Modelling Regional Economic Growth: The Role of Human Capital and Innovation

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Abstract

This thesis investigates the role of human capital and innovation activity in the process of economic growth within a system of regions.

It starts by reviewing existing theories of economic growth paying particular attention to the literature on "endogenous growth", the large body of empirical literature addressing economic growth and that has investigated the "convergence issue".

A methodology based on the direct analysis of cross-sectional distributions of per capita income is then developed and applied to per capita income data for 122 European Union (EU) functionally defined regions over the period 1979-1990. The results show a clear tendency for some of the richest European regions to grow away from the others. The comparison of these results with those derived from a similar analysis for the commonly used administrative regions of the EU reveals some significant distortions imposed by adopting an administrative definition.

A formal theoretical explanation of these results is then offered. In particular, it is argued that regional disparities in per capita income owe their existence to the pattern of specialisation between 'knowledge creating' and 'knowledge applying' regions. Specialisation is explained in terms of differences in the availability of useful knowledge at different locations. In the perfect foresight, stable equilibrium of the two-region model developed here, therefore, the region that specialises in innovation related activities (knowledge creating) enjoys a permanently higher level of per capita income. Moreover, it is shown that, on reasonable assumptions, a process of integration that reduces the cost of physical distance leads to faster growth in the long-run for the system as a whole, but at the expense of an increase in regional disparities.

Finally, some predictions are derived and tested empirically. Using cross-sectional regressions, the fundamental determinants of the growth rate of a region are investigated. The results are supportive of the model, confirming the role played by the concentration of innovative activities and spatial spillovers of knowledge.

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Needless to say, all errors and remaining infelicities of style are my responsibility.

Chapter 1
Introduction

Disparities in per capita output and income across regions have been a concern for the European Community since its inception. The objective of reducing disparities across regions, laid down in the preamble to the Treaty of Rome in 1957, has been further emphasised in the 1980s with the entry of Greece, Portugal and Spain into the Community. In 1987, with the Single European Act, the Community was granted explicit competence for undertaking a regional policy aimed at reducing existing disparities. Growing political concern for the 'regional problem' has also meant that a considerable, and increasing, amount of resources have been spent in an attempt to mitigate its manifestations. Thus, the funds devoted to structural regional policies reached 21 billion ECU in 1993 (E.C. 1994) and are expected to increase to 30 billion ECU by 1999, which will include the new Cohesion Fund created to provide additional aid to the poorest Member States with a per capita GDP of less than 90% of the Community average (E.C. 1994).

The European Commission's focus on regional disparities has been paralleled by a renewed academic interest, both empirical and theoretical, in the economic analysis of growth and convergence. On the one hand, empirical analyses investigating the process of economic growth and, in particular, aimed at confirming the existence of a process of convergence across national and regional economies have flourished, facilitated by the availability of new data sets. A substantial proportion of this empirical literature is made up of cross-sectional and panel data regression analyses. In general, however, these empirical analyses seem to suffer from two distinct problems. Firstly, they do not provide evidence which would allow one to distinguish between different theoretical explanations of the growth process. Secondly, cross-sectional regression analyses of convergence focus on the behaviour of a representative economy and rely on the implicit assumption that each economy is characterised by a steady-state growth path along which it is moving.

Although developed within the framework of the traditional neoclassical model of growth, cross-sectional and panel data regression analyses of convergence do not appear to represent a valid test for this theory. Indeed, their typical results, that economic systems are converging at a stable rate of 2 per cent per year, are consistent with many other explanations of the growth process. They could be equally consistent, for example, with the evolutionary approach to economic growth or to the endogenous growth literature. Other sources of empirical evidence on the determinants of economic growth need to be utilised, therefore, in trying to evaluate the relative merits of the different theories. The findings of analyses alternative to traditional cross-sectional convergence regressions suggest that the study of economic growth cannot abstract from the study of technological change and its determinants.

This has stimulated the formulation of new theoretical accounts of the relationship between economic growth and technological progress that differ substantially from the traditional neoclassical one. Within the traditional neoclassical model technological change is interpreted as a purely exogenous phenomenon and thus no economic explanation of its evolution is provided. By contrast, the 'evolutionary approach' has developed a framework in which technological change is explained by the action of economic agents. Much of the theoretical work within the evolutionary tradition has relied primarily on appreciative theory, that is on less abstract, more descriptive modelling. This work has then been a source of inspiration for recent work on 'endogenous growth' within the formal modelling tradition of mainstream economics which has tried to codify some of the fundamental elements of the evolutionary view. As a result, although differing profoundly in many ways, both frameworks interpret technological progress as either the by-product of other economic activities or the intentional result of research efforts carried out by profit seeking agents and therefore consider human capital and innovation as fundamental elements in the explanation of the process of economic growth.

One of the aspects that has not received sufficient attention from endogenous growth theorists is represented by the relationship between technological progress, knowledge spillovers and space. Fagerberg emphasises that “appreciative theorising often describes technology as organisationally embedded, tacit, cumulative in character, influenced by the interaction between firms and their environments, and geographically localised” (Fagerberg 1994, page 1170). Tacit knowledge, in particular, being the non-written personal heritage of individuals or groups is naturally concentrated in space. Moreover, because of its personal nature, tacit knowledge spills over space essentially through direct, face-to-face, contacts. It seems therefore important to analyse the geographical dimension of these spillovers explicitly. This is a feature of knowledge creation and transmission that has been entirely neglected in formal theories of endogenous growth. Chapter 5 and 6, therefore, present a formal model of regional growth that that tries to incorporate these features. The model, which builds on the existing literature on endogenous growth and, in particular, on the work of Romer (1990a and b), Rivera-Batiz and Romer (1991a and b) and Rivera-Batiz and Xie (1993), presents three main features. Firstly, economic growth is endogenous and driven by the research activity of profit-seeking agents. Secondly, an explicit role in regional production structures is assigned to human capital. In particular, this factor of production is considered as the crucial input in the research sector. Thirdly, knowledge spillovers across space are an essential feature of research activity aimed at designing and developing new products.

The second problem that characterises cross-sectional regression analyses of convergence is that they focus on the behaviour of a representative economy and rely on the implicit assumption that each economy is characterised by a steady-state growth path along which it is moving. This assumption however appears excessively strong and, as a result, several authors have presented different empirical approaches that concentrate on the evolution of cross-sectional distributions of per capita income whilst requiring absolutely no assumptions about the nature of the steady-state. Another important advantage of these approaches is that they provide information on the dynamics of the entire cross-sectional distribution of income rather than on the transition of the representative economy towards its own steady-state. The results of many empirical analyses employing this new approach look quite unlike the pattern of convergence implied by the traditional neoclassical model. The reduction of national barriers with the consequent increase in competition, the encouragement of factor mobility, the promotion of infrastructure investment in lagging regions are all measures that should have assisted the equilibrating mechanisms characterising the neoclassical model in the process of 'regional convergence': that is towards the achievement of a more equal distribution of income across the regions of the European Union. By contrast, according to many of these new studies, the most affluent and innovative regions appear to have further strengthened their economic advantage over peripheral, less advanced parts of the system in recent years.

Chapter 4 presents a methodological alternative to cross-sectional or panel data regressions, in the spirit of Quah (1993a and b, 1994, 1996a and b, 1997a and b). Following Quah, this methodology analyses the cross-sectional distribution of per capita income directly, studying its intra-distributional dynamics and the change in its external shape, whilst requiring absolutely no assumptions with respect to the nature of the steady-state. Rather than allowing it to be continuous, it is chosen to make the distribution of income discrete, because through discretisation it is possible to gain more information on the features of the growth and convergence process under study. Indeed, the choice between discrete and continuous space methods of analysis can be interpreted as a trade-off between information and subjectivity. The view implicit in the analysis presented in Chapter 4 is that, rather than reducing the set of information obtainable from the analysis, it is worth trying to develop less subjective discretisation criteria which reduce the risk of distorting the underlying model. In other words, the methodology adopted here tries to overcome the subjectivity involved in the choice of the discretising grid whilst not only allowing the study of the one-period dynamics and the resulting ergodic distribution, but also the analysis of the transitional dynamics as well as the calculation of the speed at which any steady-state may be approached.

The methodology developed here is then used to investigate the convergence issue among the regions of the European Union between 1979 and 1990. The first important element of the study is represented by the definition of regions that is to be used. National territories may be subdivided into regions according to different criteria which, in general, range between two extremes: normative criteria and functional criteria. One example of the definition of regional units according to normative criteria is represented by the administrative regions for which data are normally published and which, hitherto, have constituted the set of regions analysed in all studies. The use of administrative regions, however, is likely to have distorted their results.

The boundaries of administrative regions are in fact the result of political and historical factors which are country-specific so that not only do they bear no relationship to the socio-economic factors that form the basis of a functional region, but they also vary from country to country making comparison unreliable. By contrast, because of the very nature of regional economic disparities, any empirical study on the subject should take space into consideration and opt for a definition of region which is economically as self-contained as possible and is defined by the spatial sphere of socio-economic influence of foci of economic activity. Since the functional links between spatial units are limited by space, functional regions take explicit account of the distance factor and appear therefore as the best alternative. The analysis developed in Chapter 4, therefore, adopts the set of Functional Urban Regions (FURs) derived by Hall and Hay (1980) for 1971, and adopted by Cheshire and Hay (1989) in their analysis of urban problems in Europe between 1951 and 1981.

A further important and practical reason for using FURs rather than administrative regions is simply that the economic indicator which is of interest – per capita GDP – is a product of two components, total regional GDP and population which are measured with respect to different organisational methods. GDP is measured at workplaces while population is counted on residential basis. Thus if population centralises or decentralises with respect to the location of employment entirely spurious ‘growth’ will result. As is shown in Cheshire (1997) it can be as much as 39 per cent of actual growth once changes in that commuting have been allowed for. In addition, this source of statistical distortion of measured growth rates will tend to be systematically concentrated in the richest regions given the existence of net inward commuting. Both levels and changes in net commuting into generously bounded regions such as the South-East of England are only very minimal; in the context of an ”underbounded” region, such as Greater London, not only does positive net inward commuting bias measured GDP upwards but changes in net commuting over time are far more likely to distort measured growth rates.

Also the findings of the convergence analysis will contribute to the development of the theoretical model of regional growth. Its fundamental results, particularly with respect to the implications of a process of economic integration for the evolution of the differences in per capita income levels between regions, will be outlined in Chapter 6. A general empirical test of its main predictions will be carried out in Chapter 7. In particular, the economic growth performance of the regions will be analysed with respect to a set of determining factors which relate to the economic structure of the regions and their ability to produce innovations. As with the analysis of convergence and for the same reasons, this empirical investigation makes use of the data set for the FURs.

Chapter 2
A Review of the Main Theoretical Contributions

2.1 Introduction

There has recently been a revival of interests in theoretical and empirical work on differences in growth and per capita income levels across countries and regions. This renewed interest has focused on the relation between economic growth and technological progress. Obviously, this is not a new issue. Apart from classical economists, like Smith and Marx, who have extensively discussed this question, the work of Schumpeter, particularly his *Theory of Economic Development*, is often cited as the seminal contribution to the understanding of technological progress. His work emphasised that the process of technological change is endogenous to the economic system, being brought about by the activity of profit-seeking entrepreneurs (Schumpeter 1934). More or less at the same time, Harrod (1939) and Domar (1946) tried to integrate the elements of economic growth with Keynesian analysis. Writing in the period between the Great Depression and World War II, these authors shared the widespread belief that the capitalist system was inherently unstable. The period of stable growth that followed determined a profound revision of this belief and the traditional neoclassical model set out by Solow (1956), Swan (1956) and others clearly reflected this change. This model predicted the existence of a unique and stable growth path determined by technological progress and the growth rate of the labour force.

What follows is an overview of the most important developments that followed. Particular attention will be focused on three fundamental issues:

1. how the contribution of technology to economic growth is conceived by the different strands of analysis;
2. what their main predictions are in terms of disparities in levels and growth rates of per capita income across countries and regions, and, where possible,

3 what their main predictions are in terms of the likely outcome of the process of economic integration.

2.2 The Traditional Neoclassical Model of Growth

Probably the most influential, and criticised, model of economic growth is the traditional neoclassical model originally set out by Solow (1956) and Swan (1956), and subsequently refined by Cass (1965) and Koopmans (1965) following the work of Ramsey (1928). As with earlier contributions to the analysis of economic growth, this model allowed for the role of technological progress as the fundamental engine of the growth process. However, essentially for analytical convenience, technological progress was assumed to be a pure public good created outside the economic system.

The simplest neoclassical model can be briefly presented in its version for open economies as developed by Borts and Stein (1964). The basic hypotheses of this version are equivalent to those for a closed economic system and in particular are:

1 there are constant returns to scale in production;
2 all markets for goods and factors are perfectly competitive;
3 production factors move freely in response to differentials in rates of remuneration;
4 price flexibility ensures full employment;
5 rewards for factor of production are directly determined by their marginal productivity;
6 technological knowledge increases at an exogenously given, constant rate.

Consider an open economic system in which physical capital, K, and labour, L, are used in order to produce a homogeneous consumption good. The usual Cobb-Douglas production function with constant returns to scale represents the production process:

$$Y_t = A_t K_t^{\alpha} L_t^{1-\alpha} \tag{2.1}$$

where A_t, the level of technological knowledge existing at time t, is assumed to increase at the exogenously given rate μ: $A_t = A_0 e^{\mu t}$. A fraction, s, of output is saved, and invested in new physical capital; the rest of output is consumed. Rational households with perfect foresight choose the saving rate by comparing costs and benefits of present and future consumption. To simplify the analysis, it is assumed that the saving rate is constant as in the original model by Solow and Swan.

In per capita terms, the production function becomes:

$$y_t = A_t\, k_t^{\alpha}$$

from which it can be shown that the growth rate of per capita output is determined by the exogenous rate of technological progress and the growth rate of the capital-labour ratio:

$$\frac{\dot{y}_t}{y_t} = \mu + \alpha \frac{\dot{k}_t}{k_t} \ . \qquad (2.2)$$

where a dot over a variable denotes differentiation with respect to time.

Capital and labour rates of return are given by factor marginal productivity:

$$r_t = \alpha\, A_t k_t^{\alpha - 1}$$

$$w_t = (1-\alpha) A_t k_t^{\alpha}$$

showing that the higher the level of the capital-labour ratio, the higher the wage level and the lower the return to capital.

Assuming that physical capital does not depreciate, its growth rate is given by:

$$\frac{\dot{K}_t}{K_t} = \frac{sY_t}{K_t} + F_K\left(r_t - r_t^o\right) \qquad (2.3)$$

where r_t and r_t^o represent the rates of return to capital within and outside the region, whilst F_K describes the interregional flows of capital as a function of differential rates of returns on capital. In particular, F_K shows a positive, negative, or zero value according to whether there are positive, negative, or no interregional differentials in the rate of return.

Similarly, the rate of growth of labour can be expressed as:

$$\frac{\dot{L}_t}{L_t} = n + F_L\left(w_t - w_t^o\right) \tag{2.4}$$

where n represents the natural rate of growth of the population, whilst w and w^o are respectively the level of wages within and outside the region. As with physical capital, F_L describes the interregional migration flows as a function of interregional wage differentials. Again, the value assumed by this variable will be positive, negative, or equal to zero depending on whether there are positive, negative, or no interregional wage differentials.

As is clear from equation 2.2, the dynamic properties of the system depend on the behaviour of the capital-labour ratio. From equations 2.3 and 2.4 it is easy to obtain the fundamental differential equation of the model:

$$\frac{\dot{k}_t}{k_t} = \frac{\dot{K}_t}{K_t} - \frac{\dot{L}_t}{L_t} = s\,A_t k_t^{\alpha-1} + F_K\left(r_t - r_t^o\right) - n - F_L\left(w_t - w_t^o\right) \tag{2.5}$$

and, from equation 2.2, the growth rate of per capita output can be expressed as:

$$\frac{\dot{y}_t}{y_t} = \mu + \alpha\left[s\,A_t k_t^{\alpha-1} - n + F_K\left(r_t - r_t^o\right) - F_L\left(w_t - w_t^o\right)\right]. \tag{2.6}$$

which states that the growth rate of regional per capita output depends on the rate of technological progress, the internally financed growth of the stock of capital per worker, and the interregional differentials in capital and labour rates of return.

Suppose for the moment that labour and capital rates of return are the same for all the regions so that F_K and F_L are equal to zero. Equation 2.5 then simplifies into:

$$\frac{\dot{k}_t}{k_t} = \frac{\dot{K}_t}{K_t} - \frac{\dot{L}_t}{L_t} = s\frac{A_t k_t^{\alpha}}{k_t} - n \tag{2.7}$$

and attention can be concentrated on the steady state of the system, the situation in which the various quantities grow at a constant rate. By definition, the growth rate of k is constant in the steady state. Since s and n are constant, equation 2.7 then implies that the average product of capital is also constant in the steady state or, in dynamic terms, that the growth rate of per capita output, y, and capital per worker, k, must be equal:

$$\frac{\dot{y}_t}{y_t} - \frac{\dot{k}_t}{k_t} = 0\,. \tag{2.8}$$

Moreover, since per capita consumption c_t is simply $(1-s)\cdot y_t$, the steady state growth rate of c must also be equal to that of y. Finally, by substituting equation 2.2 into the last equation, it is easy to show that:

$$\frac{\dot{y}_t}{y_t} = \frac{\dot{k}_t}{k_t} = \frac{\dot{c}_t}{c_t} = \frac{\mu}{1-\alpha}. \tag{2.9}$$

In other words, the system is characterised by a steady state equilibrium in which the level of output per capita, consumption per capita and the capital-labour ratio all grow at the same constant rate that depends on the exogenous rate of technological progress and on the capital-share coefficient.[1] An interesting result demonstrated by Cass (1965) is that, for any initial level of the capital-labour ratio $k_0>0$, the optimal capital-consumption path will converge asymptotically to the balanced path. While the system is approaching its steady state, equation 2.2 implies that the dynamic properties of the system depend on the behaviour of the capital-labour ratio. The 'Law of Diminishing Returns', implicit in the assumption of homogeneity of degree one for the neoclassic production function, implies that the growth rate experienced by an economic system is negatively related to the level of capital-labour ratio: the lower the capital-labour ratio and, therefore, the lower the per capita output, the further the economy is from its balanced path, and the higher its growth rate.

It is now possible to see what happens to regional trends of per capita output in the case of differences in regional rates of return. Given the assumption that the rate of technological progress is the same for all the regions, it is clear from equations 2.3 and 2.4 that off-steady state capital and labour rates of return may differ between regions only if the existing levels of capital-labour ratio differ. Again, the 'Law of Diminishing Returns' implies that the marginal product of capital is higher in the regions with a lower capital-labour ratio, whereas the marginal product of labour is higher in the regions presenting a higher capital-labour ratio. Since there are no constraints to interregional flows of capital and labour, capital will tend to flow from the regions with a higher capital-labour ratio to the regions with a lower level of capital per worker. As a consequence, the function describing interregional capital flows F_K will show a positive

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[1] It can also be shown that this solution satisfies the transversality condition.

value for those regions with a lower capital-labour ratio and a negative value for the regions with a higher level of the ratio. Labour, on the contrary, will tend to flow in the opposite direction and F_L will present positive (negative) values for regions characterised by higher (lower) capital-labour ratio.

As is clear from equation 2.6, while these flows of capital and labour are taking place, the regions with lower capital-labour ratios will show higher output per capita rates of growth. This process of opposite flows will continue until capital-labour ratios, and hence labour and capital returns, are equalised within the system. In the long run therefore the value assumed by both F_K and F_L will be zero and the already described steady state equilibrium will be reached by each region. All the regions therefore will be characterised by the same rate of growth and the same level of per capita output.

To sum up, the traditional neoclassical model describes an inherent tendency for the economic system to reach a situation of equilibrium not only for the regional markets but for the relationships between the region and the rest of the economic system as well. The regional economies that form the system described by the authors are populated by people sharing similar technological systems. The obvious implication is that these regional economies also share the same steady state. Within this context, therefore, any differences in regional economic growth are fundamentally the result of gains deriving from a progressive reduction of an initial inter-regional misallocation of resources. Existing disparities in both levels and growth rates of per capita output will eventually vanish as time passes and regional economies approach the common steady state. Moreover, a process of social and economic integration, like the one that the European Union (EU) is undertaking, should reinforce the convergence mechanism by facilitating the interregional flows of factors.

2.3 Earlier Reactions to the Traditional Neoclassical Model

Critics of the traditional neoclassical model have concentrated on three major issues. First, as became dramatically evident in OECD countries during the 1970s, a steady state characterised by stable growth bears no resemblance to the real world. Regions, countries and groups of countries have generally exhibited medium to long term accelerations and decelerations in their per capita income, consumption and investment growth rates. Secondly, increasing scepticism mounted with respect to the traditional neoclassical expectation of a strong tendency towards convergence in per capita income levels and growth rates. Economists have thus become increasingly aware of a 'convergence' problem not only among countries, but within them as well. Thirdly, growing dissatisfaction mounted with the traditional neoclassical model because it was providing no explanation for the rate of technological progress. Indeed, the traditional neoclassical model constituted a natural theoretical framework for empirical work on the role of labour and capital growth in explaining economic growth. However, the first analyses of this kind (Abramovitz 1956; Solow 1957; Kendrick 1961; Denison 1962) found that only a minor part of per capita GDP growth could be explained by factor accumulation, and that the major determinant of growth was instead the 'residual', accounting for the effect of exogenous technological change. Thus, although technological progress appeared the key element of long run growth, from a theoretical point of view it remained "the *terra incognita* of modern economics" (Schmookler 1966, page 3).

2.3.1 Productivity Slowdown and the Growth of the Service Sector: Baumol's model

One interesting attempt to explain the productivity slowdown that characterised the more developed economies during the 1970s, and the parallel process of urban decline of those years, is the model of unbalanced growth derived by Baumol (1967). His explanation focused on the relation between sectors within an urban setting. He noted that advanced economies have witnessed a remarkable growth in the relative importance of service activities in general and of information-handling services in particular. This relative growth of the service sector is not evenly spatially distributed throughout the economic system but tends to be mainly concentrated in cities. The author therefore considered the case of an isolated urban economy in which a manufacturing and a service sector are present. The fundamental hypothesis formulated by Baumol is that, whilst the manufacturing sector is characterised by a high, and exogenous, rate of labour productivity growth, labour productivity in the service sector is constant. Assuming that labour is the only factor, production in the service sector can be represented as:

$$Y_S = aL_S$$

where a is the constant level of labour productivity. The production function for the manufacturing sector instead is:

$$Y_M = A_0 e^{\mu t} L_M$$

where μ is the usual exogenous rate of technological progress.

For simplicity's sake, the wage level, w, is assumed to be the same in the two sectors because of a high degree of intersectoral mobility of workers. Similarly to the traditional neoclassical model the level of wages is determined by labour productivity, but in this case the relevant marginal productivity of labour is the one that characterises the manufacturing sector. Finally, also the profit rate, assumed constant over time, is the same in the two sectors.

Within this setting, it is easy to show that the cost per unit of output in the service sector, C_S, rises without limit over time

$$C_S = \frac{wL_S}{Y_S} = w_0 e^{\mu t}$$

while the unit cost of manufacturing, C_M, remains constant:

$$C_M = \frac{wL_M}{Y_M} = \frac{w_0}{A_0}.$$

As a consequence, if market prices are proportionate to costs, market demand for the output of the service sector will tend to decline. The way in which this will actually take place depends on the price elasticity of the demand for the two goods.

Assuming that the demand functions for both goods are unit elastic, with respect to both price and income, the relative outlays on the two commodities remain constant. Given the fact that the profit rate is the same in the two sectors and that market prices are proportionate to costs, and also that the ratio between total costs in the two sectors stays constant, then the distribution of the labour force between the two sectors does not change over time:

$$\frac{C_S Y_S}{C_M Y_M} = \frac{w_0 e^{\mu t} L_S}{w_0 e^{\mu t} L_M} = \frac{L_S}{L_M} = G_L$$

where G_L is a constant. As a consequence, the ratio between the output levels of the two sectors tends to decline towards zero with the passage of time:

$$\frac{Y_S}{Y_M} = \frac{aL_S}{A_0 L_M e^{\mu t}} = \frac{a G_L}{A_0 e^{\mu t}}.$$

In other words, there is a tendency for the output of the 'static' sector, whose demand is not highly inelastic, to decline steadily with respect to the output of the 'dynamic' sector.

It is now possible to relax the hypothesis concerning the elasticity of the demand and consider the case in which the demand for services is price inelastic or income elastic so that the ratio between output levels of the two sectors is maintained constant at level G_M. The result is:

$$\frac{Y_S}{Y_M} = \frac{aL_S}{A_0 e^{\mu t} L_M} = G_M$$

For a given city size $L = L_S + L_M$, it is easy to show that:

$$L_S = L \frac{G_Y A_0 e^{\mu t}}{1 + G_Y A_0 e^{\mu t}}$$

$$L_M = L \frac{1}{1 + G_Y A_0 e^{\mu t}}$$

Hence, as time approaches to infinity, the level of employment in the service sector, L_S, tends to represent total employment, L, whilst employment in the manufacturing sector, L_M, falls to zero. As the process proceeds, total output and total productivity growth tend to decline until, eventually, the manufacturing sector disappears and the whole economy comes to a stop.

2.3.2 Kaldor's Model of Cumulative Causation

A more radical departure form the traditional neoclassical model is represented by the work of Kaldor (Kaldor 1970, 1975, Kaldor and Mirlees 1962; but see also Dixon and Thirlwall 1975, Thirlwall 1979). Following Myrdal's principle of 'circular and cumulative causation' (Myrdal 1957), Kaldor (1970) argues that regional prosperity can be self-reinforcing if a region's rate of productivity growth is tied to its rate of growth of output, both in absolute and per capita terms, opposing, in this way, the optimistic neoclassical view that postulates the existence of spontaneous re-equilibrating processes. In Kaldor's view, this process of cumulative causation is due to the existence of increasing returns to scale in manufacturing production. These increasing returns, moreover, are not represented by static economies of large-scale production but are the result of the cumulative development of know-how and technological spillovers (Kaldor and Mirlees 1962). The author also stresses the role of specialisation on the extent of increasing returns. In particular, increasing returns brought about by the enlargement of the market are due not only to the increase in specialisation of labour employed in the production of the existing set of products as in Smith (1776), but especially to the introduction of new specialised intermediate inputs as in Young (1928).

