that represents a carrier of such knowledge. Some even argue about a region's institutional environment as a key determinant of its capacity to create technological progress (Rauch, 1993). According to this view, the creation of technological progress is determined by a collective learning process within which many individuals interact and exchange ideas and information (some of which are tacit). There are economies of scale to be gained from the geographical concentration of highly educated people as this results in a more rapid transfer of knowledge through their proximity. In addition to this, some regions are said to possess an institutional environment or culture that better facilitates such a collective learning process (Saxenian, 1994). In addition to universities and research institutes, a vertically-disintegrated industrial structure, a high mobility of skilled workers, and an abundance of venture capital are often found in such an environment.

Regarding mobility of human capital between regions, Bradley and Taylor (1996) argue that there is a sequential interaction between the local education and training system and the locality's stock of highly-skilled workers. This is shown in Figure 2.

The rate of enrolment in education is influ-

^{(&}lt;sup>23</sup>) This weakness is mitigated when discussing disparities between nations because international mobility of labour is restricted by immigration regulations.

⁽²⁴⁾ Based on the assumption, Romer argues that a country's economic growth is correlated with the degree of its integration into worldwide markets.

⁽²⁵⁾ The classic study of the diffusion of hybrid corn by Griliches (1957) looked at inter-state differentials but did not explicitly investigate the spatial spread of the innovation (Richardson, 1979, p.125).

^{(&}lt;sup>26</sup>) Innovations diffuse over space and time. A common way of representing general spatial diffusion radiating out from the innovation source is expressed by a distance-decay function: $p(r) = ae^{-br}$



Figure 2: Interaction between the local education and training system and the locality's stock of highly-skilled workers (adopted from Bradley and Taylor, 1996, p. 3)

enced by the socioeconomic background of pupils, employment and career prospects in the local economy, and the quality of local schooling. Enrolment, in turn, determines the locality's workforce skills, labour productivity, and economic performance. Its economic performance then determines the volume and occupational mix of inward migrant workers into the locality. Economic growth also provides employers with more worker training, facilitating further skills increase. A shift in the occupational mix towards skilled workers will have beneficial effects on the locality's human capital formation. While skilled workers are often keen to invest in education for their children, an improved economy also provides better employment opportunities and induces other pupils to seek for education and training. Hence, Bradley and Taylor argue that the education and training system interacts with the local economy in such a way that spatial disparities in economic well-being are exacerbated through the cumulative causation mechanism.

A summary of our review of regional studies is given in Figure 3. While regional studies literature

shares a basic understanding of production with economics literature, it pays more attention to the way space affects economic production.

It particularly elaborates more on the effects of spatial agglomeration of economic activity and attempts to identify causes of spatial agglomeration as well as its effects. Distinction between codified knowledge and tacit knowledge is emphasised in the attempt. It is argued that tacit knowledge is embodied in skilled workers and less mobile than codified knowledge. Hence, the assumption of frictionless diffusion of technological knowledge is under attack. Also drawing on more institutional studies than mainstream economics, such as the theories of transaction costs (Williamson, 1975 and 1985) and social embeddedness (Granovetter, 1985), the literature often examines social aspects of relations between economic agents. These efforts lead to the conceptualisation of other types of production factors, such as social capital and network capital. Another area of focus is economic disparities between regions that arise from spatial divisions of labour. It is often argued that high-order



Figure 3: Schematic model of knowledge and production

functions that require significant human capital are concentrated in core regions (due to agglomeration effects), creating regional disparities. Regional studies and economic studies of growth hence intersect at the issue of convergence.

2.8. Summary of literature review

The literature review shows that human capital attracts more attention as economic growth

models attempt to account for technological progress in greater detail. In the classic Solow-Swan model, technological progress was identified as a residual that is not explained by capital and labour. Though capital in the model can theoretically include both human and physical capital, human capital was, in practice, not considered in many empirical studies employing the model. As a step towards accounting better for the role of technological progress in economic growth, the Fankel's AK model related it to an increase in capital per worker, seeing knowledge as a sort of disembodied capital. Romer (1986) refined the model by incorporating maximisation of lifetime utility with an intertemporal utility function. Yet, both the original Frankel AK model and the first Romer model did not give any explicit role to human capital.

In contrast, Romer's second endogenous growth model (1990) recognises human capital as a primary source of technological progress and, therefore, economic growth. Romer views research workers as the source of new ideas and hence profits. In the model, Romer also distinguishes patent-protected technology from the stock of knowledge that is shared by the community of research workers. Other endogenous growth models, including the Aghion-Howitt model, also set R&D at the centre of their frameworks. Such R&D-based growth models produce implications that are distinct from the neoclassical Solow-Swan model. An example of this is prediction of scale effects.

There remains disagreement on how human capital affects economic growth. While the approach initiated by Lucas (1988) views accumulation of human capital as the source of economic growth, the approach of Nelson and Phelps (1966) and Benhabib and Spiegel (1994) assumes that stock of human capital determines the ability of an economy to develop and assimilate technologies and thus produce economic growth. This difference in their positions mirrors different treatments of technological progress and R&D in the Solow-Swan model and R&D-based endogenous growth models.

These economic growth models are, however, criticised for their spaceless analysis. Their weakness is said to be acute when accounting for disparities in economic development between regions in which all production factors are assumed to be mobile. The assumption of frictionless diffusion of technological knowledge is under particular attack. It is argued that tacit knowledge is embodied in skilled workers and less mobile than codified knowledge. Furthermore, a mechanism of cumulative causation is said to work in the location of highly-skilled workers through education and training. Such discussions in spatial studies imply increasing disparities between regions. This implication is in stark contrast to neoclassical models of economic growth predicting convergence due to decreasing returns on capital.

3. Empirical analysis of regions in Europe

This chapter presents results of an empirical analysis of regions in EU Member States. The first part looks into relationships among aspects such as investment in education/training, demand for human capital, and economic indicators of regions. The second part provides empirical evidence relating to the debate between the Lucasian approach and the Benhabib-Spiegel approach.

Unless otherwise noted, we use data provided by Eurostat that covers regions and countries in the EU (Belgium, Denmark, Germany, Greece, Spain, France, Ireland, Italy, Luxembourg, the Netherlands, Austria, Portugal, Finland, Sweden, and the UK). We use the EU's definition of regional units, NUTS (Nomenclature of territorial units for statistics) level 1 (²⁷). Because of the definition, some nations are included as regions (i.e. Denmark, Ireland, Luxembourg). Regions in Sweden, as well as regions in some parts of Portugal and Finland, are based on NUTS level 2, a lower level of units.