In its basic form, the Kaldorian model of growth can be presented as follows (Dixon and Thirlwall 1975). Under the influence of the Keynesian income multiplier, the model assigns a determinant role to demand, and to export demand in particular, in the actual establishment of the process of cumulative causation (Kaldor 1975). The rate of growth of output is thus expressed as a linear function of the rate of growth of exports:

$$\frac{\dot{Y}}{Y} = \varepsilon_1 \frac{\dot{X}_W}{X_W} \qquad (2.10)$$

where ε_1 is the elasticity of output with respect to export growth and X_W is the level of exports. In turn, the level of exports is explained as:

$$X_W = P^{\varepsilon_2} P_W^{\varepsilon_3} Y_W^{\varepsilon_4}$$

where P is the regional price level, P_W and Y_W are the levels of price and income outside the region, ε_2 is the price elasticity of demand for exports (<0), ε_3 is the cross-price elasticity of demand, and ε_4 is the world income elasticity of demand for exports. Taking logs and differentiating with respect to time:

$$\frac{\dot{X}_W}{X_W} = \varepsilon_2 \frac{\dot{P}}{P} + \varepsilon_3 \frac{\dot{P}_W}{P_W} + \varepsilon_4 \frac{\dot{Y}_W}{Y_W} . \qquad (2.11)$$

The rate of growth of income outside the region and the rate of change in the price level in competing regions are both considered exogenous to the region. Moreover, institutional factors and interregional labour mobility imply that the level of money wages in the region, *w*, and their rate of increase, are close to the national level or, more generally, that the regional dispersion of the productivity growth rates is wider than the regional dispersion in money wage rates of growth.

The rate of growth of domestic prices is instead endogenous. In particular, Kaldor (1970) explicitly assumes that competition is imperfect and that manufacturing producers are price-makers, rather than price-takers as in the neoclassical model. The price level can then be assumed to be determined on the basis of a constant percentage 'mark-up', *m*, on unit labour costs:

$$P = (1+m)\frac{w}{y}$$

where *y* is average labour productivity. In dynamic terms, the last equation can be rewritten as:

$$\frac{\dot{P}}{P} = \frac{\dot{m}}{m} + \frac{\dot{w}}{w} - \mu . \qquad (2.12)$$

where μ is the rate of productivity growth.

The model becomes 'circular and cumulative' by introducing the 'Verdoorn Law' which states that the rate of productivity growth in a region is a positive and increasing function of the regional growth rate of output. Assuming that the function is linear,

$$\mu = \mu_a + v\left(\frac{\dot{Y}}{Y}\right) \qquad (2.13)$$

where μ_a is the autonomous component of productivity growth, whilst *v* is the Verdoorn coefficient.

Combining together equations 2.10-2.13, it is possible to express the equilibrium growth rate of regional output as:

$$\frac{\dot{Y}}{Y} = \frac{\varepsilon_1}{1 + \varepsilon_1\,\varepsilon_2\,v}\left[\varepsilon_2\left(\frac{\dot{w}}{w} - \mu_a + \frac{\dot{m}}{m}\right) + \varepsilon_3\,\frac{\dot{P}_W}{P_W} + \varepsilon_4\,\frac{\dot{Y}_W}{Y_W}\right].$$

The result is that a process of integration that increases trade between regions by reducing transport costs or artificial barriers (such as tariffs), triggers a divergence of regional growth paths. This is explained by the fact that the region which is initially more industrially developed tends to enjoy a comparative advantage relative to other regions since its producers may command lower prices due to the increasing returns to scale.

Another interesting point in Kaldor's analysis concerns the possibility of the development of 'growth clubs'. Indeed, the increase in production and income in one region stimulates the demand for 'complementary' goods produced in other regions. The result would be the concentration of industrial production within a group of successful regions that hold each other in balance through increasing specialisation between them.

The divergence in per capita income among regions, or groups of them, is not without limits. Workers tends to move towards the successful regions being attracted by higher real wages and better job opportunities. The concentration of manufacturing activities and population is seen by Kaldor as the main determinant of agglomeration diseconomies such as congestion, pollution, housing problems, and so on. These diseconomies "… at some stage should serve to offset the technological economies resulting from faster growth" (Kaldor 1970, page 344), and consequently eliminate the comparative advantage enjoyed by the more industrialised regions. As the aforementioned diseconomies are often external to the individual producer and are not completely reflected in the movement of prices, it is possible that, if left to market processes alone, regional concentration of manufacturing activities will drive the system far from a situation of Pareto optimality.

Investment and technological change are tightly linked in Kaldor's view: new ideas generally need new vintages of capital goods for their implementation so that it makes little sense to make a distinction between increases in productivity due to capital accumulation and those due to technological progress. As a result, Kaldor rejects the notion of a 'production function' describing the production effort of a representative firm, concentrating instead directly on the dynamics of the entire economic system. The consequent lack of microeconomic foundations however has generally been considered the most important weakness of Kaldor's explanation of economic growth. This lack of microeconomic foundations hampered subsequent developments of this approach so that there has been little if any work following in this tradition of analysis (for an overview of existing literature see McCombie 1988).

2.4 More Recent Reactions to the Traditional Neoclassical Model

Interest in economic growth recently rekindled within mainstream economics when a solution was found to the treatment of the relationship between the endogenous nature of technological change and the public aspect of technological change, which was introduced in the neoclassical literature by Arrow (1962), Levhary (1966a and b) and Sheshinski (1967).

Romer (1986) and Lucas (1998) present two models of endogenous growth in which technological change is generated as a by-product, or external effect, of other economic activities. This perspective, however, overlooks what is commonly regarded as one of the most important sources of technological progress in capitalist economies: innovation as the result of intentional investment in Research and Development (R&D) by private firms. This aspect, however has later been explored within this body of literature, as the theory developed to analyse product diversity (Dixit and Stiglitz 1977; Ethier 1982) has been applied to the analysis of the impact of increasing specialisation of production (Romer 1990 a, b and c).

Before the new growth theorists, however, the body of literature initiated by Nelson and Winter (1982) and usually labelled 'evolutionary', also started to provide an endogenous explanation to the process of technological change. Although both streams of work stress the endogenous nature of technological change, many profound differences divide them in the characterisation of the fundamental mechanisms at the basis of the functioning of modern economic systems.

2.4.1 The Evolutionary Approach

The evolutionary approach to economic growth represents a radical departure from traditional neoclassical analysis. It requires neither price-taking nor explicit maximisation[2] for its description of the growth process in which innovation is placed at the centre of the analytical framework.

Central to the theory is the concept of a 'technological paradigm', inspired by the definition of scientific paradigm suggested by Kuhn (1970) in the modern philosophy of science. A technological paradigm can be defined as a "pattern of solutions of selected technoeconomic problems based on highly selected principles derived from the natural sciences, jointly with specific rules aimed to acquire new knowledge and safeguard it, whenever possible, against rapid diffusion to competitors". "Putting it another way, technological paradigms define technological opportunities for further innovations and some basic procedures on how to exploit them" (Dosi 1988a, page 1127; Dosi 1988b, pages 224-225; but see also Dosi 1982 and 1984). Once a technological paradigm is in place, further innovation tends to evolve in cumulative fashion, through the modification of dominant designs using the established principles, rather than seeking fundamentally different designs. The result is a 'technological trajectory', i.e. "the activity of technological progress along the economic and technological trade-offs defined by a paradigm" (Dosi 1988a, page 1137). In addition to being cumulative, technological change also possesses a path-dependent nature, accounting for irreversible technological processes possibly leading to selection of inferior technologies (David 1985; Arthur 1989).

Much of the literature that views technological change as an evolutionary process emphasises how innovation is fundamentally a learning process taking place within firms as the combined result of two intrinsically interrelated sources. On the one hand,

[2] Also Kaldor's model did not require price taking and explicit maximisation.

firms directly engage in R&D activities, devoting resources to research activities aimed at the solution of technological problems. Innovation, however, is by no means exclusively the result of learning processes taking place in dedicated research departments: learning in production in its various forms, such as Arrow's 'learning-by-doing' or Rosenberg's 'learning-by-using' (Rosenberg 1976 and 1982), is therefore considered as a non-negligible source of technical change (Dosi 1988b). As for the role of economic incentives in explaining innovation, Rosenberg explains how "the ultimate incentives are economic in nature; but economic incentives to reduce costs always exist in business operations and precisely because such incentives are so diffuse and general, they do not explain much in terms of the particular sequence and timing of innovative activity…. Technology is much more of a cumulative and self-generating process than the economist generally recognises" (1976, page 110). It is therefore crucial to concentrate on the specific characteristics of the processes taking place inside firms, in order to account for the observed results.

The extent to which learning in its various dimensions actually produces technical change is determined by the firms' level of 'technological capabilities' which can be defined as the body of abilities developed through the accumulation of experiences and in relation with other institutions, both private and public. In other words, technological capabilities can themselves be viewed as the result of learning processes (Nelson 1992). A firm's 'technological competence' can then be defined as "the result of the common learning process that binds the different departments together, creating a specific technological tradition within the firm" (Cantwell 1994, page 42). This is reminiscent of the related concepts of 'firm-specific knowledge accumulation' (Penrose 1959), 'firm-specific central skills and resources' (Rumelt 1974), and 'dynamic capabilities' (Teece *et al.* 1990). This also underlines the existence of a tacit dimension in the generation and transmission of technological knowledge, a concept derived from Polany (1967) and adapted to the present context as a description of uncodified elements of knowledge which can only be shared through common experience (Dosi 1988a).

The cumulative character of technological change, and the linkages between technological change, learning processes and skills embodied in people and organisations imply that technological capabilities of firms can be profoundly different and extremely difficult to transmit (Nelson and Winter 1982). If true, technological change would be localised (meaning that the development of new techniques is likely to take place in the neighbourhood of the techniques already in use), a result the existence and implications of which had already been investigated, in the context of a neoclassical production function, in the work of Atkinson and Stiglitz (1969).

However, to account for the more complex view of technology expressed here, evolutionary theories abandon the traditional assumption of optimisation through perfectly rational behaviour in favour of a concept of constrained choice under conditions akin to those described in the 'bounded rationality' approach (Simon 1986). Indeed, an essential element of the innovation process is that it "involves a fundamental element of uncertainty, which is not simply lack of all the relevant information about the occurrence of known events but, more fundamentally, entails also (a) the existence of techno-economic problems whose solution procedures are unknown … and (b) the impossibility of precisely tracing consequences to actions" (Dosi 1988a, page 222). Because of the strong element of uncertainty pervading innovative activities, decision makers develop simple 'routines' based on a crude description of the environment, and incorporating subjective attitudes towards the strong uncertainty, in order to guide their action.

At the system level, drawing again a parallel with the role of anomalies in Kuhn, a change in technological paradigm can be described in general terms as a response to a situation of crisis; the consequence of dissatisfaction with the ability of the existing paradigm to answer a set of questions. Technological advance is also described partly as a result of the effort to cope with imbalances which it creates, so that there exist bottlenecks acting as focusing devices for technological effort (Rosenberg 1976). Changes in techno-economic paradigm are then determined through combinations of interrelated product and process, technical, organisational and managerial innovations involving an increase in potential productivity for all or most of the economy (Freeman and Perez 1988). The emergence of a new paradigm is likely to be accompanied by a change in the distribution of the local technological competencies within the system in such a fashion that cannot be predicted in advance (Dosi 1988). However, another essential aspect of the evolutionary approach is represented by the explicit recognition that, whilst the decisions of business firms are crucial in the process of technological change, other institutions play an important role. Within a country, the local network of public and private institutions supporting the initiation, modification and diffusion of new technologies shapes the 'national system of innovation' (Freeman 1987; Lundvall 1992; Nelson and Rosenberg 1993; Patel and Pavitt 1994). The innovation process is shaped by this system; and the degree of conformity of the innovation system to the dominant technological paradigm constitutes an important aspect of understanding why the ability to innovate differs among countries.

Although the existing body of mathematical modelling within the evolutionary tradition is very diverse, the core of the typical formalisation is represented by the 'fundamental equation of natural selection', which was originally used in biology. In a model set out by Nelson and Winter (1982), the price which any firm charges is determined by the routines it employs: more efficient routines lead to lower unit costs and, for a given level of profitability, to lower prices. The level of the firm's profitability, on the other hand, represents its degree of 'fitness'. The equation of selection thus states that the growth of the market share of a firm depends on the difference between the firm's degree of fitness and the average within the market (Silverberg 1988). In other words, which firms come to dominate the industry depends on which are most profitable relative to the average.

This mechanism is captured by the following differential equation:

$$\dot{f}_i = A\left(E_i - \overline{E}\right)f_i$$

where f represents the market share of a firm, A is an adjustment parameter, E is a measure of fitness or profitability, and

$$\overline{E} = \sum_i f_i E_i$$

is an industry-wide weighted average of that measure. Other authors within the tradition have provided different economic interpretations of the degree of fitness. For instance, Silverberg *et al*. (1988) have interpreted fitness in terms of a firm's delivery lag, whilst

Iwai (1984a and b) and Metcalfe (1986) have seen it in terms of its unit costs. The unifying feature of all models, however, is represented by the fact that the firm's technological competence is ultimately the fundamental determinant of fitness.

2.4.2 The 'New Growth Theories'

The process of endogenous technological change is also the central element of the growth process in the recent body of literature usually labelled as 'new growth theories' or 'endogenous growth theories'. Differently from the evolutionary approach, endogenous growth theories are clearly in the mainstream tradition in their style of modelling. They are presented in abstract mathematical terms, making use of a mathematical function to describe the production process, and adopting the framework of utility and profit maximisation in order to define a state of equilibrium.

A key element which is shared by all the models belonging to this thread of work is that they recognise that technological knowledge is a nonrival good, since its use by one firm or person does not preclude its use by another. This has profound implications for the analyses based on the production function. The standard assumption in the neoclassical model is that the production function is homogeneous of degree one in the rival inputs: by doubling the amount of labour and physical capital output will double. But if it is possible to produce more nonrival input, technological knowledge, which makes it possible to produce more output from the same quantity of rival inputs, then the production function ceases to be concave and the output elasticity with respect to all the inputs is larger than one (Romer 1990c).

In general, the growth models that interpret technological knowledge as a nonrival input which is produced within the economic system as a direct consequence of agents' behaviour fall into two different groups. The first group comprises models of economic growth in which the process of technological change is endogenous because of the presence of knowledge externalities (Romer 1986; Lucas 1988). Improvements in the existing stock of technological knowledge emerge as a side effect of the other activities; however, they cannot be appropriated by the originator but are assumed to be completely nonexcludable and, therefore, represent a pure external effect. Because of the nonexcludable nature of technological knowledge, firms can still be assumed to be price-takers and the traditional assumption of perfect competition is retained. However, the resulting competitive equilibrium of the system, due to the presence of externalities, is not Pareto optimal.

The second group of endogenous growth models constitutes a more radical departure from the traditional neoclassical framework. In the models belonging to this group technological knowledge is now partially excludable and, hence, created intentionally by profit-seeking agents (Romer 1990a and b; Grossman and Helpman 1989, 1990, 1991a and b; Aghion and Howitt 1992 and 1998; amongst others). Indeed, this partial excludability has two main consequences. On the one hand it determines the abandonment of the hypothesis of perfect competition and price-taking behaviour in all markets and, hence, the equilibrium is one with monopolistic competition. On the other hand, the fact that knowledge is only partially excludable implies the presence of externalities and hence the fact that the equilibrium is not Pareto optimal.

2.4.2.1 Unintentional Creation of Technological Knowledge

Romer (1986) and Lucas (1988) present two models in which the unintentional creation of knowledge by a firm or agent drives economic growth through its positive external effect on the production possibilities of other firms. Lucas, in particular, extends the closed economy, one-good model in which the 'engine' of growth is represented by technological change due to externalities arising from the accumulation of human capital, to a two-good setting with international trade. Each consumption good is produced according to:

$$y_i = h_i u_i N$$

where h_i is the level of human capital specialised in the production of the particular good, N is the total level of labour, and u_i is the fraction of total workforce devoted to the particular production. In this model, human capital accumulation, and technological change, are the result of learning-by-doing. As production of a good proceeds, human capital specific to the particular production is developed according to:

$$\dot{h}_i = h_i u_i \delta_i$$

where δ_i describes the speed with which human capital is accumulated and is assumed to be different in the two sectors. Consumers maximise utility described by a constant elasticity of substitution function of the two consumption goods, which are assumed to be good substitutes. In equilibrium, production patterns are determined by comparative advantage which, in turn, depends on the initial endowments of the two forms of human capital. Given the learning function, countries accumulate human capital by doing what they are already good at doing and, consequently, strengthen their initial comparative advantage even further. It is clear, therefore, that technological knowledge is essentially cumulative in this model. As a result, rates of output growth can vary across countries, depending on the sector in which they specialise and the speed with which human capital is accumulated within the sector.

2.4.2.2 Intentional Creation of Technological Knowledge

In the second group of models, economic growth is driven by technological change that arises in large part from intentional investment decisions made by profit-maximizing agents. As a consequence, market power is explicitly introduced into the framework: the entrepreneur who realises an innovation can exploit it and hence enjoys an advantage with respect to other entrepreneurs. It is the very existence of this advantage that represents the incentive to invest in research activity.

The first of these models was set out by Romer (1990a and b) and several others have subsequently been developed along similar lines. The economic system consists of three sectors and four types of input. The research sector uses human capital and the existing stock of knowledge to produce new knowledge. In order to provide a measure of knowledge, Romer assumes that this sector produces designs for new intermediate goods and therefore A indicates the number of designs that have already been produced. The accumulation of knowledge is described by:

$$\dot{A} = \delta\, A H_A$$

where H_A is the share of total human capital employed in research and δ is a productivity parameter.

The intermediate goods sector is characterised by monopolistic competition. Romer assumes that the number of goods that could potentially be produced is infinite, but that only a finite number of these potential inputs, the ones that have already been invented and designed, are actually available for use at any time. So $x(a)$ is the quantity of input a produced at any time. Moreover, in order to produce any intermediate input, it is necessary to face both a fixed cost, the cost of purchasing a design from the research sector, and a variable cost, expressed in terms of physical capital.

The final good sector uses labour, human capital and intermediate inputs to produce an homogeneous consumption good on the basis of the following production function:

$$Y = H_Y^{\alpha} L^{\beta} \int_A x(a)^{1-\alpha-\beta} da$$

where H_Y is the stock of human capital used in manufacturing. This function, which had previously been used by Ethier (1982), is an additively separable function of all the different kinds of capital goods, so that the marginal product of a certain intermediate input does not depend on the amount of other inputs actually used in production. Given this characteristic of the function, it is important to know whether an increase of the availability of intermediate inputs is due to an increase in the supply of the already existing inputs or to the introduction of new kinds of intermediate inputs. Only in the former case, in fact, does capital exhibit the usually decreasing returns. Therefore, it is interesting to note that the role played by research activity in the model is essentially twofold. On the one hand, it determines an increase in the number of intermediate inputs used in the production of the final good. On the other hand, it increases the level of existing knowledge and, hence, the productivity of human capital employed in the research sector. Whilst the benefits arising from the first role are completely excludable, the second set of benefits is completely nonexcludable and represents an externality.

Finally, consumers maximise discounted, constant elasticity preferences, and make saving and consumption decisions taking interest rates as given. Moreover, they decide the allocation of the given stock of human capital between the research and the manufacturing sector. The stock of physical capital grows by the amount of forgone consumption.

The solution of the model for a balanced growth equilibrium is characterised by the fact that final output, consumption, and knowledge grow at the same constant rate:

$$g = \frac{\delta H - \tau\rho}{\tau\sigma + 1}$$

where τ is a constant that depends on α and β, ρ is the intertemporal rate of discount, and σ is the intertemporal rate of substitution between goods. One may note immediately that the rate of growth depends on the total stock of human capital H available in the economy. First of all, the rate of growth will be positive only if this level of human capital is larger than $\rho\tau/\delta$. If this condition does not hold, the economy comes to a halt. In this case, in fact, all the feasible growth rates for knowledge are too small relative to the discount rate to justify the sacrifice in current output necessary for growth to take place. On the other hand, if the condition holds, an increase in the stock of human capital available in the economy speeds up growth.

This basic framework has subsequently been expanded by several authors to a two-country case in order to analyse the effects of trade restrictions and integration between countries on output growth rates. Within this thread of work, integration is represented by the elimination of existing barriers to international trade of intermediate goods, and to the international flow of knowledge. In general, Rivera-Batiz and Romer (1991b) show that integration produces three effects. Firstly, integration produces an 'allocation effect' since, as trade opens, each country reallocates resources towards the sectors in which they have a comparative advantage. Secondly, there could be international 'integration' within a given sector if the production presents increasing returns to scale. Finally, there could be a 'redundancy effect' if the international flow of knowledge reduces redundant research efforts. Moreover, they show that whilst integration and redundancy effects are positively related to the output growth rate of the integrated economy, the effect of resource reallocation brought about by the integration process could be detrimental for the growth rate. When integration occurs between similar countries, they show (Rivera-Batiz and Romer 1991a and b) that the allocation effect is generally small and tends to reinforce the positive influence of the growth rate played by the other two effects. By contrast, when integration occurs between asymmetric countries, Grossman and Helpman (1990 and 1991b) and Rivera-Batiz and Xie (1993) explain that the allocation effect can be sizeable and, in particular instances, overwhelm integration and redundancy effects.

2.4.3 Krugman and The 'New Economic Geography'

Strictly speaking, the last group of contributions presented cannot be classified as growth models: rather than concentrating on the growth rate of output they focus on "the location of production in space" (Krugman, 1991a, pg.1). However, the models presented by Krugman (1991a, b, c, d and e, 1992, 1993) possess several interesting features for the present analysis. Firstly, and perhaps most importantly, they explicitly address the issue of where a specific production localises as a function of the localisation of other activities. Secondly, they interpret the geographic concentration of production as "clear evidence of the pervasive influence of some kind of increasing returns" (Krugman, 1991a, pg. 5) which imposes the necessity of adopting a framework characterised by imperfect competition. Finally, in these models the centripetal force represented by the interaction between economies of scale and local market size is counterbalanced by a centrifugal force that works against agglomeration. Rather than being represented by land rent as common in the urban economics literature (see, for example Henderson 1974 and 1988), Krugman describes this force as the result of the need for producers to locate in proximity to a dispersed agricultural hinterland.

The basic structure of these models consists of two regions[3] and two sectors, agriculture and manufacture. Individuals share the following utility function

$$U = C_M^{\mu} C_A^{1-\mu}$$

where C_A denotes consumption of agricultural good and C_M is consumption of a manufactures aggregate. This aggregate is defined by

$$C_M = \left[\sum_{i=1}^{N} c_i^{(\sigma-1)/\sigma} \right]^{\sigma/(\sigma-1)}$$

where N is the number of potential products and $\sigma > 1$ is the elasticity of substitution among the products.

[3] Krugman 1992 expands this framework to a multi-region setting.

Agricultural goods are produced under constant returns to scale using a location-specific factor (land); as a result, agricultural population is exogenously divided between regions. In particular, it is assumed that agricultural population is evenly distributed between the regions and that the ratio between agricultural population and manufacturing workers is also exogenously given and equal to $(1-\mu)/\mu$.

The production of an individual manufactured product i involves a fixed cost and a constant marginal cost:

$$L_{M\,i} = \alpha + \beta\, x_i$$

where x_i is the output and $L_{M\,i}$ is the number of workers employed in its production. Manufacturing workers are perfectly mobile between regions in response to real wage levels.

Finally, agricultural goods can be transported at no cost whilst transportation costs for manufactured goods take on Samuelson's 'iceberg' form: of each unit shipped from one region to another, only the fraction $\tau < 1$ arrives.

In equilibrium, $\sigma/(\sigma-1)$ is shown to represent an index of the importance of the economies of scale. When these are sufficiently strong, a 'circular causation' process similar to the one described by Myrdal and Kaldor can be established: manufacturing production concentrates in one of the regions and, in so doing, increases the size of the local market thus strengthening the incentive to concentrate. Another analogy with Kaldor's model concerns the dynamics of real wages; because of the assumed cost structure, the concentration of manufacturing production in one region reduces production costs and output prices, hence determining an increase in regional real wages.

In two cases, however, the 'circular causation' process will not lead to the concentration of manufacturing. When the share of population employed in manufacturing, μ, is too small, the centrifugal force represented by the need to locate close to the spatially dispersed agricultural market may outweigh the centripetal force generated by the combination of scale economies and local market size. Similarly, a combination of weak economies of scale and high transportation costs may induce suppliers to the agricultural producers to locate in proximity to their markets.

Finally, it should be noted that the scale economies generating the dynamics just described are produced by externalities which are profoundly different in nature from those stressed in the previous sections. Indeed, the type of externalities described by Krugman are entirely *pecuniary*, associated with demand and supply linkages, rather than *real* externalities, like technological spillovers. The importance of technological externalities is explicitly downplayed by the author in favour of externalities arising from labour pooling or availability of nontraded inputs for two fundamental reasons. Firstly, Krugman appears to refer to a very narrowly defined form of technological spillovers and confines their importance to high technology sectors only (Krugman 1991a). Secondly, he chooses to focus on pecuniary externalities only because they are “more concrete” than invisible flows of knowledge (Krugman 1991a and c). As a result, however, the models developed by Krugman confine themselves to the task of explaining the localisation of production but are unable to describe the process of economic growth and its interaction with localisation. Moreover, by excluding from his analysis knowledge and information spillovers, Krugman’s models are better suited to describe the process of manufacturing concentration which characterised industrial economies up to the early 1970s rather than the developments which have followed.

2.5 Conclusions

This chapter has reviewed some of the most important theoretical contributions to the analysis of economic growth. In particular, the presentation has focused on the different ways in which the relationship between technological change and economic growth is conceived in the different streams of theoretical work. Whilst all traditions place the process of technological change at the centre of their explanations of economic growth, this process differs profoundly in its fundamental features. At one extreme, the traditional neoclassical model interprets technological change as a purely exogenous phenomenon and thus provides no economic explanation of its evolution. By contrast, all the other approaches reviewed here try to develop frameworks in which technological change is explained by the action of economic agents. Within these frameworks, technological progress is either seen as the by-product of other economic activities or the intentional result of research efforts carried out by profit seeking agents.

The evolutionary tradition, in particular, seems to provide deeper insights into the nature of the process of technological change. Much of the theoretical work within this tradition, however, has relied primarily on appreciative theory, that is on less abstract, more descriptive modelling. Recent work on endogenous growth within the formal modelling traditions of mainstream economics has tried to codify some of the elements emphasised by evolutionary theorists. One of the aspects that has not received sufficient attention from endogenous growth theorists is represented by the relationship between technological progress, knowledge spillovers and space. Indeed, in many of the existing endogenous growth models, the flow of knowledge cannot be separated from the flow of intermediate goods whilst in others knowledge spillovers are exogenously limited by national boundaries, regardless of the trade regime. In contrast, Fagerberg emphasises that “appreciative theorising often describes technology as organisationally embedded, tacit, cumulative in character, influenced by the interaction between firms and their environments, and geographically localised” (Fagerberg 1994, page 1170). Tacit knowledge, in particular, being the non-written personal heritage of individuals or groups is naturally concentrated in space. Moreover, because of its personal nature, tacit knowledge spills over space essentially through direct, face-to-face, contacts. It seems therefore important to explicitly analyse the geographical dimension of these spillovers. The development of an abstract mathematical model of economic growth that tries to incorporate these features will be presented in Chapters 5 and 6.

Chapter 3
An Overview of the Empirical Literature on Growth and Technology

3.1 Introduction

The traditional neoclassical model of growth has provided the theoretical background for a vast body of empirical analyses on economic growth. The focus of the thread of work usually referred to as 'growth accounting' has been the decomposition of the growth rate of GDP into the contributions from capital, labour, and the exogenous rate of technological progress on the basis of the traditional neoclassical production function. A linearisation of the neoclassical transitional dynamics of an economic system towards its steady state represents the theoretical underpinnings of cross-sectional and panel data regressions of growth rates over initial levels. This latter thread of work will be referred to as the 'mainstream empirical approach' to the analysis of growth. This approach is often criticised for being substantially uninformative. Some authors emphasise that its findings are consistent with very diverse theoretical explanations and hence the approach does not make it possible to test different theories of growth. Different empirical analyses that investigate the determinants of economic growth and that can help discriminate between different theories will be also presented. Other authors instead suggest that the approach fails to illuminate the dynamics of the cross-sectional distribution of per capita income and the convergence issue. Alternative approaches to the analysis of convergence will be briefly presented together with their basic findings.

3.2 Growth Accounting

A typical 'growth accounting' analysis starts from the usual neoclassical production function described in equation 2.1. The dynamics of output are then described by:

$$\frac{\dot{Y}_t}{Y_t} = \mu + \alpha \frac{\dot{L}_t}{L_t} + (1-\alpha)\frac{\dot{K}_t}{K_t} \tag{3.1}$$

where μ is the growth rate of exogenous technological change or, equivalently, of 'Total Factor Productivity' (TFP),[1] and α the share of wage payments to labour in total income. The growth rates of GDP can therefore be expressed as the sum of the growth rate of TFP plus the weighted sum of the growth rates of the two factors, where the weights are the corresponding input shares. If data on the functional distribution of output, on the growth rate of the labour force and of the capital stock are known, the contribution of the factors of production to output growth can be estimated directly from equation 3.1. The part that remains, 'the residual', is then interpreted as an estimate of the contribution of the rate of technological progress.

One of the first analyses of this type was carried out by Abramovitz (1956). He concluded that the unexplained residual was the major determinant of US productivity growth. Similar results were reported by later analyses (Solow 1957; Kendrick 1961; Denison 1962 and 1967). Two threads of work have subsequently concentrated on the 'explanation' of the residual. The first concentrates on qualitative improvements of the factors in general, and of labour in particular (Jorgenson and Griliches 1967; Christensen, Cummings and Jorgenson 1980; Jorgenson *et al*. 1987; Elias 1990; amongst others). In the early applications of the growth accounting methodology, labour input was measured only by the number of hours worked. Jorgenson and Griliches (1967) argue that this way of calculating the contribution of labour overlooks the effect of improvements in the quality of labour due to increases in the average years of schooling and better health. Similar arguments apply to the improvement in the quality of capital. As a consequence, the contribution of labour is determined by constructing a new labour variable as a weighted sum of different categories of labour based on schooling, experience, gender and so on. The weight for each category is then represented by the corresponding observed average wage. Similarly, a new measure for capital is

[1] In this body of literature the level of technological knowledge, A_t, is usually called 'Total Factor Productivity'.

calculated as the weighted average of different categories of capital, where the weights are the corresponding rental rates.

Following the work of Denison (1962), a second line of research has introduced other explanatory variables in the analysis. After having applied the standard growth accounting technique, the resulting residual is regarded by Denison (1967) and Denison and Chung (1976) as determined by structural changes in the employment mix, economies of scale, other less important effects, and technological progress. Griliches (1973 and 1988) and Griliches and Lichtenberger (1984) instead regard the residual from the standard growth accounting analysis as determined by R&D expenditure and view the regression coefficient of this variable as the social rate of return to R&D. It is interesting to note that this second line of development of the standard growth accounting methodology in fact represents a departure from the traditional neoclassical framework. The first group of analyses takes into account structural disequilibria and economies of scale although technology is still considered a pure public good. The analyses that include R&D as an explanatory variable of the TPF growth rate are instead much more in line with the theoretical analyses based on the more recent model by Romer (1990). The results of the studies show very high social rates of return to R&D which range between 20 to 40 percent in the US (Griliches and Lichtenberg 1984; Griliches 1988; Lichtenberg 1992) and around 100 percent for 21 OECD countries plus Israel (Coe and Helpman 1995), although Engelbrecht (1997) shows that somewhat lower rates are found when the role of human capital in innovation outside the R&D sector is allowed for.

Despite the fact that social returns in excess of private ones are to be expected within the endogenous growth framework, the implausibly high values for the social returns to R&D point to one of the most important limitations of these developments of the growth accounting methodology: the causality between productivity growth and the explanatory variables. This appears to be particularly true for R&D, since R&D spending tends to respond positively to growth opportunities (Barro and Sala-i-Martin 1995). As pointed out by Abramovitz (1979), similar problems arise in the analyses by Denison (1967) and Denison and Chung (1976), in which TFP growth and the measure of the economies of scale are likely to be interdependent.

3.3 The 'Mainstream Empirical Approach': Cross-sectional and Panel Data Regressions of Growth Rates over Initial Levels

A key property of the traditional neoclassical model is that it predicts convergence between different economic systems characterised by similar savings rates and technological levels. In a seminal study, Baumol (1986) implements a method of testing the neoclassical prediction of convergence based on a simple cross-section regression:

$$\ln(y_t / y_0) = a + b\ln(y_0) \qquad (3.2)$$

where the left-hand-side of the equation represents the growth rate over the period $(0,t)$. Obviously, a negative value for the coefficient b is interpreted by the author as evidence of convergence, as this would mean that the economies with low initial levels of per capita GDP have experienced the fastest growth rates. Baumol finds that, as predicted by the traditional neoclassical model, countries that initially started with a low level of per capita GDP have subsequently been able to close the gap with richer countries. These results, however, have been criticised for two reasons. Firstly, Abramovitz (1986) points out that, although Baumol's analysis covers the period 1870-1979, convergence took place only after 1950. Secondly, Romer (1986) and DeLong (1988) argue that the results suffer from an ex-post sample selection bias: the data set includes only those economies that had been able to become industrialised by 1979. In line with the implications of this argument, empirical analyses that enlarged the data set to a broader number countries have found that poor countries did not systematically grow faster than richer ones.

These results stimulated the work of Romer (1986), Lucas (1988) and others in the direction of a description of the process of economic growth in which technological change is endogenous and technological opportunities are not the same in all economic systems (see Section 2.3.2.1). Romer (1987) estimates a model in which technological knowledge is determined locally by knowledge spillovers arising from capital accumulation. In this model, the level of technological knowledge, A, is assumed to be an increasing function of the level of physical capital and a negative function of the size of the labour force:

$$A_t = K_t^{\gamma} L_t^{-\gamma}$$

with $\gamma>0$. As a result, the model predicts that diminishing returns to capital accumulation set in more slowly than in the traditional neoclassical model. To test this prediction, Romer runs a cross-country regression based on an equation similar to 3.2 in which the rate of investment is introduced as an additional explanatory variable. This variable is found to have a positive influence on growth, and the implied social rate of return to physical capital is calculated to be in the vicinity of unity. This result is interpreted by the author as supporting the claim that investment in physical capital is accompanied by the creation of new knowledge, and as an indication of the need to investigate, both theoretically and empirically, the issue of technological change. From a theoretical perspective, Romer (1990a, b and c) emphasises that the recognition of the nonrival character of technological knowledge together with the presence of activities essentially aimed at creating technological progress leads to the departure from the assumption of perfect competition of the traditional neoclassical model in favour of a framework characterised by the existence of monopoly power (see Section 2.3.2.2).

From an empirical point of view, the attention of mainstream work has instead focused on a different aspect of Romer's empirical analysis: the negative coefficient on the initial level of per capita GDP. Indeed, this result has two important implications. Firstly, the existence of a statistically significant negative coefficient meant that the process of convergence was still taking place once the effect of investment in physical capital had been taken into account. Secondly, the estimated magnitude of the coefficient suggested that convergence was proceeding at a very slow pace and, in particular, at a much slower pace than what the traditional neoclassical model would predict.

The first contributor to the new stream of empirical analyses on convergence was Barro (1991). His analysis of economic growth, based on an expanded version of the Summers and Heston (1988) data set for 98 countries, confirmed the low speed of convergence found by Romer and found that the growth rate of per capita GDP was substantially positively related to the initial the level of human capital.

Barro and Sala-i-Martin (1991 and 1992) expanded and refined this approach. Firstly, they point out that the traditional neoclassical model predicts that the growth rate of an economy is inversely related to the distance from its steady state. Therefore, poor economies grow faster than rich ones only if different economies share the same steady state. By contrast, if differences in technological levels and attitudes toward saving exist among economies, then these economies are characterised by different steady states and the negative relationship between the growth rate of per capita GDP and its initial level does not hold in a cross-sectional sample. Convergence towards the same steady state is then labelled by these authors as ‘absolute convergence’, whilst the second type of convergence is labelled as ‘conditional convergence’.

The fundamental element of the empirical analyses carried out by Barro and Sala-i-Martin is derived from the logarithmic linearisation of the transitional dynamics of the traditional neoclassical model around the steady state. The result is represented by the following equation:

$$\frac{1}{t}\ln\left(\frac{y_t}{y_0}\right) = c - \frac{1}{t}\left(1 - e^{-\beta t}\right)\ln\left(y_0\right) + u_t \qquad (3.3)$$

where the constant c depends on the level of output per worker and the growth rate of per capita output in the steady state, and u_t is a random disturbance. The analogy with the approach of Baumol is apparent: the two ways of testing the neoclassical model’s predictions are perfectly equivalent, provided that the coefficient a and b in equation 3.2 are substituted with the terms $t\ c$ and $-(1-e^{-\beta\ t})$ respectively. The key parameter to be empirically estimated is represented by the speed of adjustment to the steady state, β, the rate at which the economies approach their steady state growth paths. This parameter crucially depends on the capital-share coefficient, $1-\alpha$:

as this coefficient tends to one, so that diminishing returns to capital no longer apply, the rate of convergence tends to zero.

To test the neoclassical prediction that the growth rate of an economy is inversely related to the distance from its steady state, or β-convergence as Barro and Sala-i-Martin label it, data sets have to be conditioned on the steady state. These authors suggest two possible ways of overcoming the problem. The first is to identify a group of economic systems which are likely to converge towards the same steady state. In this case, absolute convergence is expected and equation (3.3) can be used directly. The second way is to introduce additional explanatory variables in the cross-sectional regression. These variables represent proxies for the different steady states so that the economies can be analysed as if they shared a common steady state.

Examples of analyses of the first type are Barro and Sala-i-Martin 1991, 1992, and 1995, Holtz-Eakin 1992, and Sala-i-Martin 1996, in which attention is concentrated on regional data sets on the grounds that, since regions share similar technologies and cultures and the same legal system, they are more likely to end up in the same steady state. The results show the existence of absolute convergence across the states of the US over the period 1880-1990 and across 47 Japanese prefectures between 1930 and 1990. As for the case of 90 European regions in 8 countries, country dummies have been included to allow for differences in the steady states given the greater extent of cultural and institutional heterogeneity characterising the European system. Even for the European case, the convergence hypothesis is apparently confirmed also in this case, although it is conditional rather than absolute. In all three cases, it is found that regions converge at a speed of 2 percent per year. Similar result for a data set of 85 European regions are obtained by Armstrong (1995a and b) although the estimated speed rate of convergence is closer to one percent than to 2 percent.

In order to check the robustness of this result, Barro and Sala-i-Martin note that the assumption of independence across economies for the error term implicit in equation 3.3 is far from being realistic as in practice some disturbances tend to affect different groups of regional economies in different ways. If this is the case, $\ln(y_0)$ and u_t are not uncorrelated, and the least-squares estimations of β are biased. This problem is overcome by decomposing the error term u_t into two separate components. The equation describing the behaviour of an economic system around its steady state thus becomes:

$$\frac{1}{t}\ln\left(\frac{y_t}{y_0}\right) = c - \frac{1}{t}\left(1 - e^{-\beta t}\right)\ln\left(y_0\right) + \phi\, s_t + v_t \qquad (3.4)$$

where v_t is an independent disturbance, s_t is an aggregate disturbance and ϕ measures its effect on the growth rate of the economy. Assuming that ϕ is distributed independently of v_t and that $\text{cov}[\ln(y_0),\phi]=0$, the composite error term is not correlated with $\ln(y_0)$ and the least-squares estimate of β is not biased. Again, even when additional explanatory variables are added in the cross-sectional regressions to allow for asymmetric shocks, there is evidence of convergence at a speed of 2 percent per year.

Similar results are also found in a large number of cross-country regressions in which additional explanatory variables are added to hold the steady state constant empirically (Mankiw *et al.* 1992; Levine and Renelt 1992; Barro and Sala-i-Martin 1995; amongst others). Conditional convergence is always manifest, and its speed is again estimated in the vicinity of 2 percent per year.

The interpretation of these results from a theoretical perspective is not clear. As clearly pointed out by several authors (Romer 1993, 1994; Fagerberg 1994, Barro and Sala-i-Martin 1995, Sala-i-Martin 1996; amongst others), widely different theoretical interpretations of the growth process are consistent with the results. In general, it is acknowledged that the traditional neoclassical model presented above (Section 2.2) cannot immediately accommodate the outcomes of the cross-sectional regressions. Indeed, the low speed of convergence found in all these studies requires the capital share to be close to 0.7 or 0.8, a value much higher than the conventional value of 0.3 usually accepted in the neoclassical tradition.

Mankiw *et al*. (1992) and Barro and Sala-i-Martin (1992) might be thought of as representing one extreme of the range of the possible explanations of the empirical evidence. They note that even a pure, closed version of the traditional neoclassical growth model can explain the observed rate of conditional convergence among national economies provided that the usual production function is extended to allow for human capital:

$$Y = AK^{1/3}H^{1/3}L^{1/3}.$$

By thinking of capital in a broad sense that includes human capital elements, the labour share is reduced to a value that is thus consistent with the cross-country evidence of the speed of convergence. According to this interpretation, therefore, the traditional neoclassical assumptions of perfect competition and exogenous technological change can still be retained.

Barro and Sala-i-Martin (1995) and Barro *et al*. (1995) realise that the assumption of a closed economy is difficult to justify, particularly when applied to a regional context. However, if capital is assumed to move freely across regions, then the neoclassical growth model would predict convergence at a much faster rate than is observed. As a consequence, they develop a model that retains most of the features of the traditional neoclassical model and in which capital is only partially mobile. As with the previous model, capital is interpreted in a broad sense to include human capital elements but borrowing is now assumed to be possible only to finance accumulation of physical capital, and not accumulation of human capital. This new version of the neoclassical model, somewhat less conservative than the previous one but still relying on the assumptions of perfect competition and exogenous technological progress, is thus able to accommodate the results of the empirical literature on the speed of convergence across regions.

At the other extreme of the range of the possible explanations for the reported evidence it is possible to find endogenous growth with technological diffusion. Within mainstream economic theory, the models presented by Romer (1987), Lucas (1988), Grossman and Helpman (1990, 1991), Rivera-Batiz and Romer (1991b), Helpman (1993), and Barro and Sala-i-Martin (1995 and 1997) contain predictions that conform to the evidence on the speed of convergence. In general, according to these models, the slow speed of convergence is motivated by the fact that technology does not instantaneously flow across all countries. The theoretical reason for such a low speed of technical adaptation may be the existence of imitation and implementation costs. Moreover, these diffusion models predict that higher human capital speeds up convergence, another finding of the empirical analyses.

3.4 Criticisms to the 'Mainstream Empirical Approach': Testing Growth Theories

One limitation of cross-sectional regressions of per capita GDP growth over its initial level that is evident from the above discussion is that such regressions do not make it possible to distinguish between alternative and conflicting theories (Romer 1993, 1994; Fagerberg 1994; Cheshire and Carbonaro 1995). These authors do not suggest that formal statistical investigations in the form of cross-sectional regressions are not a useful tool in general. Rather, they warn that if the aim of the empirical work is to provide a test of the different theories, it is essential to abandon the narrow framework pursued so far in mainstream empirical work. Tests of competing theories have to be set up in such a way that they can distinguish between them. The cross-sectional regression techniques so far discussed at best produce results which are consistent with neoclassical growth theories. But since they are also consistent with other explanations, they do not confirm neoclassical theory. Cross-sectional regressions can still provide a valuable contribution to the understanding of the role played by different factors in shaping the growth process. However, it is important that attention is shifted away from the task of providing an unbiased estimation of the speed of convergence. Therefore, what these authors suggest is to use cross-sectional regressions of per capita GDP in a broader fashion and, at the same time, to turn to other types of analyses both within the mainstream empirical tradition and outside of it.

In evaluating different models of growth, other useful evidence comes from the analysis of migration flows. Lucas (1988) observes that, contrary to the predictions of the neoclassical model, people with high human capital tend to migrate away from locations where human capital is scarce towards locations where it is abundant. Other evidence on the role of migrations is presented by Barro and Sala-i-Martin (1995). Firstly, they concentrate on the prediction that migration is an important source of convergence and, on the basis of the results obtained using three regional data sets, they conclude that migration flows play only a very small role in explaining β-convergence. Secondly, they test the prediction that economies with a higher income elasticity of migration will also have a higher convergence coefficient. The empirical results are not supportive of the neoclassical model in this case, either, since they show a very weak positive relationship between income elasticity of migration and the speed of convergence.

Other interesting empirical evidence is provided by the literature on technology-gap within the evolutionary tradition. As already explained, within the evolutionary tradition technological change is analysed as the joint outcome of innovation and learning activities within firms, and interaction between these and their environments. A fundamental element of the environment is represented by the 'national system of innovation'. The basic idea behind the technology-gap hypothesis is that the rate of technological change in any country is a function of the technological gap between the country and the world leader in technology (Gerschenkron 1962). The process whereby this happens is technology transfer and innovation.

In operational terms, since gaps in productivity levels across economies are considered to reflect technological difference, productivity, as measured by per capita GDP, should be correlated with measures of national technological activities, such as R&D or patenting activity. Empirical support for this hypothesis is found by Pavitt and Soete (1982) and by Fagerberg (1988) and by others at a firm level (Levin *et al*. 1987; Cohen and Levinthal 1989). Whilst their findings also indicate that a certain level of R&D is a necessary condition for successful imitation, Fagerberg (1987) shows that when convergence in productivity takes place the levels of R&D and patenting activity also tend to converge.

Fagerberg (1987, 1988, 1991) expands the analysis to investigate not only the role of imitation but also that of indigenous innovation. It is interesting to note that this study is based on a linear regression which appears very similar to the cross-sectional regressions considered before. Indeed, the growth rate of an economy is explained by the initial level of per capita GDP (interpreted as a proxy for the scope for imitation of existing knowledge), investment (interpreted as a proxy for the effort to exploit existing technology), and growth in patents. Apart from this latter variable which is used to proxy for the national ability to innovate, the others are the same variables used in mainstream empirical analyses but are simply interpreted in a completely different way. The results of the analysis suggest that both imitation and innovation play a role in economic growth. Verspagen (1991) confirms these findings using a nonlinear framework. Moreover, the author shows that countries characterised by a large technology gap and by a low level of education, run the risk of being caught in a low-growth trap. The possibility of the existence of a low-growth trap is suggested also by Amable (1993). In particular, the author estimates a model of simultaneous equations in which growth is explained by imitation (per capita GDP), education, public expenditure and investment which, in turn, is endogenously explained by growth, the level of innovative activity measured by patents and public expenditure. The results for 59 countries between 1960 and 1985 suggest that countries with a low level of education and high share of public expenditure over GDP are likely to be caught in a low-growth trap, whilst most countries tend to converge towards a level of per capita GDP below that of the most advanced countries.

Strictly related to the analyses based on the technology-gap hypothesis is the recent thread of empirical work on knowledge spillovers and on the spatial dimension of knowledge spillovers and innovative activity. Jaffe (1989), Acs *et al*. (1992 and 1994), and Feldman (1994) show that R&D activity performed in both universities and private corporations indeed produces positive effects that benefit other firms. Coe and Helpman (1995) consider international trade as a fundamental carrier of productivity gains and therefore focus on imports of machinery and equipment, although they admit that direct foreign investment is another important source whose role should be investigated. Using a data base for 22 industrial countries, they find evidence supporting the importance of international technological spillovers (see also Section 3.2). These results are substantially confirmed by Engelbrecht (1997), who also suggests distinct roles for human capital and investment in R&D in both domestic innovation and in the absorption of international knowledge spillovers. Coe *et al*. (1997) instead analyse the extent of technological spillovers accruing to 77 developing countries over the 1971-1990 period. Consistently with the findings for industrialised countries, their results suggest that knowledge spillovers, as measured by the elasticity of total factor productivity in developing countries with respect to investment in R&D in industrial countries, are sizeable. In particular, they show that total factor productivity in developing countries is positively and significantly related to R&D in their industrial country trade partners and to their imports of machinery and equipment. At a more spatially disaggregated level, Jaffe *et al*. (1993) find that citations to patents are more likely to come from the same state or Standard Metropolitan Statistical Area (SMSA). In other words, there appears to be evidence supporting not only the actual existence of knowledge spillovers but also their geographic localisation.

Audretsch and Feldman (1996) move from these results to analysing the extent to which innovative activities tend to cluster spatially. Even after controlling for geographic concentration in production, they find clear evidence that industries where knowledge spillovers are expected to be the strongest tend to have greater spatial concentration of innovative activity. All regressions performed by the authors indicate that the level of geographic concentration of innovative activity in an industry is significantly explained by the level of R&D activity, the share of employment accounted for by skilled workers, and the amount of university research. Moreover, there appears to be, at the same time, a tendency for innovative activities to locate away from where the bulk of production is located.

3.5 Criticisms to the 'Mainstream Empirical Approach': Convergence Analysis

Another line of criticism has instead questioned the informative content of estimates of the parameter β. Cheshire and Carbonaro (1995) argue that running cross-sectional and panel data regression analyses to study convergence represents an uninformative exercise: finding a positive, statistically significant value for β in cross-sectional regression is not a robust indication that convergence is taking place. In their view, the cross-sectional dynamics observed over a period of time are the net result of opposing forces; some of these forces lead towards convergence, others push in the opposite direction. As already discussed, a common way of analysing convergence in these studies involves the inclusion of some explanatory variables to allow for differences in the steady states and asymmetric shocks. The estimated value for β, therefore, represents convergence conditioned on these variables and depends on the choice of the conditioning variables. If some of these variables are in fact proxies for forces leading towards divergence, it is obvious that β will turn out positive and statistically significant. Instead, a fully specified empirical model including proxies for all the economic forces affecting the growth process is bound to find no β-convergence. This is indeed the result found by Cheshire and Carbonaro (1995) for growth in the urban regions of Europe for the period 1980-1990

Chatterji (1992), observes that a growth equation like those usually analysed in cross-sectional analyses is in fact a standard difference equation of the type:

$$y_{t+1} + d\, y_t = a \qquad (3.5)$$

where d is equal to -(1+b) in equation 3.2 or, equivalently, to $e^{-\beta t}$ in equation 3.3, provided that y is now interpreted as the logarithm of per capita GDP. The general solution to this difference equation consists of the sum of two components: the particular (integral) solution, and the complementary function. The general solution to this equation is given by:

$$y_t = C(-d)^t + \frac{a}{1+d} \qquad d \neq -1$$

$$y_t = C(-d)^t + at = C + at \qquad d = -1$$

where C is a constant depending on the initial conditions. From a mathematical point of view, whether the equilibrium is dynamically stable is a question of whether the complementary function $C(-d)^t$ will tend to zero as t tends to infinity. In particular, the time path of $(-d)^t$ will be convergent and the equilibrium stable when $|d|<1$ or, analogously, when $-2<b<0$. On the other hand, if $|d|>1$ or, equivalently, $b<-2$ and $b>0$, the time path of $(-d)^t$ will be divergent and the equilibrium unstable. Finally, when $|d|=1$ the general solution y_t will take on a constant value. In other words, from a mathematical point of view, a negative relationship between the growth rate and the initial level of a variable in not sufficient to ensure convergence. The author propounds a 'strong' criterion for convergence: $|d|<1$ or, in terms of equation 3.2, $-2<b<0$. However, it is easy to show that this requirement for 'strong convergence' is always satisfied when $\beta>0$. Since $b = -(1-e^{-\beta t})$, it is clear that the condition $-2<b<0$ implies $-1<e^{-\beta t}<1$. Given that the exponential function can never take on negative values, it follows that Chatterji's criterion implies a positive value for β. In other words, any positive value of β implies strong convergence in Chatterji's sense. It is also worth noting, however, that the case in which $-1<e^{-\beta t}<0$ is actually not feasible, which implies that the usual cross-sectional regressions cannot accommodate the particular situation $-2<b<-1$, and the only possible interval for the parameter b is between -1 and 0.