Data availability restricts the majority of the analysis in the second part to Denmark, Germany (excluding regions in ex-German Democratic Republic), France, Ireland, and Italy whereas the first part covers a greater proportion of the Member States. Also a majority of data, including numbers of students enrolled in education by educational level, are available at the regional level only for short periods in the mid 1990s. This constrained our analysis in the majority of the first chapter.

3.1. Relationship between investment in education/training and demand for human capital

3.1.1. Human capital development and employment patterns

First, we looked at relationships between investment by individuals in education/training and employment size of sectors/functions that require high-order human capital. We use the numbers of students as a percentage of the working age population (15 to 64 years old) as a proxy for investment by individuals in human capital development (²⁸). We chose ICT-related sectors, including manufacturing of ICT devices and ICT services, as requiring high order human capital (²⁹). The two variables are correlated and results are as follows, quantified by enrolments:

- (a) for both general and vocational types of upper secondary education, no significant correlation is found between students as a percentage of the working population and employment in the high-tech sectors;
- (b) for tertiary education, correlation between students as a percentage of the working population and employment in the high-tech sectors is positive (0.41) and significant (0.005) – see Figure 4.

Similarly there is strong association, as shown in Figure 5, between students in tertiary education as a percentage of working age population and volume of R&D staff (including business, government, and higher education institutions). Correlation between the two is positive (0.54) and significant (0.000). We found close association (correlation: 0.31; significance: 0.01) between students in tertiary education as a percentage of the working

⁽²⁷⁾ The NUTS was set up at the beginning of the 1970s as a single, coherent system for dividing up the EU to produce regional statistics. Of its three levels of regions, level 1 is the largest unit that can be compared in size to some smaller member countries of the EU.

⁽²⁸⁾ Mankiw et al. (1992) used this proxy in their study.

⁽²⁹⁾ NACE 30 (office machinery and computers), 32 (telecommunications equipment), 64 (post and telecommunications), 72 (computer-related services) and 73 (R&D services) are included. In Eurostat, the data for NACE 64, 72 and 73 (and NACE 30 and 32 as well) is collated and made available as a single group, not allowing NACE 73 to be separated from the rest.





Students in tertiary education as a percentage of working age population average of 1995-97

Figure 5: Students in tertiary education as a percentage of working age population and R&D staff





population and number of business R&D staff as well. In contrast, no significant association was found between number of R&D staff and students in both general and vocational types of upper secondary education as a percentage of the working population (not in Figure 5).

The results show the tendency that investment by individuals in development of high-order human capital (i.e. tertiary education) is strong in those regions where there is a strong demand from activities requiring it (e.g. high-tech industries, R&D departments).

3.1.2. Human capital development and public science base

We saw close association between human capital development and R&D capacity of private-sector firms above. The R&D capacity of regions is also influenced by public R&D effort from governments and higher education institutions. An examination of the relationship is shown in Figure 6.

As expected, students in tertiary education as a percentage of the population aged 20 to 24 years and public R&D expenditures have close association, with a positive correlation (0.43) at the 1 % significance level (0.000). In contrast, there is no significant correlation between students in upper secondary education as a percentage of the population aged 15 to 19 years and public R&D expenditure (³⁰).

3.1.3. Urban/rural settings and human capital development

One of the arguments found in regional studies is that urban areas in which economic activity concentrates tend to facilitate diffusion of knowledge (particularly tacit knowledge) through the ease of face-to-face interactions. With agglomeration effects, such urban areas hence often host high-order corporate functions (e.g. headquarters and R&D departments) and firms operating in high-tech industries as well as universities and research institutes (³¹).

Given this association between investment in

human capital development and high-tech industries/R&D functions, close association is expected between investment in human capital development and density of economic activity. We use population density as a proxy for economic activity density. Figure 7 shows the relationship.

It is clear that individuals in regions with large metropolitan areas, such as Berlin, Bremen, Hamburg, Île de France, and Comunidad de Madrid, heavily invest in tertiary education. Correlation between the two variables is positive (0.27) and significant (0.02). Metropolitan areas hosting high-order corporate functions have a disproportionate supply of universities which provide suitable human capital.

In contrast, regions with large metropolitan areas have a relatively small number of students in upper secondary education as a percentage of the working population. This is shown in Figure 8 (³²).

Whereas individuals in regions with large metropolitan areas heavily invest in higher education, there is some evidence that gaps between regions are closing. Figure 9 shows the relationship between population density and change in students in tertiary education as a percentage of the population aged 16 to 19 years from 1995 to 1997. Correlation between the two variables is negative (-0.23) and significant at the 10 % level (0.07). As the period is short, the change in enrolment rate is susceptible to short-term shocks. Accordingly, the finding is only suggestive. The figure indicates that an increase in enrolment rate in regions with large metropolitan areas is more likely to be slower while the rate is growing faster in some non-metropolitan regions (i.e. low population-density regions) (33).

3.1.4. Relationship between human capital development and entrepreneurship

The creation of new businesses is an important source of economic dynamism. High-technology industries in particular evolve through technology-based start-ups and spin-offs by entrepreneurs who are often supported by venture

^{(&}lt;sup>30</sup>) The same relationships are found between the numbers of students as a percentage of the working population by level of enrolment and public R&D expenditure.

^{(&}lt;sup>31</sup>) Lucas (1988) discusses this, referring to the work of Jane Jacobs.

^{(&}lt;sup>32</sup>) Correlation between the variables is negative (-0.20) at the 10 % significance level (0.09).

^{(&}lt;sup>33</sup>) As might be expected, no significant correlation was found between population density and change in students in upper secondary education as a percentage of the population aged 16 to 19 years.



Figure 6: Students in tertiary education as a percentage of population aged 20 to 24 years and public R&D expenditures

Figure 7: Students in tertiary education as a percentage of working age population and population density



average of 1995-97



Figure 8: Students in upper secondary education as a percentage of working age population and population density

Figure 9: Change in students in tertiary education as a percentage of population aged 16 to 19 years and population density



Change in students in tertiary education as a percentage of population aged 16-19 years from 1995 to 1997

capital. We examined the relationship between human capital development and entrepreneurship, using the average size of firms in selected high-tech sectors as proxy for the rate of new business formation.

We focused upon ICT-related industries as their importance in the economy dramatically increased in the 1990s along with the development of the Internet and related technologies. The industries are divided into ICT-related services and ICT manufacturing (³⁴).