Quah (1993b and 1996b) points out that, although different concepts of convergence exist in the literature, the type of convergence implied by the neoclassical model, and at the basis of the cross-sectional and panel data regression analyses that focus on the behaviour of a representative economy, requires that each economy eventually becomes as rich as the others and the cross section dispersion diminishes over time. Moreover, according to Quah (1993a and 1996b) these empirical analyses make the implicit assumption that the transition towards the steady state follows a smooth monotonic path.

Four fundamental arguments are then put forward to question the validity of cross-sectional regressions of growth rates over initial levels as instruments for analysing convergence. Firstly, Quah (1993a and 1996b) points out that the statistical tools used are inappropriate for the study of convergence when the underlying process of growth is unstable. Secondly, several researchers suggest that testing for the convergence hypothesis on the basis of β is plagued by Galton's fallacy of regression towards the mean. Thirdly, it has been argued (Quah 1996b; Canova and Marcet, 1995), the 2 per cent convergence speed commonly found in many cross-sectional and panel data regressions could arise for reasons independent from the dynamics of economic growth. Finally, Quah (1993b, 1996b) emphasises that all these criticisms apply to all cross-sectional regressions independently of whether they focus on absolute convergence, as in the case of analyses of regional data sets, or on cross-country conditional convergence.

The first argument is investigated by Quah (1993a). The author presents cross-country evidence that does not seem to support the hypothesis of a smooth monotonic transition to the steady state. The data for 118 countries between 1962 and 1985 show strong instability in the underlying patterns of growth and suggest that important disturbances are present throughout the period. Consequently, the author emphasises that "assuming that each country has a stable growth path and then studying their cross-country variation produces results that are difficult to interpret" (Quah 1993a, pages 428-429).

Secondly, several researchers (Friedman 1992; Quah 1993b; Hart 1994; amongst the others) emphasise the analogy between cross-sectional regressions of growth rates over the initial levels and Galton's fallacy of regression towards the mean. In other words, they demonstrate that a negative relationship between growth rate and initial value does not indicate a reduction in the cross-sectional variance and, moreover, that it is also possible to observe a diverging cross-section distribution even when such a negative relationship holds. Taking the case in which each economy's growth process is described by equation 3.3

$$\ln\left(\frac{y_{i,t}}{y_{i,t-1}}\right) = c + \left(1 - e^{-\beta t}\right)\ln y_{i,t-1} + u_{i,t} \qquad (3.6)$$

where u is independent and identically distributed in time and has finite variance $\sigma_u^2 > 0$ and suppose that $\beta > 0$, so that 3.6 shows β-convergence. Suppose further that all

$\ln(y_{i,0})$ are independent of $u_i(t)$ for $t \geq 1$, and all $\ln(y)$'s are independent and identically distributed over space[2] and time. Equation 3.6 then implies:[3]

$$\sigma_t^2 = e^{-2\beta}\sigma_{t-1}^2 + \sigma_{ut}^2$$

and, as t tends to infinity,

$$\sigma^2 = \lim_{t\to\infty}\sigma_t^2 = \left(1 - e^{-2\beta}\right)^{-1}\sigma_u^2$$

As a result, the observed β-convergence is accompanied by a reduction in cross-sectional convergence, σ-convergence, if and only if the initial value for the cross-sectional variance, σ_0^2, is greater than its steady state value, σ^2.

The fact that a positive coefficient β is a necessary but not a sufficient condition for a reduction in the cross-sectional dispersion is acknowledged by Barro and Sala-i-Martin (1991, 1992, 1995). A positive value for β is thus interpreted as indicating the existence of forces reducing the cross-sectional distribution whilst ongoing disturbances are seen as forces pushing in the opposite direction. The practical value of this interpretation is however downplayed by Quah (1993a) who observes that even if information about these shocks were used in a cross-sectional regression, still a positive value for β would not imply that the cross-sectional distribution is collapsing.

The third argument concerns the nature of the convergence speed rate found in cross-sectional regressions. As reported in Section 3.2, the vast majority of the analyses on β-convergence report that convergence is taking place at a speed of around 2 per cent per year. It has also been emphasised that this result appears particularly robust, being confirmed by widely different cross-country and regional data sets. However, it is precisely this robustness that has attracted the attention of several researchers who have started to question whether it could be at least partially explained by reasons quite independent from the dynamics of economic growth. Quah's (1996b) hypothesis is that the 2 per cent convergence rate could be partly the result of a unit-

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2 This implies that also u_t is independent and identically distributed over space

3 This result can be derived by adding $\ln(y_{i,t-1})$ to both sides of equation 3.6, computing the variance, and using the condition that the $\text{cov}[u_{i,t}, \ln(y_{i,t-1})]=0$.

root in the time series data. Indeed, if the regression disturbance $u_{i,t}$ in equation 3.6 is correlated with $y_{i,t-1}$, the OLS estimator for $e^{-\beta t}$ is biased at all sample sizes. Suppose however that $e^{-\beta t}$ has the special value of 1. Unit-root regression theory says that the OLS estimator of $e^{-\beta t}$ converges to its correct value of 1 regardless of the correlation between the disturbance term and the regressor, but that, for finite values for t, the OLS estimator is biased downwards. It is interesting to note at this point that a value of 0.98 for $e^{-\beta t}$ implies a value of 0.02 for β. In other words, Quah suggests that cross-sectional regressions could be unit-root regressions with finite sample bias. To check for this possibility he performs a Monte Carlo experiment to see whether it is possible to reproduce the 2 per cent convergence results even when the true data generating models show no convergence. Using a model comprising cross-sectional independent random walks, Quah finds that β is approximately equal to 2 per cent for moderate-sized samples and tends to 0 as both t and the sample size increase.

Another possibility is suggested by Canova and Marcet (1995). In particular, they explain the 2 per cent estimates as arising from a 'fixed effect bias', well known in the panel data literature (Hsiao 1985; Pesaran and Smith 1995), which is mechanically obtained from the data when observations from heterogeneous units are pooled as if their data generating process were the same.

Finally, Quah (1993b, 1996b) emphasises that all these criticisms are very general and apply to both conditional and absolute convergence regressions. As already pointed out, it is customary in the mainstream empirical literature on convergence to distinguish between 'absolute convergence' (when all economies converge to the same steady state) and 'conditional convergence' (when different steady states exist). Usually, regional data sets are used to check for the former type of convergence on the grounds that regions should be characterised by the same steady state given the relatively high degree of homogeneity in terms of technology, preferences and institutions. In these cases, therefore, convergence implies that poor regions effectively grow faster than rich ones and catch up to them. Instead, when different countries are considered, technology levels, taxes and attitudes towards savings can be very heterogeneous leading to very different steady states. In these instances, the transition towards the steady states is not necessarily accompanied by a tendency for poor economies to grow faster than rich ones. Apparently, therefore, the above arguments questioning the validity of cross-sectional regressions of growth rates over initial levels apply to the analyses of absolute convergence only. However, Quah points out that those criticisms "extend – in a straightforward way – to cover these cases of conditional convergence: simply apply the arguments to the *residuals* of output growth, after conditioning on exogenous variables of interest" (Quah 1993b, page 429).

3.6 Convergence Analyses Following Different Approaches

The fundamental message of the previous section is that concentrating on the behaviour of a representative economy can only shed light on the transition of this economy towards its own steady state whilst giving no information on the dynamics of the entire cross-sectional distribution of income. Consequently, several authors argue that the concept of β-convergence is irrelevant. However, concentrating on the concept of σ-convergence solves only part of the problem. Analysing the change of cross-sectional dispersion in per capita income levels, as measured by the standard deviation of the sample, gives no information on the intra-distribution dynamics. Indeed, it can easily be shown (Quah 1996b) that a constant standard deviation is consistent with very different dynamics ranging from criss-crossing and leap-frogging to persistent inequality and poverty traps. Distinguishing between these dynamics is, however, of essential importance. It is therefore interesting to develop different approaches to the analysis of convergence which examine directly how the cross-sectional distribution of per capita output changes over time, putting emphasis on both the change in its external shape and the intra-distribution dynamics.

The methodology suggested by Quah (1993a and b, 1994, 1996a and b, 1997a) concentrates directly on cross-sectional distributions of per capita income, using stochastic kernels to describe their law of motion. The implications for the convergence debate are then drawn either on the basis of the ergodic distribution of the process when the distributions are discretised so that the kernel becomes a simple transition probability matrix or, in the continuous case, directly analysing the shape of a three-dimensional plot of the stochastic kernel.

The results suggest polarisation and divergence across world economies with the development of a 'twin peaks' distribution: middle-income classes tend to vanish whilst world economies cluster either in the very rich or in the very poor classes (Quah 1993a and b, 1996a and b, 1997a). However, the picture is substantially different for the US states. Here the mobility among classes is much higher than in the cross-country case and the ergodic distribution does not present the bimodality of rich and poor observed in the world distribution (Quah 1996b). A simpler analysis on 71 administrative regions belonging to 6 European countries suggests that the cross-sectional distribution is converging towards a tighter, more concentrated distribution but also finds support for the hypothesis that spatial spillovers are important in understanding regional cross-sectional dynamics (Quah 1997b). A similar analysis, but on a broader data set, suggests the existence of two separate convergence clubs for the European regions (Neven and Gouyette 1995).

Fingleton (1997) also analyses convergence among the regions of the EU between 1975 and 1993 using a Markov Chain model. In particular, the author discretises the cross-sectional income distribution into four large classes and adopts a log-linear modelling approach to investigate the stationarity of the initial distribution, as well as the features of the ergodic distribution. The results show that European regions are converging towards a limiting distribution characterised by sizeable differentials in per capita income levels and consistent with the existence of multiple steady states from which economies are continuously displaced by shocks. There is also some evidence suggesting that the limiting distribution of the Markov process had been attained in 1975.

Finally, Canova and Marcet (1995) develop a Bayesian procedure to estimate different convergence rates for different steady states for each cross-sectional unit. This procedure is applied to two European data bases, one including 144 administrative regions (from 1980 to 1992) and the second including 17 Western European countries extracted from the Summer and Heston (1991) database. Their average estimates of the convergence rate are much higher than those usually found in the literature: about 11 per cent for countries and 23 per cent for regions, with each unit converging to its own steady state. These estimates imply a capital share in a neoclassical production function ranging between 0.20 and 0.35. Moreover, the hypothesis that the steady state is the same for all cross-sectional units is rejected by the data, both for regions and countries. In other words, poorer regions and countries stay poor.

3.7 The definition of the spatial units of analysis

Another important empirical issue concerns the definition of the spatial units used in the analyses. Researchers spend a great deal of attention in ensuring that the techniques they apply are appropriate and up to date, so that the level of econometric sophistication of empirical test of theories of growth is considerable. However, much less attention is paid to the definition of the spatial units of analysis and to the consequences that the definition adopted might have on the results. Unfortunately, however, the potential bias that could derive from an erroneous choice of the spatial units of analysis is certainly substantial (Cheshire 1997).

Different criteria may be used in subdividing national territories into regions. In general, these criteria range between two extremes: normative criteria and functional criteria. The first set of criteria can broadly be seen as reflecting political factors. Regional boundaries are generally defined according to the tasks allocated to the territorial communities; to the size of population which is optimal in order to implement these tasks; to historical factors, and so on. At the other extreme, functional criteria can be used to define regional units so as to satisfy specific principles of nodality which may be required by the nature of the particular analysis performed.

Because of the very nature of regional economic disparities, any empirical study on the subject must take space into consideration and opt for a definition of region centred on the spatial sphere of socio-economic influence of any basic unit. Since the functional links between spatial units are limited by space, functional regions take explicit account of the distance factor and appear therefore as the best alternative.[4]

In spite of these arguments, due mainly to the availability of data, administratively defined regions are commonly used in empirical analyses without a careful investigation of the possible bias that this choice may introduce into the results. Within the European context, one typical example of regional definition according to normative criteria is represented by the Nomenclature of Territorial Units for Statistics (NUTS), established by the Statistical Office of the European Communities in order to provide a single breakdown of territorial units for the production of Community regional statistics. The boundaries of these administrative regions, however, are the result of political and historical factors which are country-specific so that not only do they bear no particular relationship to the socio-economic factors that form the basis of a functional region, but they also vary from country to country making comparison extremely problematic.

The nature of the problems arising from the use of administrative regions can be summarised as follows. Firstly, in all cities employment tends to be concentrated in central areas – the Central Business District (CBD) – while substantial residential location is on the outskirts. At the same time, all large cities exhibit residential segregation with poor neighbourhoods and rich neighbourhoods, ethnically specific areas, areas of social housing, and so on. But different cities have different patterns: whilst the poor in Britain tend to concentrate in the city-centres, the predominant residential location for the poor in Italy and France is on the outskirts. Consequently, unless the definition of a region has been selected to abstract from patterns of

[4] This is better recognised in the US, where a number of studies makes use of Standard Metropolitan Statistical Areas (SMSAs) as its spatial units of analysis. The analysis of Jaffe *et al*. (1993) on the geographic localisation of knowledge spillovers, and those of Glaeser *et al*. (1992) and Henderson *et al*. (1995) on the relative role of inter-industry and intra-industry local spillovers of knowledge are just a few examples. By contrast, within the European context only Cheshire and Carbonaro (1995 and 1996) base their analyses of regional growth on functionally defined regions.

residential location and commuting, the measured levels of per capita income will depend on the definition of region being used. Secondly, since the early 1970s, decentralisation – the outward diffusion of people from urban cores – interacts with the simultaneous absolute decline of employment in the manufacturing sector in all the older industrial countries of the EU. Again, the extent to which decentralisation appears as a loss of population and/or jobs and activity for the region crucially depends on the definition of regional boundaries.

It may seem that resorting to relatively large regions, for instance NUTS1 regions within the European context, could reduce the incidence of the problems just described. Careful examination shows this to be untrue, however. On the one hand, using larger regions runs the risk of 'aggregating away' truly spatial differences once more. On the other hand, even at the NUTS1 level, it is possible to find regions that are in fact metropolitan areas (Bruxelles, Berlin, Bremen, Ile de France, and Hamburg), alongside larger regions that contain several metropolitan areas, such as Nordrhein-Westfalen.

In the case of Hamburg, Bremen and Bruxelles, for example, the NUTS1 boundaries are very narrowly drawn with respect to the corresponding functional regions. Employment is concentrated in their central areas whilst residential areas extend well beyond the NUTS boundaries so that substantial in-commuting takes place. As a result, the calculated per capita GDP of these regions is largely over-estimated since the total GDP produced within the regions' workplaces is divided among too few residents. In addition, the residential areas of the cities which lie outside the NUTS boundaries show a strong over-representation of lower income residents. Consequently, per capita income for these NUTS1 region is highly inflated.

Not only are per capita GDP values influenced by where boundaries are drawn but growth rates are also affected (Cheshire 1997). Bremen and Hamburg, together with several other north European cities, experienced significant decentralisation during the 1980s. This meant that the resident population in the NUTS region was falling compared to employment during the 1980s. Thus, the increase in the extent of the upward bias in per capita GDP at the end of the period compared to the start determined an over-estimation of the measured growth rate.

Probably, the extent of the problem can be better appreciated with an example. Table 3.1 reports the levels of per capita GDP in 1980 for the five richest NUTS 1 and for the Functional Urban Region (FURs) derived by Hall and Hay (1980) for 1971, and adopted by Cheshire and Hay (1989) in their analysis of urban problems in Europe between 1951 and 1981 and by Cheshire and Carbonaro (1995 and 1996).[5]

Table 3.1 Per capita GDP in PPS(ECU), 1980: NUTS1 and FURs

	NUTS 1	GDP/Hab	**FURs**	GDP/Hab
1	Hamburg	13273	Frankfurt	11778
2	Bruxelles-Brussel	11788	Paris	11394
3	Ile de France	11459	München	10592
4	Bremen	10625	Stuttgart	10563
5	Noord-Nederland	9586	Düsseldorf	10524

In the case of Bruxelles, per capita GDP in the NUTS1 region was 11788 ECU(PPS) in 1980; in the Functional Urban Region it was only 5920 ECU(PPPs), less than the European average of 7082 ECU(PPS). Moreover, the proportionate growth rate in Bruxelles between 1980 and 1990 was almost the same (0.71) for the two definitions and very close to the average growth rate for the Community as a whole (0.72) so that the inclusion of the NUTS1 region of Bruxelles would bias the results towards convergence. The administrative boundaries for Ile de France, on the other hand, are very similar to those for the FUR of Paris. Consequently, there is very little difference between measured per capita GDP levels and growth rates for these alternative regional definitions. The last case to consider is the one of Noord-Nederland. The output of this region is dominated by the activity of Gröningen that was one of the most affluent NUTS 2 regions in the EU in the early 1980s. This, however, is unrealistic as all income generated from the Dutch production of gas from the North Sea is recorded in Gröningen. As a result of the sharp decrease in energy prices throughout the second part of the 80s, per capita GDP for Gröningen

[5] Each of these regions is derived from a two-step procedure described in the Data Appendix.

and Noord-Nederland fell dramatically and the inclusion of Gröningen in the data set may bias the results towards convergence.

3.8 Conclusions

This chapter presented an overview of the main empirical work on growth and technological change across economies. In particular, attention has been paid to both the findings of different threads of work and to methodological issues.

The starting point has been represented by those streams of analysis that employ the traditional neoclassical model of growth as a theoretical background. 'Growth accounting' analyses show that a large part of economic growth cannot be explained by the accumulation of factors of production. When they depart from the traditional neoclassical framework, very high social rates of return to R&D are found. However, the causality between productivity growth and explanatory variables has been indicated as one possible explanation for these high values.

The 'mainstream empirical approach' is derived from the transitional dynamics of the traditional neoclassical model of growth and is represented by cross-country and panel regressions of growth rates of per capita income over initial levels. The fundamental aim of these analyses is the estimation of the speed – reflected in the estimated value of β – with which different economies converge to a steady state equilibrium, allowing for differences in the positions of the steady states. The vast body of analyses that focus on β-convergence has produced a remarkably homogenous set of results. Poor and rich economies appear to be converging at a stable rate of about 2 per cent per year. Moreover, the estimated rate appears to be roughly the same for data sets which differ widely in terms of time samples, overall geographical extension and level of geographical disaggregation of the basic units of analysis.[6]

6 Exceptions are Cheshire and Carbonaro 1995 and 1996.

The ‘mainstream empirical approach’ has, however, attracted many criticisms. Several authors criticise cross-sectional and data panel regressions of growth rates over initial levels from a methodological point of view. The fundamental argument is that these analyses, focusing on the behaviour of a representative economy, are not informative of the dynamics of the entire cross-sectional distribution and thus provide little information on the convergence issue. Other methodologies for the analysis of convergence have then been presented. These methodologies differ from cross-sectional regression in that they analyse directly the cross-sectional dynamics. They suggest that divergence and polarisation between poor and rich economies is a common tendency both across countries and among the regions of the EU.

A methodology building on that elaborated by Quah is developed in the following chapter. In particular, this methodology directly analyses the cross-sectional distribution of per capita income, studying its intra-distributional dynamics and the change in its external shape, whilst requiring absolutely no assumptions with respect to the nature of the steady-state. The methodology is then used to investigate whether a convergence process has characterised the recent history of the European regional system. Moreover, in the light of the discussion on the crucial importance of an adequate definition of regions, the study is not conducted on the basis of administratively defined regions but makes use of a large dataset, the spatial units of which are derived on the basis of functional criterion: Functional Urban Regions (FURs).

Finally, it has been pointed out that the ‘mainstream empirical approach’ is unable to distinguish between different and, in important aspects, conflicting theories of economic growth. Indeed, its findings could be interpreted as providing support to both the traditional neoclassical model with exogenous technological change and to endogenous models of economic growth with technological diffusion. Instead, empirical analyses on migration patterns and growth determinants cast doubts on the validity of the traditional neoclassical model of growth and appear to support endogenous explanations of growth. Therefore, the formal model of regional growth developed in Chapters 5 and 6 will combine the results of the empirical analysis of convergence presented in the next chapter with some important features of the endogenous growth models discussed in the previous chapter.

Chapter 4
Income Differentials within the European Union

4.1 Introduction

The aim of this chapter is to analyse the convergence issue within the EU. In light of the results of the discussion on the validity of cross-sectional or panel data regressions, it is chosen to develop a methodological alternative to these analyses, in the spirit of what suggested by Quah. Similar to Quah's approach, this methodology directly analyses the cross-sectional distribution of per capita income, studying its intra-distributional dynamics and the change in its external shape, whilst requiring absolutely no assumptions on the nature of the steady-state. In particular, it is chosen to discretise the income space rather than allowing it to be continuous (Quah 1996a and 1997a), because through discretisation it seems possible to gain more information on the features of the growth and convergence process under study. Indeed, the choice between discrete and continuous space methods of analysis can be interpreted as a trade-off between information and subjectivity. Whilst discretising the income space allows to get more information on the features of the growth process, discretisation criteria are generally subjective and it is well known that an inappropriate discretisation can remove the Markov property from a first-order Markov process (Chung, 1960).

The research line adopted here is that rather than reducing the set of information obtainable from the analysis it is worthwhile trying to develop less subjective discretisation criteria which tend to minimise the risk of distorting the underlying model. In other words, the methodology adopted here, tries to overcome the subjectivity involved in the choice of the discretising grid whilst not only allowing the study of the one-period dynamics and the resulting ergodic distribution, but also the analysis of the transitional dynamics as well as the calculation of the speed at which the steady-state is approached.

4.2 The Definition of the Regions and of the Time Period

Many empirical analyses have recently tried to determine whether European poor regions are effectively catching-up with richer ones. However, as emphasised in the previous chapter, these empirical analyses seem to suffer from an important problem. The administrative definition of regions commonly used does not bear any relationship to the socio-economic factors that determine the existence of these spatial disparities.[1] Therefore, to reduce the bias associated with such a definition, the present analysis adopts a set of 122 major European FURs, that is, resorts to a functional definition of region centred on the spatial sphere of socio-economic influence of a major urban centre.[2]

The time period covered by the present analysis runs from 1979 to 1990, a period long enough to allow for the cyclical movements in economic behaviour as it is calculated between similar phases of the economic cycle. The cycle for the EU is identified by considering the cyclical fluctuations of the performance of the European economy, in terms of Gross Domestic Product, and its medium-term trend. Figure 4.1 plots the difference between the annual growth rate of the European Economy and its medium-term trend. From a European perspective, therefore, the definition of the period adopted here appears to be consistent with the requirement of comparability between starting and ending dates. The problem is, however, that the timing of the cycle obviously differs across regions. To minimise the influence of this factor, the data on per capita GDP for a particular year are calculated as 3-year averages centred on that year.

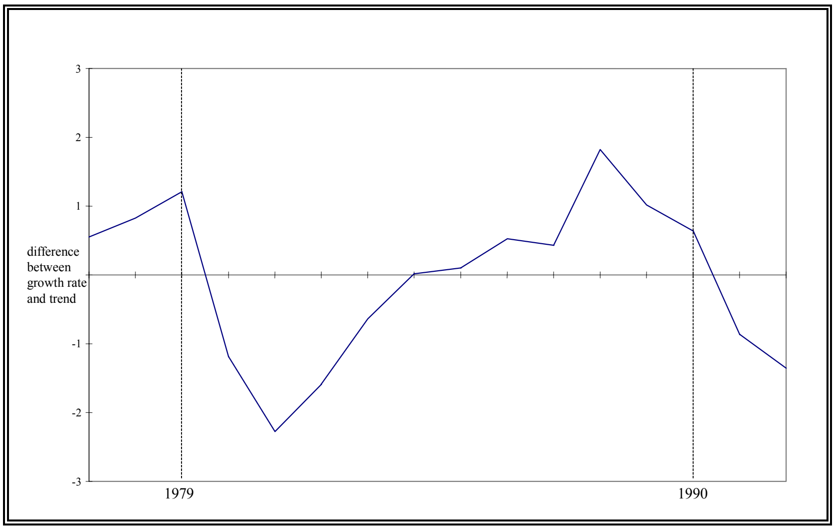
There is, however, at least one national specificity that should be taken into account. During the final part of the period under study, German cities have witnessed a substantial flow of immigrants from Eastern and Central Europe (Burda, 1993). Cheshire (1995) notes that this phenomenon overlapped with a pattern of partial urban recentralisation common to many northern European cities, leading to substantial

[1] Notable exceptions are Cheshire and Carbonaro 1995 and 1996.

[2] The complete list of the 122 major FURs – def ined as those with a core city greater than or equal to 200,000 inhabitants and a total population greater than or equal to a third of a million inhabitants – is reported in the Data Appendix.

population growth in German FURs' cores after a decade or more of population loss. This immigration flow is likely to have some consequences for the present analysis. Indeed, Cheshire and Carbonaro (1995 and 1996), in their studies of growth patterns of European FURs over the '80s, find some evidence in support of the view that these flows, because of the consequent increase in population and because migrants remained mainly unemployed during the period considered here, have exogenously reduced the growth rate of German FURs. In other words, measuring per capita GDP for these FURs as a 3-year average centred on 1990 might underestimate the growth performance of German FURs since this time span does not appear to be large enough to allow for the absorption of the shock.

Figure 4.1 The European Union Economic Cycle



4.3 A Markov Chain Approach to the Study of Convergence

It is useful to introduce first some general notions and definitions of Markov chains, and then describe the specific approach to the study of convergence adopted here.

Denote regional per capita GDP at time t relative to the European average[3] by y^t, the corresponding cross-sectional distribution by d^t, and define a set C of n income classes. The evolution of this distribution over time can be described by the following equation

$$d^{t+1} = P \cdot d^t \tag{4.1}$$

where P describes the transition from one distribution into the other and $d^t = (d^t_1, ..., d^t_n)'$ is the vector of population proportions at time t. In other words, P can be interpreted as a transition probability matrix: for any two income classes i and j ($i, j \in C$), the elements p_{ij} define the probability of moving from class i to class j between time t and $t+1$.

Supposing that a region r is in class i ($y^t_r = i$) at time t, if the sequence $\{y^0_r, y^1_r, ...\}$ satisfies the relation

$$\Pr\left\{y_r^{t+1} = i \,\middle|\, y_r^t, y_r^{t-1}, \ldots, y_r^0\right\} = \Pr\left\{y_r^{t+1} = i \,\middle|\, y_r^t\right\} \tag{4.2}$$

for any $i \in C$, and for any region, then the evolution of the cross-sectional distribution d described by equation 4.1 can be analysed as a time-homogeneous (finite) Markov chain.[4] Equation 4.2, usually referred to as the Markov property for a homogeneous chain, states that, given the knowledge of a present state, y^t, the outcome in the future y^{t+1} does not depend upon the past $\{y^0, y^1, ..., y^{t-1}\}$.

The transition probabilities, p_{ij}, in the matrix P in equation 4.1 are associated with a transition from any two income classes taking place within a single time period. Important information about the dynamics of the cross-sectional distribution can be obtained by considering higher order transition probabilities $p_{ij}(l)$. In this case, the transition matrix $P(l)$ contains information about the probabilities of transitions that take

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3 As in Quah (1993a and b, 1994), regional per capita income is measured in relative terms to the European average. This makes it possible to separate the effects on the cross-sectional distribution of aggregate (European) forces from the effect derived from regional-specific forces, having conditioned their aggregate effects out.

4 Note that the definition in equation 4.2 is not the standard definition of a Markov chain. Implicit in the definition adopted here is that the transition probability between any two states (income classes in the present case) is independent of time, giving rise to a time-homogeneous Markov chain. However, as already pointed out in the introduction, the present analysis hinges on the assumption of time-homogeneity and the definition of equation 4.2 seems to greatly facilitate the understanding of the methodology being employed.

place in exactly l periods. In general, higher order transition probabilities have the relationship

$$p_{ij}(l_1+l_2)=\sum_k p_{ik}(l_1)\,p_{kj}(l_2) \qquad \forall\, i,j,k \in C$$

or, in terms of the transition probability matrices

$$P(l_1+l_2)=P(l_1)\,P(l_2)\ . \tag{4.3}$$

For any two classes i and j ($i, j \in C$), $p_{ij}(l)$ gives the probability that, starting from income class i, a regional economy will enter income class j after exactly l periods, regardless of the number of entrances into j prior to l. If $\phi_{ij}(l)$ denotes the probability that class i is reached for the first time from class j after l periods, or first passage probability, the sum

$$\sum_{l=1}^{\infty}\phi_{ii}(l)=\phi_{ii}$$

represents the probability of eventual return to the original class i.

A typology of the classes in terms of the first return probabilities and the transition probabilities can now be introduced. A class i is called *transient* if $\phi_{ii} < 1$. In this case there is a positive probability 1- ϕ_{ii} that starting from class i a region will not return to the same class in a finite number of time periods. If $\phi_{ii} = 1$, the class is called *recurrent* and the expectation

$$\mu_{ii}=\sum_{l=1}^{\infty} l\cdot\phi_{ii}(l)$$

is the *mean recurrence time* for class i. Instead, if $\phi_{ii}(1) = 1$, the income class i is an *absorbing* class, for which it is also true that $\phi_{ii} = 1$, $\mu_{ii} = 1$. An income class is *periodic* of period $s > 1$ if $p_{ii}(l) = 0$ except for $l = s, 2s, \ldots$, where s is the largest integer with this property. A class which is not periodic is said to be *aperiodic*; an aperiodic recurrent state with a finite mean recurrence time is called *ergodic*.

Finally, it is interesting to point out the asymptotic behaviour of $p_{ij}(l)$. It can be shown (Chung, 1960) that, if the class j is transient, then

$$\lim_{l \to \infty} p_{jj}(l) = 0 \qquad (4.4)$$

and, for all i

$$\lim_{l \to \infty} p_{ij}(l) = 0 \,. \qquad (4.5)$$

On the other hand, if class j is ergodic

$$\lim_{l \to \infty} p_{jj}(l) = \frac{1}{\mu_{jj}}$$

and, for all i

$$\lim_{l \to \infty} p_{ij}(l) = \frac{1}{\mu_{jj}} \,.$$

A set S of income classes is *closed* if, for every $i \in S$,

$$\sum_{j \in S} p_{ij} = 1 \,.$$

In other words, if S is a closed set, any income class k outside the set cannot be reached from any income class inside the set or, in formal terms, $p_{ik} = 0$ ($\forall\ i \in S$). If there exists no closed subset other than the set of all income classes C, the Markov chain is said to be *irreducible* and all the income classes are of the same type. Moreover, if the income classes of an irreducible Markov chain are ergodic, the chain is also ergodic and it is possible to show (Feller, 1968) that the limits

$$\lim_{l \to \infty} p_{ij}(l) = \pi_j$$

exist and are independent of the initial income class i. Furthermore, if $\pi_j > 0$,

$$\sum_j \pi_j = 1$$

and the limiting distribution $\{\pi_j\}$ is stationary so that

$$\sum_i \pi_i \, p_{ij} = \pi_j \,.$$

In other words, for an ergodic Markov chain there always exists a stationary distribution, the limiting distribution of the chain, which is independent of time. This limiting distribution can be calculated from the eigenvalues of the transition matrix. As every row sum in P is equal to 1, the matrix is a stochastic matrix and its eigenvalues are not greater than unity in absolute value whilst one of the eigenvalues is $\lambda_1 = 1$. For an ergodic Markov chain the limiting probabilities are given by

$$\pi_j = \frac{A_{jj}(1)}{\sum_k A_{kk}(1)} \qquad j,k \in C \tag{4.6}$$

where $A_{jj}(1) = A_{jj}(\lambda_1)$ is the (j, j)th cofactor of the matrix $A(\lambda_1) = A(1) = (I-P)$.

In general, the existence of the stationary distribution and the speed with which the system approaches it, can be investigated by considering the second eigenvalue of P. When the modulus of the second eigenvalue, λ_2, is strictly smaller than 1, the transition matrix P converges to a limiting transition matrix P^* and the cross-sectional distribution converges to a stationary distribution where the conditional probability of occupying an income class in the next period is the same as the unconditional probability. In this case, the asymptotic half life of the chain, hl, that is the amount of time taken to cover half the distance from the stationary distribution, can be shown (Shorrocks, 1978) to be given by

$$hl = \frac{-\log 2}{\log|\lambda_2|} \tag{4.7}$$

which ranges between infinity -when λ_2 is equal to 1 and a stationary distribution does not exist- and 0 -when λ_2 is equal to 0 and the system has already reached its stationary equilibrium-. If the length of the time period over which the transition matrix P is defined is of τ years, $\tau \times hl$ is the number of years needed to cover half way to the steady state.

The Markov chain approach to the study of convergence across economic systems can be summarised as follows. First, a grid of n non-overlapping income classes is defined on the basis of some criterion. The choice of the grid, by providing a discrete approximation of the cross-sectional distributions that form the object of the study, uniquely determines the n^2 transition probabilities that form the Markov chain transition matrix P. The existence of a steady-state distribution is then investigated by considering the eigenvalues of P. When this stationary distribution exists, the speed with which the system approaches the steady-state is calculated using the asymptotic half life of the chain in equation 4.7. For ergodic Markov chains, the stationary distribution can be computed directly using the limiting probabilities described in equation 4.6. However, even if the transition probability matrix P is not ergodic, it still might be possible to derive the stationary distribution. In order to do this, it is necessary to identify which income classes are transient and which are ergodic. As equations 4.4 and 4.5 ensure that all transient income classes will be empty when the system reaches its steady-state, the analysis of the stationary distribution can be carried out by identifying irreducible subsets of *C*, whose elements (income classes) are all ergodic. Again, the speed of the transition phase of the system can be derived from the asymptotic half life of the individual ergodic subsets of *C*. It should be noted at this point that if the matrix *P* can be partitioned into *k* ergodic stochastic sub-matrices, the first *k* eigenvalues of *P* are all equal to 1, whilst the speed of the transition to the steady-state is governed by the (*k*+1)*th* eigenvalue. Finally, equation 4.3, also known as the Chapman-Kolmogorov equation for time-homogeneous Markov chains, can be used to visualise the shape of the cross-sectional distribution *d* after a certain number of time periods. If the asymptotic half life of the chain is very short, the transient behaviour of the system might be of relative interest. On the contrary, if the transition towards the steady-state is slow, the transient behaviour of the chain becomes very important, possibly more important than the steady-state itself.

4.4 The Choice of the Income Class Size

The direct study of the cross-sectional distribution of per capita income following a Markov chain approach is strictly linked to the estimation of the (unknown) probability density function that has generated the observed data. Given *m* regions, the cross-sectional distribution of per capita income at time *t*, represented by the vector (y^t_1, y^t_2, ..., y^t_m), can be seen as a random sample from a continuous probability function *f* where

$$f(y^t) \geq 0 \qquad \int_{\Re} f(y^t)\,dy^t = 1.$$

It is precisely the study of this density function, *f*, and of its changes over time, that represents the object of the Markov chain approach. All the information about the shape of the cross-sectional distribution at any point in time is in fact summarised by the corresponding density functions that have generated the data. Moreover, given two points in time, *t* and *s*, the information about the intra-distributional dynamics that have taken place between t and s can be derived from the analysis of the changes in the density function that have contemporaneously occurred. In particular, once a discrete approximation of the density function has been derived, the analysis of the intra-distributional dynamics can be carried out on the basis of a probability transition matrix.

The general problem is therefore to estimate f when no formal parametric structure is specified.[5] One of the two ways suggested by Quah (1993b, 1994) proceeds by using n quantiles, with n ranging between 3 and 6, and then calculating the corresponding fractile transition probability matrix. Elsewhere, the same author, discretises the cross-sectional distribution into five classes whose upper end-points are 0.25, 0.5, 1, 2 and infinity (Quah 1993a, 1996b) or 0.74, 0.88, 1, 1.16 and infinity (Quah 1997b). The implications for convergence are then drawn through the analysis of the transition probabilities and of the corresponding ergodic distributions. Whilst these choices of the income class ensure that each of the n^2 transition probabilities are calculated exactly - in the former case - or roughly - in the latter one - on the same number of observations, they are totally subjective and may represent a source of potential problems given that inappropriate discretisation can remove the Markov property from a first-order Markov process (Chung, 1960).

Even though, as Quah points out (Quah 1996b), the distortions introduced through discretisation are not likely to conceal the most important features of the distribution dynamics under study, it seems nevertheless important to reduce the existing degree of arbitrariness. In order to do this, Quah (1996a) allows the space of income values to be continuous and estimates the corresponding infinite-dimensional stochastic kernel nonparametrically. This type of analysis is then based on the visual inspection of the three-dimensional plot of the stochastic kernel, complemented by the calculation of the *passage time*, i.e. the time that an economy requires to move from one part of the income distribution to another. Whilst this solutions clearly represents an interesting improvement on the previous analysis, on the other hand it seems to reduce, rather than enlarge, the set of features of the growth and convergence process it is capable to shed some light on. Therefore, the analysis that follows suggests a possible way to overcome the subjectivity in the choice of the grid that, at the same time, allows not only the study of the one-period dynamics and the resulting ergodic distribution, but also the analysis of the transitional dynamics as well as the calculation of the speed at which the steady-state is approached.

The starting point is the recognition that the arbitrary discretising grid used to construct the transition probability matrix is in fact a crude nonparametric estimator of the probability density function that generated the observed cross-sectional data. It is therefore interesting to make use of other nonparametric methods that estimate a density function. Thus, in the present case attention is concentrated on the histogram with equisized cells,[6] a consistent estimator of the true underlying probability density function that, at the same time, provides a discrete approximation of the continuous cross-sectional distribution.

Given an origin Ω, and a bin width h, the bins of the histogram are defined by the intervals $[\Omega + kh, \Omega + (k+1)h)$ for positive and negative integers k.[7] The histogram is then defined by

$$\hat{f}(y_t) = \frac{1}{nh} \times (\text{no. of sample values in the same bin as } y_t). \qquad (4.8)$$

As a result, the construction of the histogram requires a proper choice of its two parameters: the origin Ω and the bin width h, or in terms of the previous section, the size of the income classes. If data are measured to an infinite accuracy, the choice of the origin becomes less important as the sample size increases. In the present context of analysis, however, as the data for per capita income in each region are measured as a

5 In other words, f is taken to belong to a large enough family of density functions so that it cannot be represented through a finite number of parameters. The resulting estimate of f is therefore a nonparametric estimate.

6 Variable cell histograms, and related procedures for choosing the variable cell widths, have recently been the object of analysis (Kogure 1987; Kanazawa 1992). The computation required to define the variable cell widths is intensive whilst, for normal distributions, the increase in the quality of the approximation is not significant.

7 The intervals have been chosen closed on the left and open on the right for definiteness.

proportion of the European average, the value 1 represents a natural choice for the origin.

The choice of the other parameter, h, is however quite important. If h is too small, then the histogram will be too rough and it will become more likely to find closed subsets of the transition probability matrix P that do not communicate; on the other hand, if h is too large, then the histogram will be too smooth, resulting in the loss of important information on intra-distributional dynamics. The choice of h should therefore be balanced between these two extremes by minimising a measure of the error of approximation.

Two general approaches to this problem exist, the L_1 and the L_2 approach. Assuming that f is square integrable, the latter approach generally measures the performance of the estimator, $\hat{f}$, of the probability density function in terms of the integrated mean squared error (IMSE):

$$\text{IMSE}=\int_{-\infty}^{\infty} E_f\left[\hat{f}(y_t)-f(y_t)\right]^2 dy_t=\int_{-\infty}^{\infty}\left(\text{var}\left[\hat{f}(y_t)\right]+\left\{\text{bias}\left[\hat{f}(y_t)\right]\right\}^2\right)dy_t \quad (4.9)$$

where bias[$\hat{f}(y_t)$] = $E_f[\hat{f}(y_t)]-f(y_t)$.

It is interesting to note that too small an h, leading to a rough histogram, is statistically equivalent to a large variance in equation 4.9. Similarly, a large h determining excessive smoothing in the histogram is equivalent statistically to a large bias. Therefore, the choice of the optimal width for h based on the L_2 approach seeks a balance between the bias and variance by minimising the IMSE. Scott (1979) shows that, in the case of a histogram as defined by equation 4.8, and under the condition (Freedman and Diaconis 1981) that $f'(y_t)$ is absolutely continuous, $\int f'(y_t)^2\, dy_t > 0$, and $\int f''(y_t)^2\, dy_t < \infty$, IMSE is asymptotically minimised if

$$h_n^*=\left\{6/\int_{-\infty}^{\infty}\left[f'(y_t)\right]^2 dy_t\right\}^{1/3} n^{-1/3}. \quad (4.10)$$

The optimal bin width, h^*, in equation 4.10 clearly depends upon the unknown f through f'. When the probability density function f is normal the optimal bin width becomes

$$h^*_n = 2 \times 3^{1/3} \pi^{1/6} \sigma n^{-1/3}$$

and its estimate

$$\hat{h}^*_n = 3.49\, s\, n^{-1/3},$$

where s is the sample standard deviation. Scott also shows that this data-based choice of the bin width works well for Gaussian samples, whilst it leads to too large bin widths and hence oversmoothing in the case of skewed, heavy-tailed or bimodal distributions. In these situations, the criterion can still be used if corrected downwards according to a table reported by the author.

Another interesting criterion that follows the L_2 approach has been suggested by Freedman and Diaconis (1981). Using the interquantile range, IQR, of the data as a measure of the scale of the random variable under study, they suggest a simple data-based rule

$$\hat{h}^*_n = 2(\mathrm{IQR})\, n^{-1/3}.$$

As shown by Devroye and Györfi (1985), one problem with the L_2 approach to nonparametric density estimation is that the tail behaviour of a density becomes less important, possibly resulting in peculiarities in the tails of the density estimate. To overcome this problem, which is particularly relevant to the type of analysis pursued here, these authors develop an alternative approach, the L_1 approach, that focuses on the integrated absolute error (IAE)

$$\mathrm{IAE} = \int_{-\infty}^{\infty} \left| \hat{f}(y_t) - f(y_t) \right| dy_t \ . \qquad (4.11)$$

Following this criterion they obtain

$$h^*_n = \left\{ \frac{8 \left\{ \int f^{1/2}(y_t) dy_t \right\}^2}{n\pi \left\{ \int \left| f'(y_t) \right| dy_t \right\}^2} \right\}^{1/3} .$$

When f is assumed to be a normal distribution $N(0,\sigma^2)$

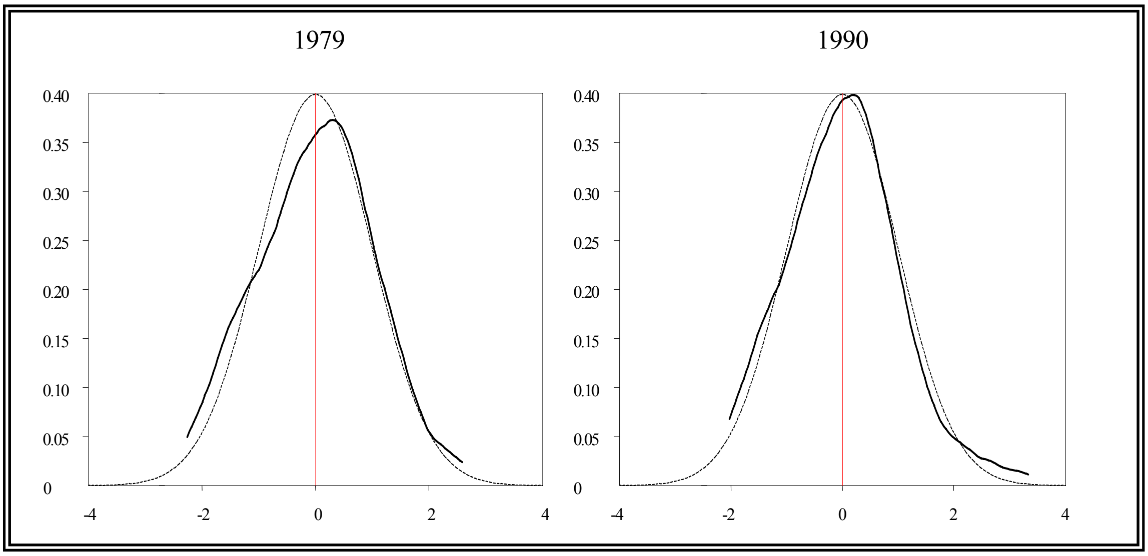
$$\hat{h}^*_n = 2.72\, s\, n^{-1/3}\ .$$

4.5 Empirical Results

The criteria for the optimal choice of the income class size are derived under the assumption that the unknown probability density function is normally distributed. Even though these criteria are generally able to deal with non-normal samples provided that the deviations from normality are not too wide, it is interesting to check whether the normality assumption holds or, in case it does not hold, to measure the size of the violation.

Figure 4.2 shows an informal investigation on the shape of the two distributions by plotting a nonparametric estimate of the unconditional distributions using the Epanechnikov kernel (Silverman 1986).

Figure 4.2 Normalised Estimated Distributions (Epanechnikov Kernel; FURs Data)



For ease of interpretation, the distributions (solid line) are compared to a standard normal distribution (dotted line). The change in the external shape of the distribution over the period under analysis seems to suggest two main features. Firstly, the right tail of the distribution, that contains the richest regions, appears to have increased its relative importance, leading to a decrease in the degree of symmetry of the distribution. Secondly, the rest of the distribution has converged towards middle income classes.

A formal test of normality can be performed using the Kolmogorov-Smirnov and the Shapiro-Wilk tests. Table 4.1 reports the tests' statistics and the corresponding *p-levels*. For the Kolmogorov-Smirnov test Lilliefors probabilities instead of usual probabilities are reported given that mean and standard deviation are estimated from the data.

Table 4.1 Normality Tests (FURs Data)

Distribution	**K-S test**	***P***	**S-W test**	***p***
1979	0.04928	>0.20	0.97871	0.3984
1990	0.04814	>0.20	0.97536	0.2434

It is clear that the normality assumption can be accepted for both distributions but the significance level is substantially lower for the 1990 distribution. A visual inspection of the shape of the distributions suggests that the poorer result for the most recent distribution could be explained by the behaviour of the richest regions: the part of the right tail of the distribution exceeding two standard deviations noticeably increases its relative importance thus leading to a higher degree of asymmetry. In such a situation, the criterion developed by Devroye and Györfi, being based on the L_1 approach and thus paying particular attention to the tail behaviour, is expected to yield a better approximation of the observed distribution than the other criteria. In other words, choosing the size of the income classes according to the Devroye and Györfi criterion should limit the loss of important information on the dynamics that underlie the observed tail's behaviour.

This expectation seems confirmed by the results in terms of goodness of approximation achieved by the criteria for the choice of the income class size. In particular, each criterion is applied to one of the observed distributions, called the reference distribution, and the resulting income class size is then used to derive the discrete approximations of both observed distributions. Four tests, three parametric and one nonparametric, are then performed on each discrete approximation derived from each estimator. The three parametric tests are the coefficient of determination between the observed distribution and its approximation, a t-test for dependent samples to evaluate differences in means, and an F test for the homogeneity of variances. The t-test for dependent samples requires that the differences between corresponding observations of the two distributions are normally distributed. When a Shapiro-Wilk test on the normality of these differences shows that this condition is not met, the nonparametric Wilcoxon Matched Pairs test is also performed. Table 4.2 reports the tests' results only for the Freedman-Diaconis and Devroye-Györfi criteria because those for the Scott's criterion are always considerably poorer.

The approximations based on the DG criterion applied to the 1990 distribution appear to outperform the alternative approximations in the F test on variance homogeneity and in both tests on mean homogeneity, whilst they are comparable to the approximations based on the FD criterion applied to the 1990 distribution and on the DG criterion applied to the 1979 distribution in terms of coefficient of determination. As a results, the analysis that follows will concentrate on the DG criterion applied to the 1990 distribution.

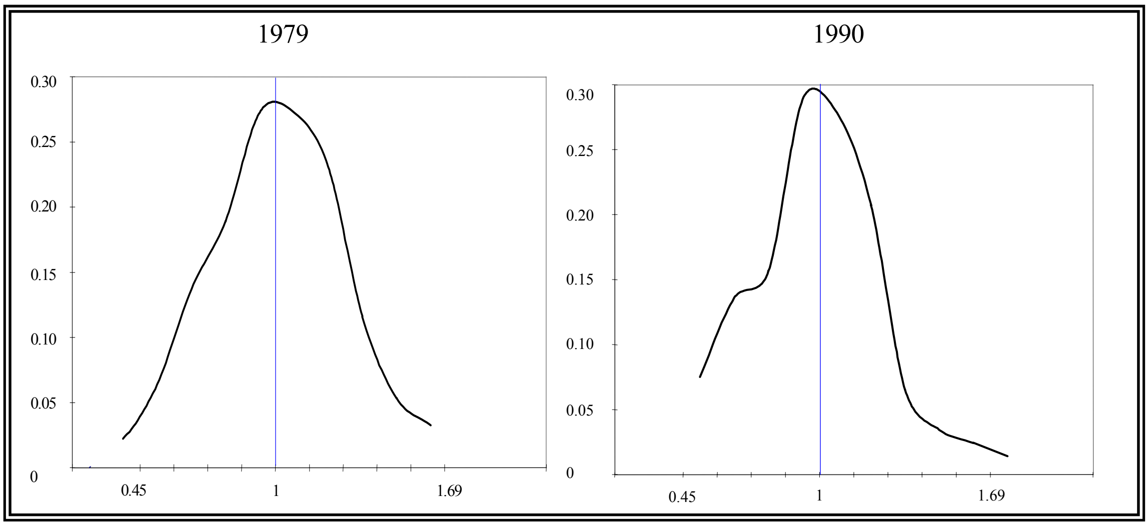
Table 4.2 Tests on the Performance of the Approximation Criteria (FURs Data)

Criterion[(1)] and reference distribution	**Approxim. Distribution**	**r^2**	**t-test**	***p***	**F test**	***p***	**Wilcoxon test**	***p***
FD 1979	1979	0.97	0.81	0.42	1.05	0.78	0.77	0.44
FD 1979	1990	0.97	0.16	0.88	1.06	0.75	0.07	0.94
FD 1990	1979	0.98	0.27	0.79	1.02	0.91	0.23	0.82
FD 1990	1990	0.98	0.14	0.89	1.01	0.96	0.12	0.91
DG 1979	1979	0.98	0.55	0.58	1.01	0.98	0.39	0.70
DG 1979	1990	0.98	0.56	0.58	1.00	0.98	0.62	0.54
DG 1990	1979	0.98	0.24	0.81	1.00	0.99	0.12	0.90
DG 1990	1990	0.98	0.10	0.92	1.00	0.99	0.00	1.00

(1) FD = Freedman-Diaconis; DG = Devroye-Györfi.

The quality of the resulting approximations may be appreciated by a comparison between Figure 4.2 and Figure 4.3, where the distributions estimated with the DG criterion are plotted by running a smooth line through the mid-class values of the resulting histograms.

Figure 4.3 Approximated Distributions (DG Criterion on 1990 Distribution, FURs Data)



It is now possible to consider the transition probability matrix. Table 4.3 reports the transition probability matrix when the income class size is derived using the DG criterion on the 1990 distribution. The transition probability matrices derived according to the DG criterion on the 1979 distribution and on the FD criterion on both distributions are in fact very similar to the one reported in Table 4.3. The same sort of conclusions to those presented here can also be drawn in these other cases.