For ICT-related services, we found no significant association between average firm size and students in tertiary education as a percentage of the population aged 20 to 24 years. However, general and vocational types of upper secondary education show contrasting relationships with average firm size in the sectors. Students in general types of upper secondary education as a percentage of the population aged 16 to 19 years show a tendency to increase with the average firm size in ICT-related services (Figure 10). Their correlation (0.62) is significant at the 1 % level (0.001). In contrast, negative association is found between students in vocational types of upper secondary education as a percentage of the population aged 16 to 19 years and the average firm size of ICT-related services (Figure 11). Their correlation (-0.82) is significant at the 1 % level (0.000) again.

These figures suggest that those regions with a high rate of new firm formation in ICT-related services have a high enrolment rate in vocational types of upper secondary education and a low enrolment rate in general types of upper secondary education.

We obtained the same findings for ICT manufacturing, although their significance is weaker.

The correlation between the enrolment rate of general types of upper secondary education and the average firm size in ICT manufacturing is 0.34 and significant at the 10 % level (0.09). For vocational types of upper secondary education, correlation is -0.36 and significant at the 10 % level (0.07).

We also examined the same relationship with respect to traditional manufacturing industries (³⁵). No significant association was found

between average firm size and enrolment rate of any educational level examined.

In summary, human capital development appears to have significant association with the rate of entrepreneurship in emerging industries such as ICT-related services and ICT manufacturing, whereas such association is not found in traditional manufacturing industries. The association with entrepreneurship in ICT sectors is, however, found at the level of vocational types of upper secondary education. The implications of this, along with the lack of significant association with higher education, are subject to interpretation and not clear. Does the finding suggest that graduates from vocational types of upper secondary education start new firms without obtaining higher education degrees? It is often assumed (in the US) that qualified engineers with higher education degrees start new ICT-related businesses with support from venture capital. The above finding seems to contradict this assumption but clarification will require further research.

3.1.5. Human capital development and unemployment rate

Before moving on to the analysis of economic growth, we examine the relationship between human capital development and unemployment rate. Figure 14 shows the relationship between students in tertiary education as a percentage of the working age population and unemployment rate. The correlation is positive (0.19) but its level of significance is slightly over 10 % (0.11). Significant correlation is found between students in upper secondary education as a percentage of the working age population and unemployment rate (Figure 15). The correlation is 0.35 and significant at the 1 % level (0.003). In other words, individuals in regions that have high unemployment rate are more likely to invest in education and training. This fits with the general observation that individuals are more likely to invest in education and training when facing unfavourable employment situations at economic downturns.

Those regions enjoying low unemployment rate tend to have more R&D functions (Figure 16). The correlation between unemployment rate and business R&D staff as a percentage of total

^{(&}lt;sup>34</sup>) ICT-related services include NACE 64 (post and telecommunications), 72 (computer-related services) and 73 (R&D services). ICT manufacturing includes NACE 30 (office machinery and computers) and 32 (telecommunications equipment).

^{(&}lt;sup>35</sup>) The industries examined include general, electrical, and transport engineering.



Figure 10: Students in general type of upper secondary education as a percentage of population aged 16 to 19 years and average firm size in ICT-related services

Figure 11: Students in vocational type of upper secondary education as a percentage of population aged 16 to 19 years and average firm size in ICT-related services



average of 1995-97



Figure 12: Students in general type of upper secondary education as a percentage of population aged 16 to 19 years and average firm size in ICT manufacturing

Students in general type of upper secondary education as a percentage of population aged 16-19 years, average of 1995-97





average of 1995-97



Figure 14: Students in tertiary education as a percentage of working age population and unemployment rate







Figure 16: Unemployment rate and business R&D staff







Figure 18: Per worker GDP growth rate and students in general type of upper secondary education as a percentage of working age population

Figure 19: Per worker GDP growth rate and students in vocational type of upper secondary education as a percentage of working age population



employment is negative (-0.27) and significant at the 1 % level (0.01). This, along with the above findings, suggests that agglomeration of high-order corporate functions such as R&D departments has a closer association with low unemployment rate than investment by individuals in higher education.

3.1.6. Human capital development and economic growth

An initial look at the relationship between human capital development and economic growth (Figures 17, 18 and 19) shows relationships between per worker GDP (i.e. labour productivity) growth rate from 1991 to 1999 and students by level of education/training as a percentage of the working age population.

The top five regions in terms of labour productivity growth rate are those in the ex-German Democratic Republic (GDR) (³⁶). Their extraordinary growth is due to the opening of their economy to the West at the beginning of the 1990s, which gave rise to an influx of capital and technology. As can be seen from the figures, the numbers of students as a percentage of working age population in relation to labour productivity growth does not follow the pattern of the rest of our sample. Accordingly, we considered the ex-GDR regions as exceptional cases and removed them from the ensuing analysis of economic growth.

Results of the analysis of our sample excluding ex-GDR regions are as follows:

- (a) negative association (-0.26) is found between per worker GDP growth rate and students in tertiary education as a percentage of the working age population. The association is significant at the 5 % level (0.05);
- (b) there is negative association (-0.35) between labour productivity growth and students in vocational type of upper secondary education

as a percentage of the working age population. It is significant at the 1 % level (0.009);

(c) the correlation between labour productivity growth and students in general types of upper secondary education as a percentage of the working age population is positive (0.21). However, the correlation is not significant at the 10 % level (0.13).

The results contradict the generally assumed association between human capital development and economic growth. This clearly indicates that a better understanding of the relationship requires a more formal analysis that takes into account the impact of physical capital.

3.2. Formal analysis of the relationship between human capital and economic growth at regional and national level

3.2.1. Estimates at the augmented Solow-Swan model: accumulation of human capital

Formal analysis based on the Solow-Swan framework requires data on stocks of physical and human capital (e.g. average schooling years of the labour force). With respect to regions in Europe, data on average schooling years of labour force is not available (³⁷). Mankiw et al. (1992) overcomes this requirement by assuming that countries in their sample are at a steady state in the Solow-Swan framework (³⁸). We used the same method and obtained the results in Table 1.

In both models, the fraction of income invested in physical capital (*I/GDP*), and $(n + g + \delta)$, has a wrong sign. Furthermore, the fraction of income invested in human capital (*SCHOOL*) has a wrong

 $H_{75} = 0.0520 + 4.4390 PRIM_{60} + 2.6645 SEC_{70} + 8.0918 HIGH_{70}$

(³⁸) See footnote 23.

⁽³⁶⁾ Namely, Thüringen, Sachsen-Anhalt, Sachsen, Mecklenburg, and Brandenburg in order of labour productivity growth rate.0

⁽³⁷⁾ We attempted to estimate average schooling years of the labour force at the regional level, following the method used by Kyriacou (1991). In his cross-country study of the growth effects of human capital, Kyriacou examined relationships between schooling years and enrolment rates by educational level and devised the following equation,

where H_{75} represents average years of schooling in the labour force, $PRIM_{60}$ represents the 1960 enrolment rate of primary education, SEC_{70} represents the 1970 enrolment rate of secondary education, and $HIGH_{70}$ represents the 1970 enrolment rate of higher education. We evaluated a similar relationship using data for countries in Europe. However, we found no significant relationship between average schooling years and enrolment rates, so, we were unable to estimate average schooling years for regions using their enrolment data.

	Model 1	Model 2
Constant	4.49 ^(a)	4.59 ^(a)
	(0.36)	(0.30)
log (I/GDP)	-0.84 ^(b)	-0.91 ^(a)
	(0.32)	(0.25)
$\log (n + g + \delta)$	0.36	0.0004
	(0.27)	(0.25)
log (SCHOOL)	0.05	-0.67 ^(a)
	(0.16)	(0.20)
Observations	32	32
R square	0.28	0.48
F statistic	3.58	8.53

Table 1: Estimation of the augmented Solow-Swan model with the assumption of a steady state

NB: - Dependent variable is log of GDP per worker in 1997.

- Standard errors are in parentheses.

- I/GDP represents gross fixed capital formation as a percentage of GDP (average of 1987-97).

- Figures of GDP and gross fixed capital formation are at constant prices in 1995.

- $(n + g + \delta)$ represents the sum of growth rate of population, growth rate of technical progress, and rate of depreciation. - $(g + \delta)$ is assumed to be 0.06 (¹).

- SCHOOL is students in tertiary education as a percentage of working age population (average of 1995-97) in model 1

and students in upper secondary education as a percentage of working age population (average of 1995-97) in model 2. - (a) and (b) represent 1 % and 5 % significance levels respectively.

- Regressions were run using ordinary least squares method.

(¹) For a broad sample of countries, Romer (1989) finds that δ is about 0.03 or 0.04. Mankiw et al. (1992) note that growth in income per capita averaged 1.7 % in the US and 2.2 % in their sample of intermediate countries, and thus suggest that g is about 0.02.

sign in model 2, too. This suggests that the assumption of a steady state is not applicable to our sample.

Accordingly, we decided to use the business R&D staff numbers as an indicator of human capital stock (³⁹). This is consistent with the study's purpose as R&D staff embodies high-order human capital that is deemed critical to technological progress in endogenous growth literature.

We applied the standard augmented Solow-Swan model $Y = AK^{\alpha} L^{\beta} H^{\gamma}$ to the data of physical capital stock, total employment, and business R&D staff in 1990 and 1997 with different depreciation rates (⁴⁰).

The period from 1990 to 1997 is adopted for the following reasons:

(a) the EU economy entered a new era of integration after the full liberalisation of capital movements in eight Member States in 1990 as well as political landmarks such as the fall of the Berlin Wall in 1989 and unification of Germany in 1990. In tandem with the revolutionary effect of ICTs including the Internet, economic integration spurred movement of money and people within

^{(&}lt;sup>39</sup>) Because total R&D staff data availability is restricted to a smaller number of regions, we could not undertake the same analysis for total R&D staff (including staff in government institutes and higher education institutions) and compare the results with those for private R&D staff only.

^{(&}lt;sup>40</sup>) Stocks of physical capital at the regional level are estimated using the Penn World Tables 5.6. A description of the tables is found in Summers and Heston (1991). First, based on a standard three-factor neoclassical aggregate production function with constant returns, $Y = K^{\alpha} L^{\beta} H^{\gamma}$, we estimated at the national level a model that accounts for GDP of EU nations. We obtained a model whose coefficients are all significant at the 1 % level. Then using the model, we estimated the stock of physical capital for each of the regions in our sample. Finally we adopted the perpetual inventory method to produce physical capital stocks for 1986 and onwards. (See Barro and Sala-i-Martín, 1995 about the perpetual inventory method.) As a depreciation rate δ , we used 0.04. See footnote 37 above. To see effects of a different depreciation rate, we also tested 0.07, following Benhabib and Spiegel (1994).

EU. This, in turn, facilitated the rapid exchange of information and knowledge, making leading-edge technology, which firms within a region aim for in their innovation efforts, more generally available. Prevalence of leading-edge knowledge or technology is often assumed in growth model literature;

(b) we used 1985 as the base year to which the perpetual inventory method was applied to estimate physical capital stock in each region. This is the earliest year we could use to estimate each region's capital stock from the national data. The 1985 capital stock data at the regional level is subject to estimating error. Because of the cumulative calculation of the perpetual inventory method, the later the start year of the Solow-Swan analysis, the more reliable the regional capital stock data. At the same time, a reasonably extensive period is necessary for the Solow-Swan analysis to measure long-term growth.

By taking log of the standard augmented Solow-Swan model, the following equation is obtained:

$$\log Y_T - \log Y_0 = \log A_T - \log A_0 + \alpha (\log K_T - \log K_0)$$
$$+ \beta (\log L_T - \log L_0) + \gamma (\log H_T - \log H_0).$$

Estimated coefficients are shown in Table 2 (⁴¹). The augmented Solow-Swan model that includes physical capital, labour, and business R&D staff accounts for the economic growth between 1990 and 1997 with R square of 0.71 and 0.72 for models 1 and 2 respectively. Although the estimated coefficient for log difference in physical capital is significant only at the

	Model 1	Model 2	Model 3	Model 4
Constant	-0.04	-0.03	0.72 ^(a)	0.73 ^(a)
	(0.05)	(0.04)	(0.16)	(0.16)
dK	0.40 ^(c)	0.42 ^(c)	0.36 ^(b)	0.38 ^(b)
	(0.22)	(0.21)	(0.17)	(0.16)
dL	0.53 ^(a)	0.49 ^(a)	0.67 ^(a)	0.63 ^(a)
	(0.16)	(0.17)	(0.13)	(0.04)
dH	0.16 ^(a)	0.15 ^(a)	0.08 ^(b)	0.08 ^(b)
	(0.04)	(0.04)	(0.03)	(0.03)
Y ₀			-0.16 ^(a)	-0.16 ^(a)
			(0.03)	(0.03)
Observations	32	32	32	32
R square	0.71	0.72	0.84	0.84
F statistic	22.8	23.6	36.6	38.3

Table 2: Estimation of the augmented Solow-Swan model

NB: - Dependent variable is the log difference in GDP.

- Standard errors are in parentheses.

- *dX* refers to the log difference in variable *X*.

- The period for comparison is 1990-97.

- K, L, H, and Y₀ represent stock of physical capital, number of workers, and size of business R&D staff, and per worker GDP in 1990 respectively.