Although the Markov chain based on the transition probability matrix in Table 4.3 is clearly not ergodic, it is still possible to identify the stationary distribution of the chain by analysing its components. Firstly, note that the first income class (<0.45) is not only transient, but becomes empty after just one time period. The only region that belonged to this class in 1979, the functional urban region of Porto, moves to the following income class (0.45-0.59) by 1990.

Table 4.3 Transition Probability Matrix, P (FURs data)

	<0.45	0.45-0.59	0.59-0.72	0.72-0.86	0.86-1.00	1.00-1.14	1.14-1.28	1.28-1.41	1.41-1.55	1.55-1.69	>1.69
<0.45	0	1	0	0	0	0	0	0	0	0	0
0.45-0.59	0	0.8	0.2	0	0	0	0	0	0	0	0
0.59-0.72	0	0.167	0.666	0.167	0	0	0	0	0	0	0
0.72-0.86	0	0	0.235	0.471	0.294	0	0	0	0	0	0
0.86-1.00	0	0	0	0.2	0.64	0.12	0.04	0	0	0	0
1.00-1.14	0	0	0	0	0.28	0.56	0.16	0	0	0	0
1.14-1.28	0	0	0	0	0	0.476	0.524	0	0	0	0
1.28-1.41	0	0	0	0	0	0	0.4	0.6	0	0	0
1.41-1.55	0	0	0	0	0	0	0	0	0.75	0.25	0
1.55-1.69	0	0	0	0	0	0	0	0	0	0.5	0.5
>1.69	0	0	0	0	0	0	0	0	0	0	0

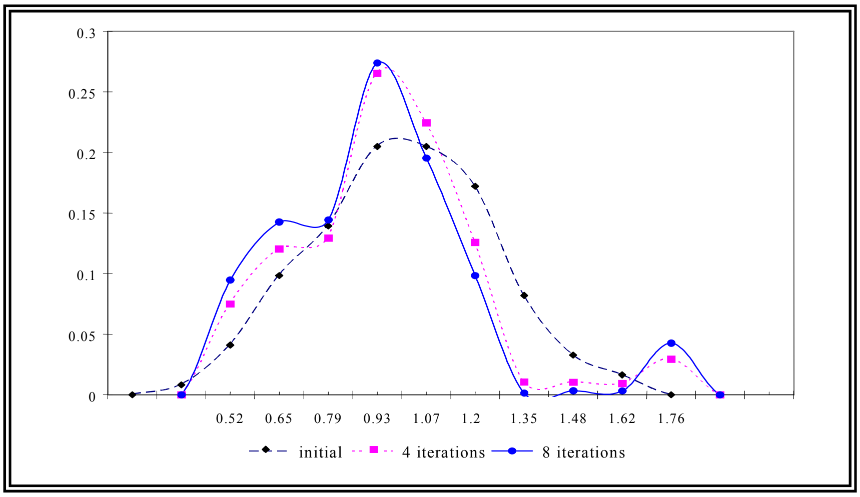
The second relevant component, P_2, is represented by the sub-matrix made up of the 2*nd* to the 7*th* class. This matrix is in fact ergodic; it is therefore possible to derive the corresponding stationary distribution that, because of the nature of the first class, will include Porto after just one time period. The 8*th* income class (1.28-1.41) is also a transient class whose elements tend to drift back into P_2. Finally, the last sub-matrix to consider is P_4, the sub-matrix made up of the three richest classes. Before analysing P_4 it is however necessary to formulate an assumption on the future behaviour of the region (Frankfurt) that entered the 11*th* class between 1979 and 1990. The most conservative assumption is that Frankfurt will remain in the same open income class (>1.69) and, consequently, in the analysis that follows the element $p(11,11)$ is assumed to be equal to 1, so that the sub-matrix P_4 is closed with an absorbing class.[8] The existence of two separate components of the chain is a particularly interesting fact. As it is clear from the analysis of the transitional dynamics, due to the partition of P into two ergodic components, the cross-sectional distribution tends rapidly to split into two separate parts. The second eigenvalues of the two closed sub-matrices of interest can then be calculated in order to determine the speed of the transition towards the stationary

[8] This assumption does not appear to be particularly strong. Exactly the same qualitative results can be obtained if it is assumed that the probability of remaining in the same class is less than one while the probabilities of moving back up to two classes are positive.

distribution. The second eigenvalues for P_2 and P_4 are equal to 0.9242 and 0.75 respectively, leading to half lives of 8.79 and 2.41 time periods. This means that the whole system needs almost 100 years ($8.79 \times 11 = 96.7$) to reach half way to its steady-state, whilst the chain corresponding to P_4 reaches the same point after about 25 years ($2.41 \times 11 = 26.51$).

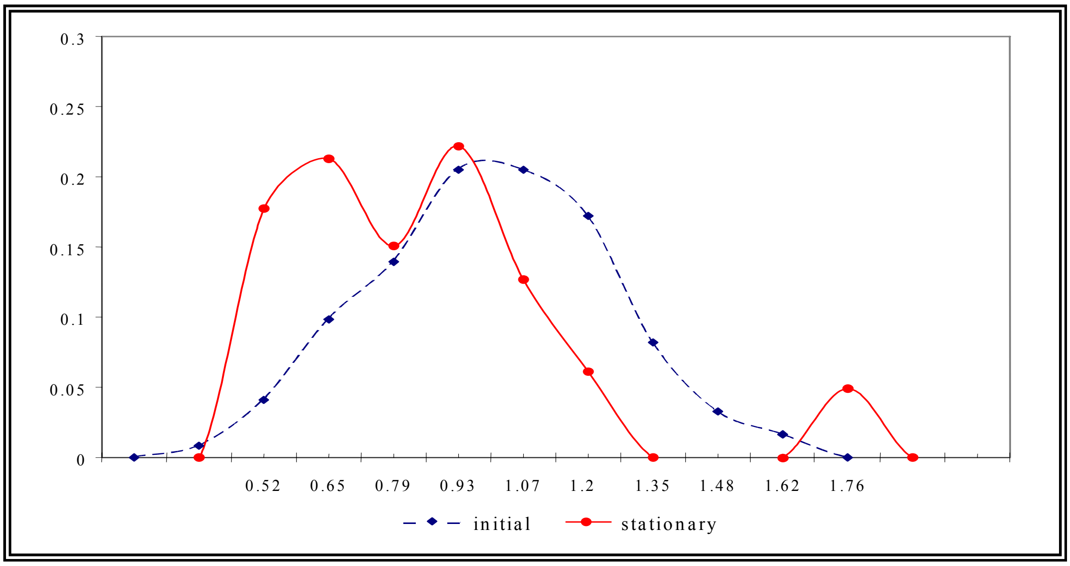
The transient behaviour of the chains and the resulting stationary distribution are reported in Figures 4.6 and 4.7. As in the previous figures, each distribution is drawn by running a smooth line through the mid-class values of the corresponding histograms. Figure 4.6 shows the transition towards the steady-state by considering the shape of the distribution after 4 and 8 iterations (44 and 88 years).

Figure 4.6 The Evolution of the European FURs System: Transitionary Dynamics



In Figure 4.7, the stationary distribution is instead compared to the initial one. These results confirm the intuition that the initial cross-sectional distribution of regional per capita income (also plotted) is characterised by a tendency to split into two separate parts: a group of six regions, Düsseldorf, Hamburg, Stuttgart, München, Paris, and Frankfurt, tends to grow away from the rest of the European regions. This result appears to be particularly strong. On the one hand, although it has been argued that measuring per capita GDP as a 3-year average centred on 1990 is likely to have underestimated the growth performance of German FURs, five of the six FURs that have grown away from all the others are in fact German. On the other hand, this split in the stationary distribution is confirmed by the results of analyses performed using income class sizes defined according to other discretising criteria.

Figure 4.7 The Evolution of the European FURs System: Stationary Distribution



As for the other regions, the corresponding part of the stationary distribution appears to be bimodal, suggesting a further distinction between middle-income regions and low-income ones. This second result is subject to some variation when other criteria for the choice of the income class size are adopted.[9]

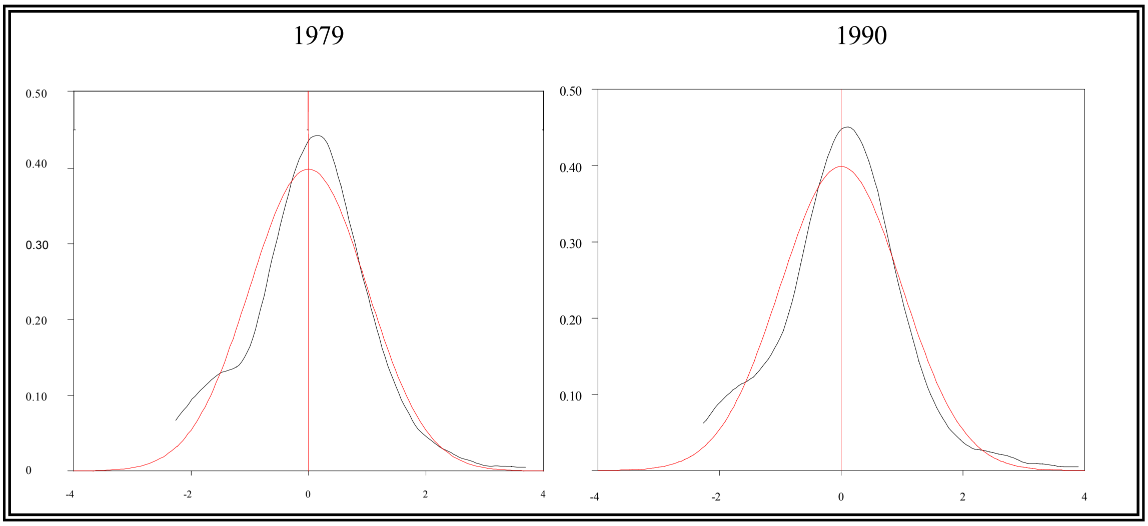
It has been noted in Section 4.2 that an incorrect definition of the spatial unit of analysis is likely to yield biased results. Moreover, and probably more importantly, the criteria for the definition of the administrative regions tend to vary across countries so that it becomes impossible to have *a priori* information on the likely direction of the bias introduced in the analysis. It is therefore interesting to compare the results obtained using the FURs database with those that can be obtained using data on administrative regions. In particular, from the data published by Eurostat, it has been possible to collect data on per capita GDP measured in ECU(PPS) for NUTS2 regions. Initially, the NUTS2 region of Gröningen is excluded from the analysis because, as explained in Section 4.2, the level of per capita income for this region is the artificial result of the

[9] Only the use of the FD criterion on the 1990 distribution totally eliminates it.

way in which income generated from the Dutch production of gas in the North Sea is recorded. Moreover, it should be noted that also the region of Bruxelles is not part of the data set. This is due a peculiar feature of the definition of Belgian NUTS regions: even though the NUTS classification is a hierarchical one, Bruxelles figures as a NUTS1 and as a NUTS3 region but not as a NUTS2 one.

As in the FURs' case, the initial and final distributions are calculated as three-year averages centred on 1979 and 1990 respectively. Figure 4.8 allows a visual inspection of their shapes by plotting the nonparametric estimates of the unconditional distributions using the Epanechnikov kernel.

Figure 4.8 Normalised Estimated Distributions (Epanechnikov Kernel; NUTS2 Data)



Comparing the two figures, it can be noted that two features similar to those identified for the FURs' case seems to have characterised the change in the income distributions during the period under analysis. On the one hand, the right tail of the distribution seems to have increased its relative importance. On the other hand, the rest of the distribution appears to be converging towards middle income classes. Moreover, it is also possible to note a substantial difference between the shape of the observed distributions of regional per capita income and the corresponding standard normal distributions. This feature is confirmed by the results of the normality tests reported in Table 4.4, where it is evident that for both distributions it is not possible to accept the normality assumption.

Table 4.4 Normality Tests (NUTS2 Data)

Distribution	K-S test	*P*	S-W test	*P*
1979	0.08	<0.05	0.97	0.06
1990	0.07	<0.10	0.97	0.02

The fact that the normality assumption can be accepted only for the distributions based on FURs data and not for those based on NUTS2 data represents an very interesting result. Indeed, it seems to confirm the argument put forward in Section 4.2 concerning the relevance of the distortion introduced in the analysis by resorting to an administrative definition of the spatial units of analysis rather than to one based on functional criteria.

Given the results of the normality test, the goodness of approximation of the different criteria is now evaluated using five tests: a further nonparametric test - the Spearman Correlation Coefficient - is added to the tests already employed in the FURs' case. The results of these tests are presented in Tables 4.5 and 4.6.

Table 4.5 Parametric Tests on the Performance of the Approximation Criteria (NUTS2 Data)

Criterion(1) and reference distribution	Approxim. Distribution	r^2	t-test	*P*	F test	*p*
FD 1979	1979	0.99	1.13	0.26	1.01	0.96
FD 1979	1990	0.68	1.16	0.25	1.04	0.81
FD 1990	1979	0.99	0.76	0.45	1.01	0.93
FD 1990	1990	0.68	1.16	0.25	1.01	0.97
DG 1979	1979	0.98	0.24	0.81	1.01	0.97
DG 1979	1990	0.98	0.60	0.55	1.02	0.90
DG 1990	1979	0.98	0.55	0.58	1.01	0.94
DG 1990	1990	0.98	0.91	0.37	1.02	0.88

(1) FD = Freedman-Diaconis; DG = Devroye-Györfi.

Table 4.6 Nonparametric Tests on the Performance of the Approximation Criteria (NUTS2 Data)

Criterion[1] and reference distribution	Approxim. Distribution	Spearman Correlation Coefficient R	Wilcoxon test	p
FD 1979	1979	0.99	1.10	0.27
FD 1979	1990	0.95	1.08	0.28
FD 1990	1979	0.99	0.75	0.46
FD 1990	1990	0.95	1.10	0.27
DG 1979	1979	0.98	0.18	0.86
DG 1979	1990	0.98	0.59	0.55
DG 1990	1979	0.98	0.56	0.58
DG 1990	1990	0.98	0.88	0.38

(1) FD = Freedman-Diaconis; DG = Devroye-Györfi.

The discrete approximations based on the DG criterion applied to the 1979 distribution appears to be the best one according to all tests with the only exception of the F test on variance homogeneity where it is outperformed by the FD criterion applied to the 1990 distribution. As a result, the analysis that follows is carried out using the approximations derived applying the DG criterion to the 1979 distributions. However, the results obtained in this way will then be compared with those obtained applying the FD criterion to the 1990 distribution.

The approximated distributions are plotted in Figure 4.9. From the comparison with Figure 4.8 it is possible to visually evaluate the quality of the approximation obtained resorting to the DG criterion on the 1979 distribution. Instead, Table 4.7 reports the corresponding transition probability matrix in which it is possible to identify three separate ergodic components. The first component corresponds to the first 9 income classes and converges extremely slowly to its steady-state as witnessed by a half-life of 772 time periods. In other words, this component of the system needs almost 8,500 years to reach half way to its steady-state. The second component corresponds to the sub-matrix made up of the *10th* to the *12th* class and reaches half way to its steady-state in just one time period. Finally, the last sub-matrix of interest corresponds to the *13th* income class and is totally isolated from the rest of the system.

Figure 4.9 Approximated Distributions (DG Criterion on 1979 Distribution, NUTS2 Data)

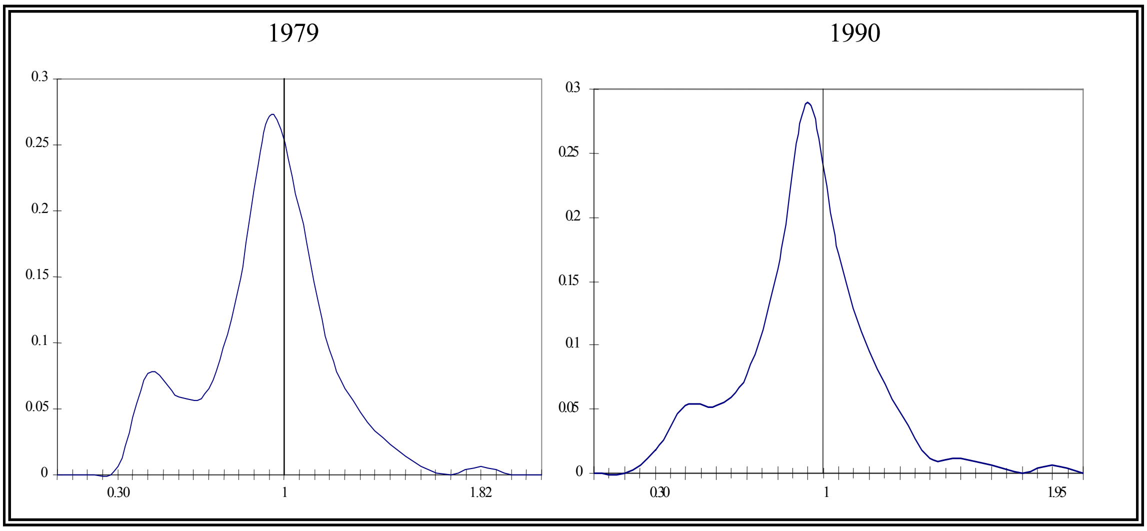
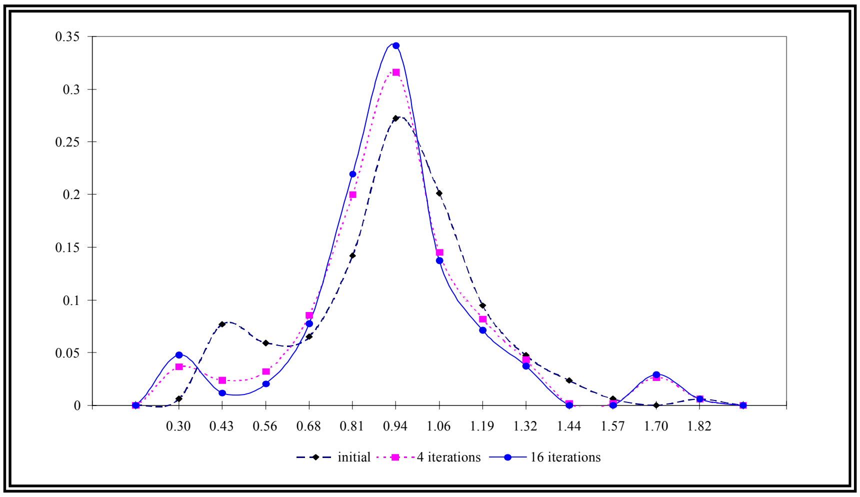


Table 4.7 Transition Probability Matrix, *P* (NUTS2 Data)

	<0.37	0.37 0.49	0.49 0.62	0.62 0.75	0.75 0.87	0.87 1.00	1.00 1.13	1.13 1.25	1.25 1.38	1.38 1.51	1.51 1.63	1.63 1.76	>1.76
<0.37	1	0	0	0	0	0	0	0	0	0	0	0	0
0.37 0.49	0.15	0.54	0.31	0	0	0	0	0	0	0	0	0	0
0.49 0.62	0	0.2	0.4	0.4	0	0	0	0	0	0	0	0	0
0.62 0.75	0	0	0.09	0.64	0.27	0	0	0	0	0	0	0	0
0.75 0.87	0	0	0	0.08	0.54	0.38	0	0	0	0	0	0	0
0.87 1.00	0	0	0	0	0.24	0.65	0.11	0	0	0	0	0	0
1.00 1.13	0	0	0	0	0	0.29	0.53	0.15	0.03	0	0	0	0
1.13 1.25	0	0	0	0	0	0	0.38	0.5	0.13	0	0	0	0
1.25 1.38	0	0	0	0	0	0	0	0.38	0.63	0	0	0	0
1.38 1.51	0	0	0	0	0	0	0	0	0	0.5	0.5	0	0
1.51 1.63	0	0	0	0	0	0	0	0	0	0	1	0	0
1.63 1.76	0	0	0	0	0	0	0	0	0	0	1	0	0
>1.76	0	0	0	0	0	0	0	0	0	0	0	0	1

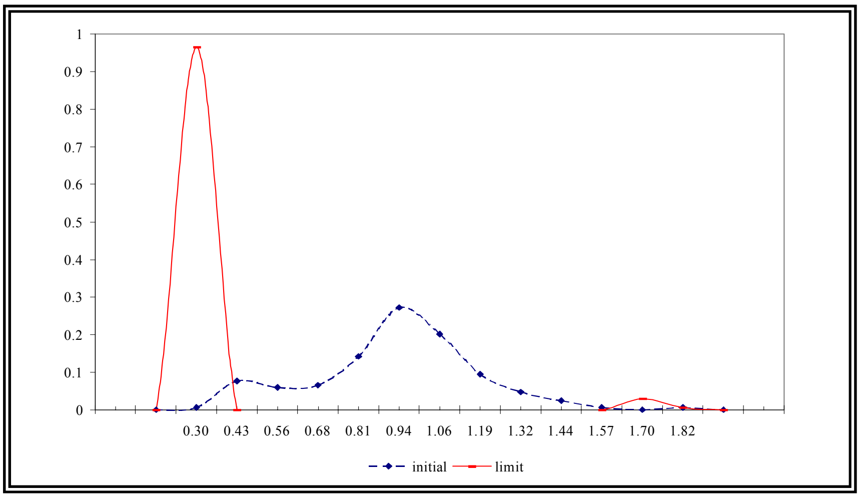
The extremely slow pace at which the system reaches the steady-state can be appreciated also from Figure 4.10 where the shape of the distribution after 16 time periods (176 years) is compared to the distribution after 44 years and to the initial one.

Figure 4.10 Transitionary Dynamics (NUTS2 Data)



The final outcome of the transition process is depicted Figure 4.11 in which the distribution in 1979 can be compared with the situation characterising the steady-state.

Figure 4.11 Stationary Distribution (NUTS2 Data)

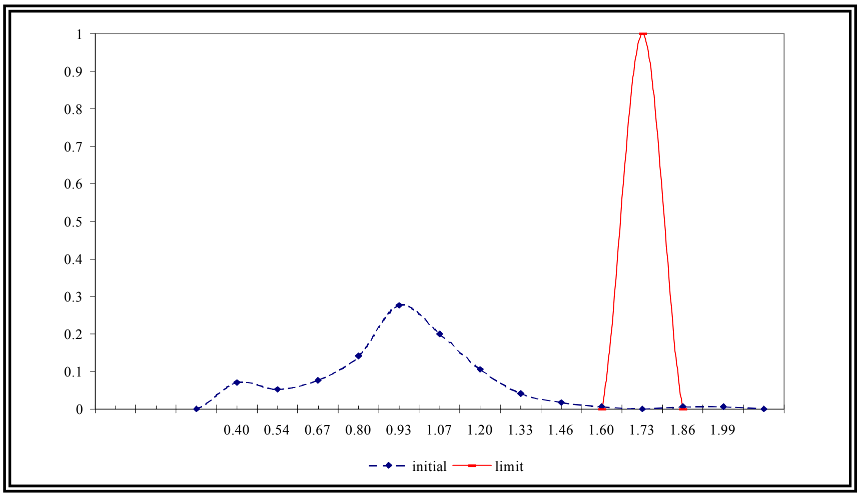


Similarly to the FURs' case, a group of high income regions manifests a tendency to grow away from the other NUTS2 regions. This group of advantaged regions includes Oberbayern, Bremen, Darmstadt, Greater London, Ile de France and, alone at the extreme right of the stationary distribution, Hamburg. The rest of the distribution is characterised by a process of absolute convergence towards to same income class. This process, although extremely slow, appears to be rather strong as it is confirmed by the analysis carried out resorting to the FD criterion applied to the 1990 distribution.

The differences in the results coming from the two data sets are quite interesting. On the one hand, in both cases it is possible to identify a small group of 'growth leaders', i.e. a group of regions clearly growing away from the other regions, the 'growth followers'; however, the composition of the group of leaders is different for the two data sets. Of the six regions that compose each group of leaders, two of them -the FURs of Düsseldorf and Stuttgart and the NUTS2 regions of Bremen and Greater London- have absolutely no correspondent in the other group. For three of the remaining four regions there is only broad correspondence: the FUR of Frankfurt is part of the NUTS2 region of Darmstadt (which also includes Darmstadt, Offenbach, and Wiesbaden), the FUR of München is part of the NUTS2 region of Oberbayern (which also includes Ingolstadt and Rosenheim) and the NUTS2 definition of Hamburg is substantially different from the functional definition (which could also explain why the NUTS2 region of Hamburg appears to enjoy a noticeable advantage over all the other NUTS2 growth leaders, whilst this is not the case for the corresponding FUR). Only in the case of Paris and Ile de France, as already noted, there is a good conformity between the relative boundaries. On the other hand, all the NUTS2 'growth followers' tend to converge to the same level of per capita income, whilst the part of the stationary distribution corresponding to the FURs 'growth followers' spreads over several income classes and presents signs of bimodality.

Finally, it is also interesting to emphasise that the NUTS2 database used in this analysis has already been polished up by excluding the observations on Gröningen. As expected, the inclusion of this Dutch region into the database has noticeable consequences as it heavily biases the results towards convergence. Following the same procedure adopted in the other cases, it is possible to identify the Devroye and Györfi criterion applied to the 1979 distribution as the best discretising criterion. As is emphasised in Figure 4.12, the resulting stationary distribution is characterised by the absolute convergence of all regions towards the same income class. Moreover, the second eigenvalue of the transition matrix is equal to 0.9966, which leads to a half life of 203 time periods (2233 years). In other words, the inclusion of Gröningen not only biases the results towards convergence but also reduces the time that the system needs to reach the steady-state.

Figure 4.12 Stationary Distribution (NUTS2 Data Including Gröningen)



4.6 Conclusions

In line with Quah's approach, the methodology adopted here made it possible to analyse directly the dynamics of cross-country income distributions. In particular, the analysis has been implemented on a discrete income space rather than on a continuous one because discretisation allows to gain more information on the growth and convergence process. Indeed, the choice between discrete and continuous space methods of analysis appears to entail a trade-off between information and subjectivity. Discretising the income space give the opportunity to gain more information on the characteristic features of the growth and convergence process under study; however, discretisation criteria are generally subjective and it is well known that an inappropriate discretisation can remove the Markov property from a first-order Markov process.