- Figures of physical capital are at 1995 constant prices.

- (a), (b), and (c) represent 1 %, 5 %, and 10 % significance levels respectively.

- Models 1 and 3 use a depreciation rate of 0.04.

- Models 2 and 4 use a depreciation rate of 0.07.

- Regressions were run using ordinary least squares method.

(⁴¹) The equation implies that the first term of the right-hand side of the equation, $\log A_{\tau} - \log A_{o}$, is constant and common for all economies under analysis. In other words, technology or knowledge is spread and available to all economies.

10 % level (0.08 in model 1 and 0.05 in model 2), log differences in labour and business R&D staff enter highly significantly. The significance of log difference in labour is 0.003 in model 1 and 0.008 in model 2, and the significance of log difference in private R&D staff is 0.001 in both models 1 and 2. The results suggest that the change in business R&D staff during the period varies in a way distinct from those in physical capital and labour and accounts for a significant part of the variation of the change in GDP. The positive sign for the coefficient of the log difference in business R&D staff means that an increase in business R&D staff led to an increase in the region's per worker GDP (i.e. labour productivity).

We also entered initial income per worker (GDP in 1990 worker), Y_0 , in the equation (model 3 and model 4). In the neoclassical Solow-Swan framework that supposes decreasing returns on capital, the level of per capita GDP will converge toward its steady state asymptotically. The speed of convergence increases with the distance to the steady state. In other words, when the determinants of the steady state are controlled for, the lower initial values of per capita GDP, the higher transitional growth rates. This is called 'conditional convergence'. As expected from previous empirical studies that support conditional convergence, initial per worker GDP in 1990 enters with a negative sign at the 1 % significance level (0.00 in both model 3 and model 4). More importantly, the coefficient for log difference in business R&D staff remains positive and significant at the 5 % level (0.03 in both model 3 and model 4) although its value becomes less than in models 1 and 2.

The results of Table 2 suggest that high-order human capital represented by business R&D staff contributes to economic growth in the same way as other production factors (i.e. physical capital, labour). That is, it is the accumulation of the human capital that affects economic growth. This is consistent with the neoclassical Becker-Lucas framework predicting that the accumulation of human capital determines the marginal productivity of education and maintains it at a positive level.

3.2.2. Estimates at the Nelson-Phelps

framework: level of human capital stock Nelson and Phelps, and Benhabib and Spiegel provide a different framework, according to which it is the level of human capital stock that affects an economy's capacity to develop and implement new technologies. The level of human capital stock is positively related to the rate of technical progress, or the growth rate of productivity parameter *A*, in their view.

R&D staff certainly reflects such a capacity in an economy. In their cross-country study, Benhabib and Spiegel used average years of schooling in the labour force as an indicator of human capital. focusing on investment in education as a whole. Unlike schooling years, R&D staff are a small segment of the labour force that embodies high-order human capital. Though small in size, this sector is considered a good representation of an economy's capacity to develop new technologies (i.e. knowledge) as argued in an endogenous growth literature. Also, R&D staff are frequently involved in transferring and implementing new technologies developed in other sectors or understanding new technologies invented by other firms in their own sectors (e.g. reverse engineering). Hence the framework of Nelson and Phelps may be applicable to R&D staff.

We tested two equations based on this framework. The first equation takes an average of human capital levels during the period under examination.

$$\log Y_{T} - \log Y_{0} = \log A_{T} - \log A_{0} + \alpha (\log K_{T} - \log K_{0}) + \beta (\log L_{T} - \log L_{0}) + \gamma (\frac{1}{T} \sum_{0}^{T} \log H_{t}).$$

Table 3 shows results of the estimates of coefficients.

In model 1, all terms, including log of an average of business R&D staff in level from 1990 to 1997, enter the equation significantly at the 1 % level. However, whereas the coefficients for log differences in physical capital and labour are positive (as expected), the coefficient for the

average business R&D staff is estimated as negative. In other words, regions with a higher level of business R&D staff experienced a slower growth from 1990 and 1997.

In model 2, we included initial per worker GDP (labour productivity) in 1990 in the equation to see the effects of conditional convergence. Log differences in physical capital and labour enter

Table 3: Cross-regiona	I growth	accounting	results: human	capital in lo	g levels
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	Model 1	Model 2
Constant	-0.16 ^(a)	0.58 ^(c)
	(0.04)	(0.30)
dK	0.92 ^(a)	0.58 ^(b)
	(0.20)	(0.24)
dL	0.50 ^(a)	0.62 ^(a)
	(0.14)	(0.14)
АН	-0.06 ^(a)	-0.02
	(0.01)	(0. 02)
Y ₀		-0.14 ^(b)
		(0.06)
Observations	32	32
R square	0.78	0.82
F statistic	33.9	30.8

NB: - Dependent variable is the log difference in GDP.

- Standard errors are in parentheses.

- *dX* refers to the log difference in variable *X*.

- The period for comparison is 1990-97.

- K, L, and Y_o represent stock of physical capital, number of workers, and per worker GDP in 1990 respectively.

- AH is an average of business R&D staff during 1990-97.

- Figures of physical capital are at 1995 constant prices.

- Depreciation rate is 0.04.

- (a), (b), and (c) represent 1 %, 5 %, and 10 % significance levels respectively.

- Regressions were run using ordinary least squares method.

significantly (0.02 and 0.00 respectively), taking a proper positive sign. The term for initial labour productivity, Y_0 , also enters significantly at the conventional 5 % level (0.03). Its negative sign shows that the lower initial per worker GDP, the faster an economy grows. In other words, conditional convergence took place among the regions. As for the average business R&D staff in level, its coefficient takes a negative sign. Furthermore, it fails to enter significantly (0.32).

The failure of business R&D staff to enter the equation significantly in model 2 is due to close association between business R&D staff in level and per

worker GDP. As the level of business R&D staff has close association with the level of labour productivity (⁴²), the average R&D staff from 1990 to 1997, *AH*, in model 1 acts as a proxy for the level of labour productivity and enters the equation with a negative sign, suggesting conditional convergence among the regions. However, when initial labour productivity, Y_0 , is included in model 2, it accounts for the convergence better than level of R&D staff does. Hence level of R&D staff loses its significance in model 2.