The present chapter has suggested a possible solution to this trade-off problem. In particular, it has been argued that the choice of the income class size represents a crude nonparametric estimate of the probability density function that has generated the observed cross-sectional data. As a consequence, attention has been concentrated on a particular nonparametric estimator, the histogram, that is characterised by the statistical property of consistency and partitions the interval containing the observed data into a grid of n non-overlapping classes. Several criteria for the choice of the size have been developed in the literature, which minimise some measure of the error of approximation. The choice of the income class size has then been made by following a procedure that guides the selection among a set of possibilities obtained by resorting to these different optimising criteria. The transition probability matrix determined in this way allows not only the study of the one-period dynamics and the resulting ergodic distribution, but also the analysis of the transitional dynamics as well as the calculation of the speed at which the steady-state is approached.

Applying the selection procedure to a data set on per capita income in 122 major FURs it has been possible to unequivocally identify the criterion derived by Devroye and Györfi (1985) - utilised on the 1990 distribution - as the best available criterion for the definition of the class size. Through the Markov chain analysis carried out on the basis of the resulting transition probability matrix, it has been possible to note that the process of economic growth at work in the EU over the period 1979-1990 has been characterised by an apparent tendency towards divergence. In particular, six of the European functionally defined regions: Düsseldorf, Hamburg, Stuttgart, München, Paris, and Frankfurt, have shown a tendency to grow away from the others. This result appears quite strong as it has been confirmed by other definitions of the income class size according to different discretising criteria. As for the other regions, the analysis has indicated the presence of bimodality within the stationary cross-sectional distribution, suggesting a further distinction between poor regions and middle-income regions.

By applying the same methodology to two different data sets of NUTS2 regions it has also been possible to emphasise the significant dangers deriving from the use of data on administratively defined regions. Specifically, it has been shown that using a data set on 169 NUTS2 regions - which excluded the Dutch region of Gröningen - the regions composing the group of leaders can be misidentified and the bimodality noticed in the remaining part of the FURs' stationary distribution totally overlooked. Moreover, the inclusion of Gröningen into the data set has heavily biased the results: not only all the regions appear to converge to the same income class, but also the speed of this absolute convergence process has been enhanced in comparison to the case in which Gröningen was excluded from the analysis.

Finally, it is important to remember that these results have been derived under the assumption of time-homogeneity for the Markov chain or, in other words, under the assumption that the transition probabilities observed over the period 1979-1990 would remain unchanged in the future. This is a strong assumption as it is obvious that economic conditions and policies change over time, implying changes in the transition probabilities. It should be noted, however, that this assumption is equivalent to analysing convergence towards a steady-state by running (cross-sectional or time series) regressions over a necessarily limited period of time. The general aim of all these approaches is to shed light on the nature of the process of economic development that has characterised the EU during the time span covered by the data, and not to provide a precise forecast of what will happen in the future.

Chapter 5

A Decentralised Model of Endogenous Growth: the Set Up

5.1 Introduction

This chapter is aimed at the identification and description of a possible mechanism that could lead to persistent disparities in regional per capita income within a system that retains most of the strong assumptions that lie at the heart of the convergence predictions of the neoclassical model, such as maximising behaviour, equalisation of factors' remuneration through free inter-regional trade of goods and free mobility of labour, human, and physical capital. The model, which builds on the existing literature on endogenous growth (Romer 1986 and 1990a and b; Lucas 1988; Grossman and Helpman 1989, 1990 and 1991b; Aghion and Howitt 1992) and, in particular, on the work of Romer (1990a and b), Rivera-Batiz and Romer (1991a and b) and Rivera-Batiz and Xie (1993), presents three main features. Firstly, economic growth is endogenous and driven by the research activity of profit-seeking agents. Secondly, an explicit role in regional production structures is assigned to human capital. In particular, this factor of production is considered as the crucial input in the research sector. Thirdly, knowledge spillovers across space are an essential feature of research activity aimed at designing and developing new products.

The model developed here generalises the existing models of endogenous growth by assuming the absence of any obstacle to the free movement of goods and factors of production and by providing a description of the research activity which takes into account ideas put forward by economists interpreting technical change as an evolutionary process (Nelson and Winter, 1982; Dosi, 1982, 1984 and 1988; Freeman, 1987 among the others). Indeed, knowledge spillovers favouring the research effort carried out in a specific location are seen as the combined result of two different sources. On the one hand, research activity produces disembodied abstract knowledge which is non rival and only partially excludable. This form of knowledge is assumed to be represented by patents for intermediate inputs which provide the exclusive right to produce the input but, at the same time, increase the stock of disembodied abstract knowledge available to all researchers, independently of their location. On the other hand, by borrowing some concepts belonging to the evolutionary literature, successful research activity is seen as the outcome of an efficient co-ordination of the research effort representing the level of competence (Winter, 1987) of the existing teams of researchers. Being primarily 'tacit', i.e. a non-written personal heritage of individuals or groups of them working collaboratively, this second form of knowledge is very spatially localised in nature. Spatial spillovers of tacit knowledge are possible but result essentially from the interaction between individuals and, therefore, are hampered by space.

In the steady-state equilibrium of the decentralised model, the region that is relatively more specialised in research activity enjoys a permanently higher level of per capita income. Moreover, it is shown that within this framework a process of integration that takes the form of a reduction in the cost of distance between two regions might lead to faster growth in the long-run for the entire system at the expense of an increase in regional disparities. The result is explained by the enhancement of the existing pattern of productive specialisation: the decrease in the cost of distance increases accessibility to technological knowledge in all locations but this result is relatively stronger for the most technologically and economically advanced regions leading to further concentration of research activity. This relocation process boosts the long-run growth rate of the system. During the transition to the new long-run equilibrium, however, the most advanced region exhibits a faster rate of growth so that the new long-run equilibrium will be characterised by a higher level of per capita income disparities. Contrary to the predictions of the traditional neoclassical model, therefore, reducing the cost of distance between regions might strengthen, rather than reduce, existing income disparities even in a system characterised by free-trade and free movements of production factors.

5.2 The Production of Intermediate Inputs

The model proposed here consists of two regions, labelled i and j, which, as in Romer (1990a and b), Grossman and Helpman (1989 and 1991b), Rivera-Batiz and Romer (1991a and b) and Rivera-Batiz and Xie (1993), produce a homogeneous consumption good employing unskilled labour, human capital, and physical capital. The crucial feature that distinguishes the production of the consumption good described in this type of model from the traditional neoclassical one is represented by the fact that here physical capital is made up of a set of specialised intermediate inputs produced by profit maximising entrepreneurs. Prior to the production of the intermediate input, in fact, these entrepreneurs must devote resources to research in order to develop the design describing the good. The research effort has also the additional effect of increasing the level of technological knowledge existing in the system.

5.2.1 The Research Effort: Some Key Theoretical and Empirical Issues

The definition of research activity, with which new abstract knowledge is produced in the form of designs for differentiated intermediate inputs, is central to the growth process characterising this type of model. In fact, the output of the research effort combines two components: abstract knowledge and patents for new products. The return to the latter component of research output is perfectly appropriable by the originator due to perfect patent protection. The former component, on the other hand, represents a positive externality that allows the system to grow indefinitely. In Romer's models, as well as in those that have subsequently been developed along the same lines, the production of new abstract knowledge, $\dot{A}_t$, depends on the stock of knowledge already created, A_t, as well as on the level of human capital available to the research sector H, and on a productivity parameter δ. In formal terms:

$$\dot{A}_t = \delta H A_t , \tag{5.1}$$

With this formulation, new knowledge spreads throughout the system, for instance by means of patent documents and scientific journals, and contributes to the productivity of further research by reducing the effort needed to develop a new product.

5.2.2 *Abstract Knowledge, Tacit Knowledge and Technological Competence*

In order to accommodate the evidence on the existence of knowledge spillovers and, in particular, the evidence linking the geographic extension of these spillovers to the tendency of innovative activities to cluster in space, a distinction between abstract knowledge and tacit knowledge is utilised, with the latter being described in the present model by the concept of 'local technological competence in research'. Abstract knowledge is represented by the set of codifiable knowledge which is created during the research effort. Embodied in a patent document for a new intermediate input or published in a scientific journal, this form of knowledge becomes potentially available to everyone, independent of their location. In other words, once created, abstract knowledge spreads freely throughout the system enhancing the productivity of every researcher.

Tacit knowledge is instead all that body of knowledge developed through experience that cannot be codified, being the non-written personal heritage of individuals or groups (Polany, 1967). This form of knowledge can also be transmitted, and positively affects the productivity of other researchers, but the flows of tacit knowledge occur essentially through direct, face-to-face,[1] contacts rather than through impersonal means such as patents or scientific papers.

Much of the literature that views technological change as an evolutionary process emphasises how innovation is by no means exclusively the result of learning processes taking place in dedicated research departments: learning in production in its various form, such as 'learning-by-doing' (Arrow, 1962), 'learning-by-using' (Rosenberg, 1976, 1982), etc., is a non-negligible source of technical change (Dosi, 1988). The extent to which such learning produces technical change is determined by the firms' level of 'technological capabilities' which can be defined as the body of abilities developed

[1] Langlois (1992) provides examples of the personal nature of the transfer of technology with relation to the development of the computer industry. On a survey of biotechnology researchers, Grefsheim *et al*. (1991) report that the most important and timely source of information is considered to be face-to-face interactions.

through accumulation of experiences and in relation with other institutions, both private and public.[2]

To simplify the analysis, the model developed here considers research activity as the sole source of innovation. Introducing innovations originated through the various forms of learning in production would refine without altering the principal message of the model at the expense of a heavier and less tractable formalisation. The main aim of the model is to emphasise a possible role for formal research organisations - firms' R&D laboratories, government laboratories, universities, etc. - in shaping the spatial distribution of wealth within an economic system.

The definition of technological competence must be adapted to the particular setting assumed in the model. Hence, it seems useful to introduce the concept of 'local technological competence in research', which represents a particular form of location-specific tacit knowledge. It can be defined as the ability to perform research characterising the 'regional innovation system' (RIS) and it allows to account for spatially bounded spillovers of knowledge arising from researchers' interaction, which are believed to be essential for innovative activities but are not included in Romer's type models.

The RIS is the local network of public and private institutions supporting the initiation, modification and diffusion of new technologies (Freeman, 1987; Nelson and Rosenberg, 1993; Patel and Pavitt, 1994). Among the factors that constitute the RIS, it is possible to emphasise the role played by: the size and quality of the education system, the availability of technical, financial and networking services, the quantity and quality of space available for innovative activities, the structure of the local industrial sector, and both the system-wide and local macro-economic setting.

The education system and, in particular, universities and other higher education institutions, play a fundamental function in the development of an environment

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2 See Section 2.4.1 for further details.

conducive to innovation through the provision of human capital. Even though this function of education institutions is fundamentally an economy-wide function, appreciable differences in the quality of education available in different regions may exist. Universities also play an essential local role as they are themselves producers of new knowledge that can positively influence the research effort of private corporations as found by Jaffe (1989), Acs, Audretsch and Feldman (1992 and 1994), Suarez-Villa and Hasnath (1993), and Feldman (1994). Consequently, both the quantitative and qualitative level of research carried out in universities, as well as the intensity of the links between these institutions and local firms, represent extremely important local factors shaping the technological competence of local researchers.

Other local factors are emphasised by Saxenian (1985 and 1991) with reference to the networks in California's Silicon Valley. According to the author, the high degree of innovative activity characterising the region is promoted on the one hand by a culture for personnel mobility and information exchanges leading to the emergence of local innovative networks assisting firms in their problem-solving activities. A survey of recent studies stressing the importance of networking in innovative activity is provided by Freeman (1991). On the other hand, innovative activity is also fostered by a variety of trade associations, local business organisations, and specialised consulting, market research, public relations and venture capital firms, providing essential technical, financial and networking services that could not otherwise be afforded by the region's enterprises. The crucial role played by business services providing innovative firms with market, financial and commercial knowledge is also stressed by Dorfman (1983), Coffey and Polese (1987), and MacPherson (1991).

The quantity and, especially, the quality of the local supply of space suitable for research activities is also particularly important. As emphasised by Malecki (1979 and 1991), the location decision for R&D is based on both organisational and labour market considerations. It is important to note, however, that these two factors ultimately point to the same direction. From an organisational point of view, R&D labs tend to be located at or near the firm's headquarters (Malecki, 1979), and this tendency is further reinforced by the fact that both facilities require good transport accessibility, especially air accessibility, and the availability of executive and professional talent (Browning, 1980; Molle *et al*., 1989). As underlined by Buswell (1983), the crucial point is that scientists and engineers, as well as executives, are geographically somewhat immobile in that they prefer to live and work in places where the 'quality of life' is high: the economic, social, and physical 'image' of the location is important (Birch 1987). On the other hand, representing a scarce resource, these workers tend to have a large influence on corporate location decisions: for instance, Keeble and Kelly (1986) and Begg and Cameron (1988) demonstrate that the locational preferences of professional workers are extremely important in determining firms' location away from traditional manufacturing within highly dynamic, highly innovative sectors such as the high-tech sector, whilst, more generally, Clark (1981) notes the difficulty of attracting skilled labour to remote sites.

The structure of the regional industrial sector is other important determinant of the RIS. In order to bring together the concepts of industrial structure, RIS, and local level of technological competence in research, it may be useful to refer to the general distinction between 'entrepreneurial' and 'routinised' technological regimes put forward by Nelson and Winter (1982). Audretsch (1996) describes the former regime as being characteristic of highly innovative industries, where small enterprises are responsible for most of the innovative activity, and where new ideas tend to be exploited outside existing firms, leading to high entry rates. The latter regime is instead typical of capital intensive, advertising intensive industries, where large firms are the most innovative. From a spatial point of view, it seems possible to infer that where a region is dominated by industries belonging to the entrepreneurial regime a more innovative industrial structure, coupled with higher entrepreneurship and smaller average firm size, is to be expected. A regional industrial structure dominated by industries pertaining to the routinised regime is, instead, more likely to coincide with a less innovative regional industrial structure in which average firm size is larger.

A separate issue relates to the degree of diversification of the regional industrial sector. The importance of a relatively specialised industrial structure becomes evident in the presence of dynamic localisation economies, that is of external economies which are external to the individual firm but internal to the industry or sector. A typical example of these economies is represented by the Marshallian "industrial atmosphere", which is able to promote a more effective innovation process and a faster diffusion of the technological progress within the RIS. An opposite viewpoint is instead expressed by Chinitz (1961), Jacobs (1969, 1984), and Bairoch (1988) who believe that industrial diversity rather than industrial specialisation creates a more innovative environment thanks to the presence inter-industry external economies. Chinitz, in particular, discussing the factors conducive to innovation and concentrating on the role of entrepreneurship believes that a more diversified regional economy is more dynamic and innovative because higher returns to innovation stimulate entrepreneurship.

An attempt to assess the importance of the industrial structure for the strength of local spillovers of knowledge and hence for firms' dynamism, is carried out by Glaeser *et al.* (1992) and by Henderson *et al.* (1995). Glaeser *et al.* find that inter-industry dynamic externalities are important in explaining local employment growth for 170 SMSAs while Henderson *et al.* show that, for 224 SMSAs, intra-industry externalities are relevant for mature industries such as machinery, electrical machinery, primary metals, transportation, and instruments while both intra- and inter-industry externalities are important for new high-tech industries such as electronic components, medical equipment, and computers. It should be noted that in both analyses dynamic inter-industry externalities, that is dynamic externalities between firms in different industries, are labelled as "Jacobs externalities", whilst intra-industry dynamic externalities, are referred to as "Marshall-Arrow-Romer (MAR) externalities". However, whilst it is surely correct that Romer refers to intra-industry knowledge spillovers in his earlier growth model (Romer, 1986) more open remains the interpretation of the externalities at the heart of the growth process in the later model (Romer, 1990a and b). This model is in fact characterised by the explicit presence of a research sector that produces designs for new intermediate inputs, taking advantage of the pure knowledge (designs) already produced. It seems therefore difficult to interpret this form of technological externalities as an explicit example of either inter- or intra-industry externalities. Indeed, this indeterminacy on the nature of the dynamic externalities favouring the growth process is intentionally retained in the theoretical model of regional growth that is developed here, whilst an attempt to evaluate empirically the role of industrial specialisation will be carried out in Chapter 7.

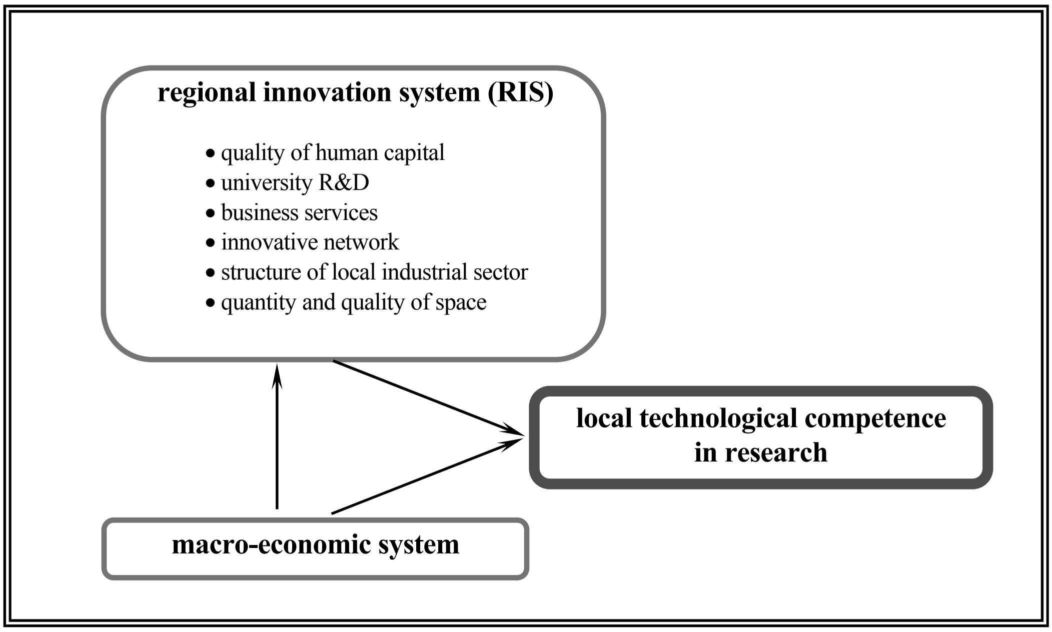
Finally, macro-economic policies in general, and industrial policies in particular, pursued by national and local governments have far reaching influences on the RIS. A classical example of the latter type of policies would be those inspired by the Japanese Ministry of International Trade and Industry (MITI) which have contributed to shaping the long-term pattern of structural change in the Japanese economy. Central to MITI's view about its role within the system is the recognition of the fact that externalities and infrastructure represent an essential factor for innovative firms and that it is part of both central and local governments' duties to provide the infrastructure investments necessary for innovation. It is important to note that macro-economic policies can also influence directly the local technological competence in research by altering the system of prices existing in the system. An obvious example is represented by exchange rate policies.

To sum up, local technological competence in research is shaped by macro-economic factors and the RIS. This, in turn, is determined by local factors and is itself influenced by the macro-economic system. Figure 5.1 summarises these relationships.

5.2.3 A Possible Extension towards the Evolutionary Approach

The unique combination of all these factors, however, can also be considered in relation to the prevailing 'technological paradigm' (Dosi, 1988). According to Dosi, inspired by the definition of scientific paradigm suggested by Kuhn (1970) in the modern philosophy of science, a technological paradigm can be defined as "a 'pattern' for solution of selected techno-economic problems based on highly selected principles derived from the natural sciences. [...] Putting it another way, technological paradigms define the technological opportunities for further innovations and some basic procedures on how to exploit them" (Dosi 1988 pg. 224-225; but see also Dosi 1982 and 1984).

Figure 5.1 Local Technological Competence in Research



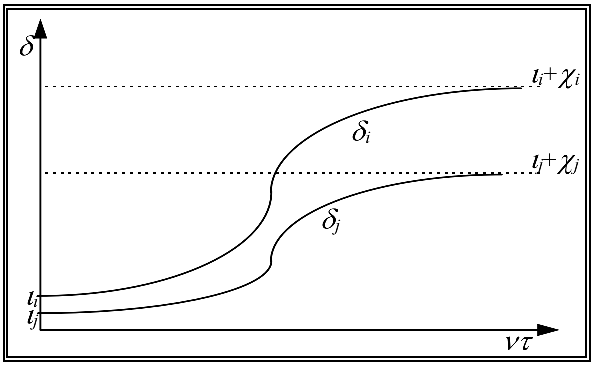
Within a given paradigm, local technological competence in research is not rigid. On the contrary, it adjusts and develops over time, consequently increasing the productivity of local researchers. However, the increase in local productivity that can be produced in this way is not without limit. In fact, the endowment of the factors shaping the RIS determines, in relation to the prevailing technological paradigm, a location-specific limit to the improvement possibilities of the regional technological competence in research. This upper limit may obviously change over time but its changes occur only slowly as they are the consequence either of policy interventions that re-model the RIS by altering the endowment of its determining factors, or of shifts in the prevailing technological paradigm. In fact, increasing obstacles to progress within a certain paradigm, coupled with some necessary scientific advances, are associated with changes in technological paradigms which, reshaping the patterns of opportunities of technical progress, may have important consequences for the spatial pattern of economic disparities as different RIS are generally characterised by different abilities to adapt to new paradigms.

To formalise the evolution over time of the regional technological competence in research within a given paradigm it is possible to resort to the following logistic function

$$\delta_i = \frac{\left(\iota_i + \chi_i\right) + \left(\iota_i - \chi_i\right) e^{-\nu_i \tau}}{1 + e^{-\nu_i \tau}} \qquad (5.2)$$

where δ_i is the level of technological competence in research characteristic of region i, τ is the time passed since the establishment of the actual technological paradigm, ι_i is the minimum level of technological competence in research at the moment of establishment of the technological paradigm, χ_i represents the margin of improvement characteristic of region i, v_i is the velocity with which the improvement takes place and the regional level of technological competence approaches its upper limit. Figure 5.2 depicts the evolution of the local technological competence in research of two regions, i and j, in the case in which the speed of improvement v is the same but region i is characterised by a superior local technological competence in research.

Figure 5.2 Evolution of Local Technological Competencies in Research



It is assumed that the following relations hold:

$$
\begin{aligned}
\chi_i &= \psi\, \iota_i \\
\chi_j &= \psi\, \iota_j \qquad (5.3)\\
v_i &= v_j = v
\end{aligned}
$$

where ψ>0. In other words, the margin of improvement characterising a RIS, χ, is a monotonic function of the minimum level of technological competence in research, ι, which, in turn, is location specific being determined by the interaction between the factors shaping the RIS and the prevailing technological paradigm. Finally, the velocity of improvement, v, is assumed exogenous and common to all regions. As a result, the ratio between the local technological competence in research of the two regions stays constant over time and is equal to ι_i / ι_j .

However, to simplify matters the analysis that follows can abstract from the existence of an underlying technological paradigm and is developed in the absence of any major regional policy interventions aimed at the modification of the local system of innovation and therefore under the hypothesis of a constant technological competence in research over time. The principal scope of the analysis is that of identifying the forces that lead to an equilibrium characterised by regional disparities in per capita income. Nonetheless, the evolutionary account of technological progress evolving through paradigms is offered as an interesting insight into long term processes of technological change and their relationship to growth. Introducing these features would by no means alter the structure of the model and the results that can be drawn from it.

5.2.4 System-wide and Spatially Bounded External Effects in Research

In the previous paragraph, a distinction has been drawn between abstract, codifiable knowledge and tacit, non codifiable knowledge. From this, it is now possible to derive a distinction between system-wide and spatially bounded external effects in research on the basis of the type of knowledge being transmitted. As just seen, system-wide external effects take the form of inter-regional spillovers of abstract knowledge due to the free circulation of patent documents and scientific papers. Clearly, differences may exist in the way this form of knowledge is codified in different firms and in different locations leading to interpretation problems and partial transmission of the underlying abstract knowledge. The issue concerning the differences in codification systems will not be addressed here under the assumption that the system of regions presents a high degree of homogeneity in the basic language with which technological information is transferred. As in Romer's model, therefore, general abstract knowledge is introduced in the model in the form of the number of designs for intermediate inputs already created, A_t. Moreover, it is assumed that the central patenting office will not grant a patent to a regional research laboratory if the intermediate input described in the patent represents a mere copy of an already existing input. In other words, any increase in the number of the patents represents a real increase in the stock of abstract knowledge. In the case of a system of two regions, these three assumptions are conveniently summarised in the assumption that the stock of abstract knowledge available to every researcher in every region results from the summation of all the patents for intermediate inputs developed in the different regions, or

$$A = A_i + A_j.$$

These economy-wide, aspatial spillovers of abstract knowledge are, however, not the only form of dynamic externalities influencing the research effort. Indeed, an important part of the flows of knowledge that characterise the innovation process is constituted by localised, intra-regional spillovers of individual tacit knowledge: that is by spillovers of non codifiable knowledge occurring between individuals located within the same region. As already pointed out, because of the particular nature of this form of knowledge, these spillovers are produced essentially through direct, face-to-face contacts. Spatial proximity, therefore, fosters these flows of knowledge by reducing the cost of contacts and increasing opportunities for the exchange.