The second equation we tested includes two terms of human capital that represent its different effects.

$$\log Y_{T} - \log Y_{0} = c + gH_{i} + mH_{i} [(Y_{\max} - Y_{i})/Y_{i}] + \alpha (\log K_{T} - \log K_{0}) + \beta (\log L_{T} - \log L_{0})$$
$$= c + (g - m)H_{i} + mH_{i} (Y_{\max} / Y_{i}) + \alpha (\log K_{T} - \log K_{0}) + \beta (\log L_{T} - \log L_{0}).$$

^{(&}lt;sup>42</sup>) We examined contributions of physical capital, labour, and business R&D staff in levels to the level of income of regions in 1990 and 1997, using a standard three-factor neoclassical aggregate production function with constant returns, Y = K^α L^β H^γ. The level of business R&D staff enters the equation significantly with a positive sign, suggesting that regions with a higher level of business R&D staff have a higher level of income per capita (labour productivity).

The term, *gH*, represents endogenous development based on the level of human capital, and the term, *mHi* [$(Y_{max} - Y_i)/Y_i$], represents catch-up of region *i* with the region leading in terms of per capita GDP, Y_{max} (i.e. the region with the highest labour productivity in the data set).

Table 4 shows the results.

In model 1, both log differences in physical capital and labour enter the equation at the 1 % significance level (0.001 and 0.009 respectively) with a proper positive sign. The coefficient estimate for (g - m) on H is negative and significant at the 10 % level (0.08). The negative sign suggests that regions with a higher level of business R&D staff in 1990 experienced a slower growth from 1990 to 1997. In contrast, the catch-up term of business R&D staff, H_0 (Y_{max}/Y_i), fails to enter the equation significantly (significance: 0.79) though it takes a positive sign.

In model 2, we added the initial ratio of the labour productivity of the leading-edge region to that of region *i* to see the effects of conditional convergence (43). As in model 2 in Table 3, the initial position of a region in terms of labour productivity, Y_{max}/Y_{i} , enters at the 1 % significance level (0.002). Its sign is positive, suggesting conditional convergence: the larger the initial gap with the leading region, the faster an economy grows. On the other hand, neither Y_0 nor $Y_0(Y_{max}/Y_i)$ enters significantly (0.62 and 0.34 respectively). In other words, conditional convergence that is due to a region's initial position in per worker GDP exerts more significant effects upon its change in GDP. Although the size of business R&D staff, H_0 , plays the role of a proxy for labour productivity level, its effects as an economy's capacity to develop and implement new technology in the Nelson-Phelps framework are found insignificant.

These findings are in stark contrast to those of Benhabib and Spiegel. In their cross-country study, Benhabib and Spiegel found that the catch-up term of human capital enters significantly. The catch-up term maintains its proper sign (i.e. positive) and significance (though significance level drops from 1 % to 5 %) even if the variable for initial position of income Y_{max}/Y_i is included. In contrast, our results show that neither of the human capital terms is found significant, whereas initial position as well as log differences in physical capital and labour enter at an equal or higher level of significance than in the case of Benhabib and Spiegel (⁴⁴).

Even if we focus on wealthier economies in the sample of Benhabib and Spiegel, their results are different. In their study, Benhabib and Spiegel divided their sample into 3 groups (26 countries each) according to wealth. For the wealthiest third of the sample, they found that the endogenous development term of human capital H enters significantly while the catch-up term is found insignificant. However, the sign for H is found positive in their study suggesting that the capacity to develop and implement new technology, which H represents, contributes to economic growth positively. In contrast (as shown in model 1 in Table 4), the sign of the term in our results is negative, suggesting that the greater the volume of human capital in level (i.e. business R&D staff in our case), the slower an economy grows.

Most important, accumulation of human capital (i.e. business R&D staff in our case) accounts for economic growth at a significant level along with accumulation of physical capital. In the study of Benhabib and Spiegel, accumulation of human capital fails to enter significantly with respect to all three measures of human capital they tested (⁴⁵) as well as alternative subsamples of the data. In addition, the sign of human capital accumulation was found negative in most of the cases they examined.

3.2.3. Human capital and growth: cross-country estimates

An obvious, possible source for the difference between the findings is the different types of human capital examined. While Benhabib and Spiegel adopt average schooling years of the labour force, we use the number of private sector workers engaged in R&D which endogenous growth literature focuses upon as a source of

⁽⁴³⁾ This follows the equation adopted by Benhabib and Spiegel. Adding initial labour productivity in 1990 (as in model 2 in Table 3 as well as many studies of conditional convergence) produces similar results. In that case, the coefficient for the variable takes a negative sign.

⁽⁴⁴⁾ In their estimates, log difference in labour fails to enter the model significantly whereas the coefficient for log difference in physical capital was found significant at the 1 % level.

⁽⁴⁵⁾ Namely, average schooling years used by Kyriacou (1991), the Barro and Lee (1993) estimate of human capital, and literacy.

	Model 1	Model 2
Constant	-0.11 ^(b)	-0.15 ^(a)
	(0.04)	(0.04)
dK	0.88 ^(a)	0.59 ^(a)
	(0.23)	(0.21)
dL	0.41 ^(a)	0.65 ^(a)
	(0.14)	(0.14)
H _o	-0.05 ^(c)	0.01
	(0.03)	(0.03)
$H_0 (Y_{max}/Y_i)$	0.006	(0.02)
	-0.02	(0.02)
Y_{max}/Y_{i}		0.04 ^(a)
		(0.01)
Observations	32	32
R square	0.78	0.85
F statistic	23.9	29.5
NB: - Dependent variable is the log difference i	n GDP.	

Table 4:	Cross-regio	onal growth	accounting	results: H	luman cap	oital in l	evels and i	n product c)1
	levels and o	differences [•]	from the lea	adina-eda	e region ir	labour	productivi	tv	

- Standard errors are in parentheses.

- dX refers to the log difference in variable X.

- The period for comparison is 1990-97.

- H_0 is the size of business R&D staff in 1990.

- Y_{max}/Y_i represents the ratio of the labour productivity of the leading-edge region to that of region i in 1990.

- Figures of physical capital are at 1995 constant prices.

- Depreciation rate is 0.04.

- (a), (b), and (c) represent 1 %, 5 %, and 10 % significance levels respectively.

- Regressions were run using ordinary least squares method.

technical progress. To see if the different type of human capital affects the results, we undertook an analysis based on average schooling years. Since data on schooling for the labour force is not available at regional level, the analysis is only at national level. The figures for persons in the

labour force (25 to 59 years old) who completed education, given by educational level, are available for 11 countries in the EU for the period from 1992 to 2000. From the data, we calculated an estimate of average schooling years (46) and tested the following three models:

$$\log Y_T - \log Y_0 = \log A_T - \log A_0 + \alpha (\log K_T - \log K_0)$$
$$+ \beta (\log L_T - \log L_0) + \gamma (\log H_T - \log H_0),$$

$$\log Y_T - \log Y_0 = \log A_T - \log A_0 + \alpha (\log K_T - \log K_0) + \beta (\log L_T - \log L_0) + \gamma (\frac{1}{T} \sum_0^T \log H_t),$$

and

⁽⁴⁶⁾ We gave 9 years, 12 years and 16 years for those who completed lower secondary education, upper secondary education, and tertiary education respectively.

$$\log Y_T - \log Y_0 = c + (g - m)H_i + mH_i (Y_{\max} / Y_i) + \alpha (\log K_T - \log K_0) + \beta (\log L_T - \log L_0).$$

Table 5 shows the results.

The estimates show lower significance, in large part due to the small sample size. However, the patterns of significance are consistent with the results for business R&D staff except for insignificant estimates for labour. In model 1, only log difference in physical capital enters significantly (0.014) although all variables take a proper, positive sign. The significance of log difference in schooling years is 0.14, being above the conventional maximum cut-off point of 10 %. However, in model 2 that includes initial level of income, log difference in schooling years and as log difference in physical capital, enter significantly at the

Table 5: Cross-country growth ac	counting results	, 1992-2000
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	Model 1	Model 2	Model 3	Model 4
Constant	-0.06	-0.15	-0.05	0.01
	(0.04)	(0.17)	(0.09)	(0.16)
dK	0.61 ^(b)	0.75 ^(b)	0.55 ^(b)	0.49
	(0.19)	(0.21)	(0.22)	(0.28)
dL	0.002	-0.14	0.02	0.06
	(0.30)	(0.31)	(0.36)	(0.41)
dH	0.33	0.56 ^(a)		
	(0.20)	(0.26)		
AH			0.0009	
			(0.006)	
H _o				0.005
				(0.02)
$H_0(Y_{max}/Y_i)$				-0.008
				(0.03)
Y ₀		-0.05		
		(0.04)		
Observations	11	11	11	11
R square	0.65	0.73	0.52	0.52
F statistic	4.3	4.1	2.5	1.6
NB: - The following 11 countries	were included. Belaium	Denmark Germany Gr	eece Spain France Ire	land Italy the Nether-

NB: - The following 11 countries were included: Belgium, Denmark, Germany, Greece, Spain, France, Ireland, Italy, the Netherlands, Portugal, and the UK.

- Dependent variable is the log difference in GDP.

- Standard errors are in parentheses.

- *dX* refers to the log difference in variable *X*.

- The period for comparison is 1992-2000.

- K, L and H represent stock of physical capital, number of workers, and average schooling years of the labour force respectively.

- AH is an average of H during 1992-2000.

- H_0 is the value in 1992.

- Y_{max}^{o}/Y_{i} represents the ratio of the labour productivity of the leading-edge region to that of region *i* in 1992.

 Y_0 is per worker GDP in 1992.

- Figures of physical capital are at 1995 constant prices.

- Depreciation rate is 0.04.

- (a), (b), and (c) represent 1 %, 5 %, and 10 % significance levels respectively.
- Regressions were run using ordinary least squares method.

levels of 10 % and 5 % (0.07 and 0.011) respectively. In other words, an improvement of educational level in the labour force led to higher economic growth during the period. In contrast, model 3 and model 4, which take schooling years in levels, fail to be significant (⁴⁷). Estimates of the coefficients for human capital terms in the two models are very small relative to standard errors, showing little significance. Though the results are not conclusive due to the small sample size, they suggest that, even if schooling years are adopted as an indicator of human capital (as in the study of Benhabib and Spiegel), their accumulation, not their stock level, accounts for economic growth.

It is most likely that catch-up effects of human capital Benhabib and Spiegel observed are found in the case of extremely wide gaps between developed countries and developing countries, including ones in Africa and Latin America. When we focus upon developed economies such as regions in the EU, the effects of human capital upon economic growth derives from its accumulation.

4. Summary and conclusions

This report has reviewed literature and empirically examined the way in which human capital development is associated with economic growth in regions in Europe in the 1990s. While powerful multinational corporations are becoming evermore 'footloose' and escaping from the control of nation states, regions are 'competing' against one another, within and across nations, at attracting investments and supporting local businesses to increase competitiveness in the global market. In this, many regions, and particularly ones in peripheries, are facing the reality of persistent regional disparities in productivity and corporate functions located. By examining the relationship between human capital formation and economic performance in European regions, this study aims to go some way towards answering the question whether, and how, human capital development provides these territorial units with comparative advantages over others.

In growth model literature, human capital has gained increased recognition as one of key production factors following physical capital and labour. The original Solow-Swan model consisted of physical capital and labour alone, failing to account for a significant part of income growth as residual (called the 'Solow residual'). This residual was considered to be an exogenous factor that derives from technical progress taking place where there is a public science base. In the meantime, a number of studies, most notably the seminal work of Becker, drew attention to investment in skills and knowledge as another factor of production. As a result, the Solow-Swan model came to be augmented with the inclusion of an additional term of human capital.

4.1. Significance of economic growth models

Another development in growth model literature is endogenous growth models. Whereas the neoclassical Solow-Swan model treats technical progress as an exogenous factor, endogenous growth models take into consideration the process of innovation and technology diffusion, making a departure from the assumption of perfect competition. The mechanism of investing in research takes centre stage in the model. As a result, R&D workers, who embody high-order human capital, are often included in the models.

An issue identified in growth model literature is the way human capital development affects economic growth. According to the framework developed by Lucas on the basis of Becker's human capital theory, growth is primarily driven by the accumulation of human capital. In contrast, Nelson and Phelps contend that the stock of human capital determines the economy's capacity to innovate or catch up with more advanced economies, which in turn drives economic growth. Hence, the level of human capital stock is, though indirectly, a determinant of per capita economic growth in this view. While the first framework is in agreement with neoclassical growth models, the second framework has revived in the Schumpeterian growth literature.

4.2. The regional dimension

These economic models are criticised in economic geography literature for their failure to consider spatial aspects of economic development. Unlike the neoclassical assumption that factors of production are completely mobile, knowledge and innovations do not diffuse instantaneously or at an even rate over the economy as a whole. Tacit knowledge in particular, whose transfer often relies on interpersonal, often face-to-face communications, is argued to be concentrated in major metropolitan areas, signifying the importance of human capital that represents a carrier of such knowledge. Furthermore, there is a view that the position of metropolitan areas is strengthened by the cumulative causation mechanism in which the education and training system interacts with the local economy to further spatial disparities in economic well-being.

Our empirical analysis of European regions

shows that investment by individuals in human capital development has distinct patterns. Those regions with a higher level of investment in tertiary education tend to have a larger concentration of ICT sectors (including provision of ICT services and manufacture of ICT devices and equipment) and research functions. On the other hand, there is no significant association between such high-order functions and investment in upper secondary education, both general and vocational types.

In relation to the density of economic activity, those regions that include major metropolitan areas show a high enrolment rate for tertiary education. While this is, to some degree, due to a concentration of higher education institutions in those areas, the association also suggests a possibility of link to high-order corporate functions that tend to concentrate in high-density metropolitan areas. However, some low-density regions have made progress in take-up of tertiary education at a faster pace, closing a gap in the formation of high-order human capital.

Generation of new firms is an important source of economic dynamism. In our empirical analysis, the rate of human capital development appears to have significant association with the rate of entrepreneurship in emerging industries such as ICT-related services and ICT manufacturing, whereas such association is not found with traditional manufacturing industries. The association with entrepreneurship in ICT sectors is, however, found at the level of vocational type of upper secondary education, not at the level of tertiary education. The implications of this are subject to interpretation and require further research.

Individuals in regions that suffer from high unemployment rate tend to invest more in education and training. This fits with the general observation that individuals are more likely to invest in education and training when facing with unfavourable employment situations at economic downturns. Another finding in relation to this is that individuals in regions with lower unemployment rate tend to have a higher level of R&D functions.

In short, a high level of investment by individuals in tertiary education is found in those regions that accommodate high-tech industries and high-order corporate functions like R&D. Regions support such high-order functions through the urban infrastructure, facilitating exchange of tacit knowledge, as well as through a public science base. They also enjoy a low unemployment rate.

However, the existing stock of human capital does not lead to a high rate of economic growth. We did not find any significant effects of scale that would favour those regions with a larger stock of human capital. Instead, our empirical analysis demonstrates that the rate of economic growth is associated with the accumulation of human capital. Furthermore, those regions with a lower per worker GDP at the beginning of the period of our analysis tend to show a faster growth rate.

4.3. Policy implications

The primary policy implication of our study is the need to support continuous human capital development. The growth of computers and digital technology has led a number of observers to a renewed enthusiasm for the Schumpeterian vision of capitalist creative destruction (Harris, 2001). With the notion of the 'knowledge-based economy' they view that creation of knowledge and its conversion to commercial use plays a greater role than ever in economic development. Knowledge is distinct from natural resources in its non-rival nature: its use by one firm or person in no way limits its use by another. Once it is created, knowledge is not depleted: it adds to the existing stock of knowledge.

This non-excludable nature of knowledge in turn allows research workers to share the stock of knowledge and act on it to create new ideas. New ideas will be then embodied in new or improved products and production processes, bringing about economic growth. A prediction drawn from this view of the knowledge-based economy is its ever-continuing growth. As an economy shifts its primary activities to knowledge creation, with its conversion to commercial value, the economy is more likely to benefit from the existing stock of knowledge that only continues to grow. The view also predicts the advantage of an economy with a large stock of research workers: the more workers are engaged in research, the more new ideas are likely to be created. Accordingly, a rosy picture of continued

growth in advanced economies emerged with the long-term boom in the US economy in the 1990s.

contrast to the prediction of the In knowledge-based economy, our findings show that there is not any significant association between the existing stock of research workers and economic growth. Instead, economic growth is found to be associated with accumulation of research workers. This suggests that a key to economic growth is continuous development of high-order human capital. While there is little doubt that advanced economies in Western Europe are becoming more knowledge-based, they cannot rest on the existing research base to grow further. Given the increasingly fast pace of technological change that makes human capital obsolete, a concerted effort needs to be made to facilitate continuous development of high-order human capital.

The development of high-order human capital does not mean education and training to increase research workers alone but refers to development of 'knowledge workers' in a broad spectrum of economic activities. As Kline and Rosenberg (1986) demonstrate, knowledge creation has shifted from a traditional linear process of innovation to a more complex chain-linked model based on interactions between knowledge workers. In this new mode, creation of new ideas takes place throughout the entire value chain spanning an organisation's different functions (e.g. R&D, production, marketing, sales) and its external partners (e.g. suppliers, customers, universities, research institutes, government organisations). Development of such an organisation-wide innovation capacity in an economy will require education and training policy that aims to upgrade continuously a broad range of human capital to a higher level.

List of abbreviations

GDR	German Democratic Republic
ICT	Information and communication technology
NUTS	Nomenclature of territorial units for statistics
R&D	Research and development

Annex 1 Technical difficulty of incorporating increasing returns to a neoclassical model

Suppose the prices of output *F* and factors *K*, *L* and *A* be *p*, w_K , w_L , and w_A respectively. If each factor is paid its marginal product,

$$w_{K} = p \frac{\partial F}{\partial K}$$
 $w_{L} = p \frac{\partial F}{\partial L}$ $w_{A} = p \frac{\partial F}{\partial A}$

Output *F* can be then written as:

$$F = \frac{1}{p} \left(w_K K + w_L L + w_A A \right) = K \frac{\partial F}{\partial K} + L \frac{\partial F}{\partial L} + A \frac{\partial F}{\partial A}$$
(5)

According to Euler's Theorem, if $f(x_1, ..., x_n)$ has continuous first partial derivatives and is positively homogeneous of degree k, then:

$$\sum_{i=1}^{n} x_i \frac{\partial}{\partial x_i} f(x_1, \dots, x_n) = k f(x_1, \dots, x_n)$$

This suggests that equation (5) holds if F(K, L, A) is positively homogeneous of degree 1, that is:

$$F(tK, tL, tA) = tF(K, L, A)$$

It is easy to see that this would mean constant returns in *K*, *L* and *A*. Hence under increasing returns, all factors cannot be paid their marginal products.

Annex 2 Growth rate of consumption in Romer (1986) model

The rate of saving is determined by the owner of the representative (i.e. average) one-worker firm who tries to maximise his lifetime utility *W*. Thus the problem is expressed as:

 $\max\int_0^\infty u(c_t)e^{-\rho t}dt$

subject to $\frac{dK}{dt} = \overline{AK}^{\alpha} - c$ (i.e. investment equals net product minus consumption) and $\frac{dK}{dt} \ge 0$.

Assuming a constant intertemporal elasticity of substitution (i.e. $u(c) = \frac{c^{1-\varepsilon} - 1}{1-\varepsilon}$), the above dynamic optimisation problem yields the Euler equation:

$$\frac{\frac{dc}{dt}}{c} = \frac{1}{\varepsilon} \left(\frac{\partial F}{\partial K} - \rho \right) = \frac{1}{\varepsilon} \left(a \overline{A} K^{\alpha - 1} - \rho \right)$$

(because of L = 1, $F = \overline{A}K^{\alpha}$ in the case of the representative one-worker firm).

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