The importance of personal interaction between people involved in the innovation process is not confined within the regional boundaries only. On the contrary, the research effort carried out in a specific region is open to the positive influence deriving from the interaction with similar efforts carried out in other regions. As in the case of the intra-regional spillovers of tacit knowledge, these inter-regional spillovers are generated from physical interaction between researchers. Clearly, the cost of physical distance between two regions plays an essential role in the determination of the size of these inter-regional spillovers of tacit knowledge. The higher the cost - in terms of both time and money - of the distance between two regions, and, *ceteris paribus*, the less likely the interaction between their researchers and the higher the probability of a loss of useful pieces of information. However, the physical dimension is not the only dimension of the distance between regional research sectors that plays an important role in the determination of the size of inter-regional spillovers. The 'catch-up' argument, developed by Gerschenkron, Abramovitz, Maddison and Fagerberg amongst the others (see Chapter 2), states that economies behind the world innovation frontier have the 'potential' advantage represented by the possibility to copy technologies already developed in technologically more advanced economies.

Following this argument, it is therefore assumed that, given the cost of physical distance, inter-regional flows of tacit knowledge between pairs of regions are not symmetrical: the less technologically advanced region enjoys a potentially larger benefit from interaction than the technologically more advanced one. This 'potential technological benefit from interaction', however, cannot abstract from spatial considerations. Indeed, depending on the physical interaction between researchers located in different regions, also this potential benefit is affected by the cost of the physical distance. Therefore, given the level of the local technological competencies in research, an increase in the cost of physical distance between two regions is assumed to reduce the potential benefit enjoyed by the less technologically advanced one.

5.2.5 A Formal Representation of the Research Effort

It is now possible to combine all the different concepts that have been developed so far into an equation describing the activity of the research sector. Consider an economic system made up of two regions, i and j, and in which the cost of moving from region one region to the other is equal to d_{ij}. The flow of new knowledge -i.e. the number of new designs- created in region i at any point in time is given by:

$$\dot{A}_i = \delta_i Hr_i \, Hr_i^{\phi} \left(Hr_j \, d_{ij}^{-1/\beta_{ij}} \right) A \tag{5.4}$$

where Hr_i is the level of human capital employed in the research sector of region i, and δ_i represents the level of technological competence characteristic of the research sector located in region i. A is the number of intermediate inputs existing in the system and the overall level of abstract knowledge created so far and available to all researcher due to a-spatial spillovers of knowledge. As far as the spatial spillovers of technological tacit knowledge are concerned, Hr_i^{ϕ} reflects the size of the intra-regional spillovers whilst the term $Hr_j \, d_{ij}^{-1/\beta_{ij}}$ represents the extent of the inter-regional spillovers of tacit knowledge that benefit the research effort in region i and originate from the interaction with the research sector located in region j. As already explained, these are function of the level of human capital existing in the other region, Hr_j, weighted by the cost of the physical distance, d_{ij}, and a measure of the potential technological benefit from interaction, β_{ij}. On the one hand, as these spillovers result primarily from the physical interaction between researchers, their size is inversely related to (the cost of) physical distance. On the other hand, it has been noticed that the 'catch-up' argument emphasises the potential benefit that can be enjoyed by technologically less advanced economies from the interaction with economies closer to the technological frontier due to the possibility of imitating technologies already developed elsewhere. On the basis of the discussion in the previous section, it is assumed that the potential technological benefit accruing to researchers located in one region from the interaction with the researchers of the technologically more advanced region is an increasing function of the relative local technological competencies in research $\delta_{\text{technological leader}} / \delta_{\text{other region}}$, and a decreasing function of the cost of the physical distance d_{ij}. The measure of the potential technological benefit accruing to region i from the interaction with region j could then be represented by:

$$\beta_{ij} = 1 + \frac{\ln\left(\dfrac{\delta_{\text{technological leader}}}{\delta_i}\right)}{\ln d_{ij}} \tag{5.5}$$

where

$$\delta_{\text{technological leader}} = \begin{cases} \delta_i & if \quad \delta_i > \delta_j \\ \delta_j & if \quad \delta_i < \delta_j \end{cases} .$$

Hence, the potential benefit for region i from the interaction with region j may assume the following values:

$$\beta_{ij} : \begin{cases} \beta_{ij} = 1 & if \quad \delta_i > \delta_j \\ \beta_{ij} > 1 & if \quad \delta_i < \delta_j \end{cases} . \tag{5.6}$$

5.2.6 The Manufacturing Production of Intermediate Inputs

As discussed before, the blueprint describing the features of an intermediate input is considered a public good only when it is used in the research sector. Instead, the use of the same blueprint in a manufacturing process is subject to patenting. The patent, granting the exclusive right to manufacture the relative intermediate input, provides the incentive for innovation. Given the nonrival character of technological knowledge, production activities which directly make use of a specific patent cannot be performed within a perfectly competitive market structure.[3] Consequently, intermediate input producers engage in monopolistic competition, earning monopoly rents. These entrepreneurs will devote resources to finance the research effort only if the present discounted value of future profits exceeds the current cost of development.[4] The Schumpeterian idea that innovative activities depend on their expected profitability is clearly a feature of this model.

As for production costs, intermediate input producers face a variable cost of production for the use of physical capital on top of the fixed cost represented by the development cost of a patent. In particular, it is assumed that one unit of intermediate input requires one unit of physical capital. Finally, intermediate inputs do not deteriorate over time, while physical capital is simply a measure of forgone output so that:

$$\dot{K}(t) = Q(t) - C(t)$$

where Q stands for the level of output of the homogeneous final good and C stands for the level of consumption.

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3 Romer (1990a and c) discusses the nonrival character of technological knowledge and its implications for market structures.

4 It is worth noticing that some economic sectors tend to profit more from disembodied technological change and, therefore, should be included within this intermediate input sector. In particular, these sectors include tertiary activity related to information processing, manufacturing sectors with products depending heavily on quality and fashion, manufacturing industry related to young industries with non-routine processes, and strategic functions related to manufacturing activity.

5.3 Production and Consumption of the Homogeneous Final Good

The residents within the system work either in a research sector or in a manufacturing one, and consume a final good. As consumers, they maximise intertemporal utility with savings devoted to the acquisition of physical capital. In particular, assuming the absence of transport costs for the consumption good, all consumption arising from the system can be aggregated in the system-wide variable *C(t)*. It is assumed that all consumers in the system maximise a Ramsey-type, constant elasticity of substitution utility function:

$$U[C]=\int_0^\infty e^{-\rho t}\frac{C^{1-\sigma}}{1-\sigma}dt \qquad (5.7)$$

where ρ is the intertemporal rate of discount and σ^{-1} (with $0<\sigma<1$) the willingness to substitute intertemporally. As pointed out by Romer (1990b), these preferences are only used to derive the intertemporal optimisation condition that relates interest rates, *r*, to the rate of growth of consumption:[5]

$$r=\sigma\frac{\dot{C}}{C}+\rho. \qquad (5.8)$$

Any other rule that relates the interest rate to the consumers' behaviour would suffice. It is also interesting to note that equation 5.8 corresponds to the 'Keynes-Ramsey rule' according to which the relation between the interest rate and ρ determines whether households choose a pattern of per capita consumption that rises over time, stays constant or falls. Here, obviously, attention is concentrated on the case in which the growth rate of per capita consumption is positive, which implies $r>\rho$. Moreover, to simplify calculations, it is assumed without loss of generality that the intertemporal rate of discount relates to the interest rate according to the following equation:

$$\rho=\Gamma r$$

with $0<\Gamma<1$ for positive growth. As a result, equation 5.8 simplifies to

$$r\,(1-\Gamma)=\sigma\frac{\dot{C}}{C}\ . \qquad (5.8b)$$

[5] An explicit derivation can be found in Rivera-Batiz and Romer (1991b).

To ensure that the integral in equation 5.7 converges, the rate of growth of current utility $\left(1-\sigma\right)\frac{\dot{C}}{C}$ is assumed to be smaller than the rate of time preference, so that

$$(1-\sigma)\frac{\dot{C}}{C} < \Gamma r \, .$$

In their role as workers, the inhabitants of the system are divided in two groups: unskilled and skilled workers. Unskilled workers are endowed with fixed quantities of unskilled labour that are supplied inelastically; similarly, skilled workers are endowed with fixed quantities of human capital that are supplied inelastically. Whilst unskilled labour is employed only in the final good sector, human capital is used both in research and manufacturing. The overall fixed supply of human capital H is therefore equal to:

$$H = Hq_i + Hq_j + Hr_i + Hr_j$$

while the overall fixed supply of unskilled labour is equal to:

$$L = L_i + L_j \, .$$

Moreover, they move freely across regions and, in the case of human capital, across sectors and evaluate locations and sectors solely in terms of wage rates. Migration flows are described by the following system of differential equations:

$$\begin{cases} \dot{L}_i = m_L \; BL_{QiQj} \, L \\ \dot{L}_j = m_L \; BL_{QiQj} \, L \\ \dot{Hq}_i = m_H \; BH_{QiQj} \; H + m_H \; BH_{QiRi} \; H + m_H \; BH_{QiRj} \; H \\ \dot{Hq}_j = m_H \; BH_{QiQj} \; H + m_H \; BH_{QjRj} \; H + m_H \; BH_{QjRi} \; H \\ \dot{Hr}_i = m_H \; BH_{RiRj} \; H + m_H \; BH_{QiRi} \; H + m_H \; BH_{QjRi} \; H \\ \dot{Hr}_j = m_H \; BH_{RiRj} \; H + m_H \; BH_{QjRj} \; H + m_H \; BH_{QiRj} \; H \end{cases} \tag{5.9}$$

where m_L and m_H represent the speed of adjustment to wage differentials whilst BL and BH represent the benefit from a permanent move across regions and sectors. In particular, these benefit correspond to the present value of the wage differential so, for instance, the benefit for human capital employed in the research sector of region i from a migration to the same sector of region j is equal to:

$$BH_{RiRj} = \int_0^{\infty} \left[w(Hr)_i - w(Hr)_j \right] e^{-rt} \, dt$$

or, if r is constant,

$$BH_{RiRj} = \left[w(Hr)_i - w(Hr_j) \right] r^{-1}.$$

The homogeneous final good is produced using labour, human capital and physical capital in the form of intermediate inputs. Given the amount of existing intermediate products, the production function for the final good exhibits constant returns to scale. But an increase in the number of available intermediate products raises total factor productivity. This result is achieved using an Ethier-type production function (Ethier, 1982) which captures the idea that an increasing degree of specialisation generates technical efficiency gains. Following Rivera-Batiz and Romer, the stock of intermediate inputs available in region i at any point in time consists of the summation of inputs produced in the same region and inputs imported from the other region. In particular, if A_i and A_j indicate the number of intermediate inputs designed and produced respectively in region i and in region j at any point in time, the quantity of any intermediate input produced in region i and employed in the same region is $x_i(a_i)$ with $a_i \in A_i$, whilst $x_i(a_j)$ - with $a_j \in A_j$- represents the quantity of any intermediate input produced in region j and employed in region i.

The number of available intermediate inputs is not the only form of externality that affects the production of the final goods, there is also a negative externality arising from the agglomeration of manufacturing activities and caused by the emergence of congestion cost. Indeed, the concentration of manufacturing within a region is assumed to determine a negative external effect on the productivity of its factors of production which is reminiscent of the agglomeration diseconomies modelled by Rabenau (1979) and Miyao (1987 a and b).[6]

[6] In fact, the concentration of manufacturing within a region is likely to adversely affect also the local research sector. Introducing such an effect within the structure of the model, however, would clearly increase its complexity without altering the results that can be drawn from it. Indeed, as it will be clearer from Section 6.1.2, the model depicts a process whereby the region characterised by lower degree of specialisation in manufacturing tends to exhibit a higher concentration of research activities. An externality from concentration of manufacturing affecting negatively the local research sector would simply reinforce this feature of the model.

The size of these agglomeration economies, however, depends also on the size of the regional research sector since the concentration of research activities within a region affects the costs faced by local firms through both wage rates and land rents. As already discussed in Section 5.2.2, the critical point is that researchers, as well as other skilled workers in short supply, are mobile in the sense that their relative scarcity gives them labour market mobility, but are in effect geographically somewhat immobile in that they are willing to live only in places characterised by good entrepreneurial possibilities and by a high level of 'quality of life' (Buswell, 1983; Malecki, 1991). In other words, managerial and research personnel are attracted by relatively expensive, sophisticated leisure and consumption amenities (Malecki, 1987). Due to its effect on land and labour markets, therefore, the concentration of research activities within one region poses a burden on the firms located there. Here, it is assumed that, whilst within the local research sector these diseconomies are more than offset by the dynamic externalities deriving from localised spillovers of tacit knowledge, the effects of the agglomeration of research are instead assumed to be important for firms belonging to the manufacturing sector.

The basic production structure in the final good sector of region i is hence represented by the following additively separable function:

$$Q_i = L_i^{\alpha} Hq_i^{\eta} \left[\int_{A_i} x_i(a_i)^{\gamma} da + \int_{A_j} x_i(a_j)^{\gamma} da \right] Hr_i^{-\lambda L_i} \tag{5.10}$$

where Hq_i and L_i stand, respectively, for the human capital and labour employed in the regional manufacturing sector. The term $Hr_i^{-\lambda L_i}$ represents the just mentioned external effect from the agglomeration of manufacturing, given the size of the local research sector, in which the size of the manufacturing sector is, for simplicity's sake, represented by L_i.

Given the assumption of perfect competition characterising the sector, the production function is assumed to be homogeneous of degree one in the three production factors, implying that $\alpha+\eta+\gamma=1$. As regards the relative size of these parameters, it is also assumed that in both regions the ratio between human capital over unskilled labour employed in this sector is lower than η/α. Given that the wage rates for the production factors are equal to the factors' marginal product, this assumption implies that the wage rate earned by human capital is higher than the wage rate earned by unskilled labour. The parameter λ instead reflects the interrelation between size of the manufacturing sector and size of the research sector on the magnitude of the negative externality and is assumed to be the common for all regions. Finally, it is also assumed that both intermediate inputs and final goods are traded freely within the system in the absence of any transportation cost.

5.4 Patents, Intermediate Inputs and Their Pricing

Having described the structure of the model, it is now possible to determine its equilibrium solution. In order to achieve this result it is first necessary to focus attention on the demand for intermediate inputs generated by each region. The role played in the model by the demand for these inputs is essentially twofold. On the one hand, the quantity of an intermediate input demanded indirectly determines the price of the corresponding patent through the value of the instant profits in the intermediate input market. On the other hand, because of the particular nature of the function describing the production of the final good, the number of differentiated intermediate inputs being adopted in the final sector is essential in order to determine the productivity of the other factors of production. Given this feature, it is important to know whether the increase of the availability of intermediate inputs is due to an increase in the supply of the already existing inputs or to the introduction of new kinds of intermediate inputs. Only in the former case, in fact, capital exhibits the usually decreasing returns.

Let the price of the final good be the numeraire, $p_i(a_i)$ be the price in region i of an intermediate input produced in region i, and $p_j(a_i)$ the price in region j of the same intermediate input. Given the absence of transport costs involved in the inter-regional trade of these inputs, it follows $p_i(a_i) = p_j(a_i)$. Analogously, the price of an intermediate input produced in region j and sold in the same region, $p_j(a_j)$, is equal to the price of the same input sold in region i, $p_i(a_j)$.

In each region, given the prices of the intermediate inputs, final good producers will determine the demand for each intermediate input solving their profit maximisation problems. These problems are described in Appendix A5.1 where it is also shown that from the corresponding first-order conditions it is possible to derive the demand functions faced by producers of intermediate inputs located in the two regions,

$$X(a_i)=x_i(a_i)+x_j(a_i)$$

$$X(a_j)=x_j(a_j)+x_i(a_j)$$

or, equivalently

$$X(a_i)=\gamma^{\frac{1}{1-\gamma}}\left(L_i^{\frac{\alpha}{1-\gamma}}Hq_i^{\frac{\eta}{1-\gamma}}Hr_i^{\frac{-\lambda L_i}{1-\gamma}}+L_j^{\frac{\alpha}{1-\gamma}}Hq_j^{\frac{\eta}{1-\gamma}}Hr_j^{\frac{-\lambda L_j}{1-\gamma}}\right)p_i(a_i)^{-\frac{1}{1-\gamma}} \tag{5.11}$$

and

$$X(a_j)=\gamma^{\frac{1}{1-\gamma}}\left(L_i^{\frac{\alpha}{1-\gamma}}Hq_i^{\frac{\eta}{1-\gamma}}Hr_i^{\frac{-\lambda L_i}{1-\gamma}}+L_j^{\frac{\alpha}{1-\gamma}}Hq_j^{\frac{\eta}{1-\gamma}}Hr_j^{\frac{-\lambda L_j}{1-\gamma}}\right)p_j(a_j)^{-\frac{1}{1-\gamma}}\ . \tag{5.12}$$

The equilibrium level for these demand functions and the corresponding prices can then be determined considering the profit maximisation problem faced by intermediate input producers. For a producer of intermediate inputs located in region i, the profit maximisation problem can be expressed as follows:

$$\max_{X(a_i)} \pi_{IG\,i} \quad = \quad \max_{X(a_i)} \left[p_i(a_i)X(a_i)-rX(a_i)\right] \tag{5.13}$$

The monopoly pricing problem specified above is that of a firm facing a constant marginal cost equal to the interest rate, r, and a demand curve with constant elasticity, ε_D $=-\dfrac{1}{1-\gamma}$. The profit maximising price can then be determined using the relationship between average and marginal revenue

$$\text{MR} \ = \ \text{AR}\,(1+\varepsilon_D^{-1})$$

and the profit maximisation condition MC=MR. These relationships yield:

$$r=\text{AR}\left[1+\left(-\frac{1}{1-\gamma}\right)^{-1}\right] \tag{5.14}$$

from which it is easy to show that the profit maximising[7] price for an intermediate input is the same in the two regions and equal to:

$$\hat{p}(a)=\hat{p}_i(a_i)=\hat{p}_j(a_j)=r\gamma^{-1}. \tag{5.15}$$

From the symmetry existing in the model between the different types of intermediate inputs, it follows that in region i all the inputs realised and produced within the region will be used at the same level $\hat{x}_i(a_i)$, whilst all the intermediate inputs realised and produced in region j will be used at level $\hat{x}_i(a_j)$. Similarly, the demand in region j for each domestically produced intermediate input will be $\hat{x}_j(a_j)$ and the quantity demanded for any imported input will be equal to $\hat{x}_j(a_i)$. As at any point in time the number of differentiated inputs actually designed in region i is A_i and A_j in region j, the amount of intermediate inputs used in region i can be expressed as:

$$\int_{A_i} x_i(a_i)^\gamma\, da + \int_{A_j} x_i(a_j)^\gamma\, da = A_i\,\hat{x}_i(a_i)^\gamma + A_j\,\hat{x}_i(a_j)^\gamma \tag{5.16}$$

and, equivalently, in region j as:

$$\int_{A_j} x_j(a_j)^\gamma\, da + \int_{A_i} x_j(a_i)^\gamma\, da = A_j\,\hat{x}_j(a_j)^\gamma + A_i\,\hat{x}_j(a_i)^\gamma. \tag{5.17}$$

Given that the profit maximising price of an intermediate input is the same throughout the system independently of where the input is produced or sold, using the equations derived in Appendix A5.1 defining the levels of intermediate inputs demanded from the two regions, it is easy to show that

$$\hat{x}_i(a_i)=\hat{x}_i(a_j)=\hat{x}_i(a)=\gamma^{\frac{1}{1-\gamma}}\,\hat{L}_i^{\frac{\alpha}{1-\gamma}}\,\hat{H}q_i^{\frac{\eta}{1-\gamma}}\,\hat{H}r_i^{-\frac{\lambda}{1-\gamma}\hat{L}_i}\,\hat{p}(a)^{-\frac{1}{1-\gamma}} \tag{5.18}$$

and

$$\hat{x}_j(a_j)=\hat{x}_j(a_i)=\hat{x}_j(a)=\gamma^{\frac{1}{1-\gamma}}\,\hat{L}_j^{\frac{\alpha}{1-\gamma}}\,\hat{H}q_j^{\frac{\eta}{1-\gamma}}\,\hat{H}r_j^{-\frac{\lambda}{1-\gamma}\hat{L}_j}\,\hat{p}(a)^{-\frac{1}{1-\gamma}}. \tag{5.19}$$

As a consequence, the functions describing the production of final goods in the two regions can be re-written as:

$$Q_i = L_i^\alpha\, Hq_i^\eta\, A\,\hat{x}_i(a)^\gamma\, Hr_i^{-\lambda L_i} \tag{5.20}$$

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[7] A hat over a variable indicates its equilibrium value.

and

$$Q_j = L_j^{\alpha}\ Hq_j^{\eta}\ A\,\hat{x}_j(a)^{\gamma}\ Hr_j^{-\lambda L_j}\ . \tag{5.21}$$

Moreover, it is clear that in equilibrium also the overall demand faced by intermediate input producers located in the two different regions will be the same:

$$\hat{X}(a) = \hat{X}(a_j) = \hat{X}(a_i) = \hat{x}_i(a_i) + \hat{x}_j(a_j) = \frac{1}{2}\left[\hat{x}_i(a) + \hat{x}_j(a)\right]. \tag{5.22}$$

Consequently, the maximum instant profits enjoyed by intermediate input producers are the same in the two regions and equal to:

$$\hat{\pi}_{IG} = r\,\hat{X}(a)\frac{1-\gamma}{\gamma}\ .$$

The decision about undertaking the production of a new intermediate input is taken comparing the discounted value of the flow of future profits to the cost of the initial investment in a patent or, more generally, in research. Assuming perfect competition in the market for patents, the price of a patent must equal the present value of the stream of future profits. Therefore, the cost of a patent in the two regions is:

$$P(a_i) = P(a_j) = P(a) = \int_{\circ}^{\infty} \hat{\pi}_{IG}\ e^{-rt}\,dt\ .$$

Because patents are infinitely lived, if the interest rate is constant the value of a patent in terms of final output is:

$$\hat{P}(a) = \hat{\pi}_{IG}\ r^{-1} = \hat{X}(a)\frac{1-\gamma}{\gamma}\ . \tag{5.23}$$

5.5 The Steady-State Equilibrium of the System

The steady-state equilibrium represents the decentralised, perfect-foresight equilibrium in which the growth rate of all variables in the model is constant. Within the framework described in the previous sections, it has been shown that, under the assumption of a constant interest rate, the equilibrium price for the intermediate inputs is constant. Assuming that the labour market is characterised by a constant allocation of unskilled labour and human capital across regions and sectors, then it is clear from equations 5.18 and 5.19 that the levels $\hat{x}_i(a)$ and $\hat{x}_j(a)$ at which each intermediate input is used respectively in region i and j are also constant. Moreover, if such a constant allocation of resources exists, it follows from equations 5.20 and 5.21, that the level of output of final goods grows in both regions at the same constant rate at which abstract knowledge grows.

As for the accumulation of physical capital, because it takes one unit of forgone consumption to create one unit of any type of intermediate input, the level of physical capital available in the system, K, is related to the intermediate inputs that are actually used in production by the following rule:

$$K = K_i + K_j = \int_A \hat{x}_i(a)\,da + \int_A \hat{x}_j(a)\,da = A\,\hat{x}_i(a) + A\,\hat{x}_j(a)\,. \qquad (5.24)$$

Given the levels $\hat{x}_i(a)$ and $\hat{x}_j(a)$, it follows from the last equation that K also grows at the same rate as output and, as a result, Q/K is constant. Consequently, the ratio

$$\frac{C}{Q} = 1 - \frac{\dot{K}}{Q} = 1 - \frac{\dot{K}}{K}\frac{K}{Q}$$

must be constant as well, so that C grows at the constant rate of the other variables. Finally, from the relation between interest rate and the rate of growth of consumption derived from the consumers' preferences it follows that the interest rate, r, is also constant.

To sum up, therefore, if the system is characterised by a constant allocation of unskilled labour and human capital across regions and sectors, it is possible to determine a steady-state equilibrium solution in which all the variables grow at the same constant rate:

$$\frac{\dot{Q}_i}{Q_i} = \frac{\dot{Q}_j}{Q_j} = \frac{\dot{Q}}{Q} = \frac{\dot{K}}{K} = \frac{\dot{C}}{C} = \frac{\dot{A}}{A}\ .$$

In order to solve the model for this balanced growth equilibrium it is therefore necessary to determine the equilibrium allocation of both unskilled labour and human capital: that is the allocation characterised by the absence of any incentive for unskilled labour and human capital to move across regions and sectors. By posing this condition to the system describing the movements of the two factors, it is easy to show that the equilibrium allocation of unskilled labour and human capital is reached when the wage for the first factor is the same in the two regions and the wage for the second factor is the same in both sectors of both regions:

$$\begin{cases} w(L)_i = w(L)_j \\ w(Hr)_i = w(Hr)_j = w(Hq)_i = w(Hq)_j \end{cases} .$$

To understand the implications of this equilibrium conditions it is convenient to consider separately the different labour market equilibria.

5.5.1 Equilibrium in the Research Sector

To analyse the equilibrium allocation of human capital between the two regional research sectors, it is necessary to derive the expressions for the wage rates earned in the different regions. Human capital, being the only factor employed, receives all the income from the research sector. Hence, the wage for human capital employed in region i is:

$$w(Hr)_i = \frac{\partial}{\partial Hr_i} \dot{A}_i P(a) , \qquad (5.25)$$

and in region j:

$$w(Hr)_j = \frac{\partial}{\partial Hr_j} \dot{A}_j P(a) . \qquad (5.26)$$

As shown in Appendix A5.2, a stable equilibrium is reached when:[8]

$$\hat{H}r_i = \hat{H}r_j \left[\frac{\delta_i}{\delta_j} d_{ij}^{-\left(\beta_{ij}^{-1} - \beta_{ji}^{-1}\right)} \right]^{\frac{1}{1-\phi}} . \qquad (5.27)$$

Given the ratio δ_i/δ_j, the equilibrium allocation of human capital depends on the physical distance d_{ij} and the values assumed by the potential benefits from technological interaction β_{ij} and β_{ji} which, in turn, depend themselves on δ_i/δ_j. Therefore, since the ratio between local competencies in research of the two regions is constant over time,

[8] The wage rates for human capital employed in research do not depend on the allocation of the other factors of production and therefore the stability of the inter-regional equilibrium in this sector can be studied independently from what happens in the other sector. The stability of the other labour market equilibria is ensured by the particular type of external effect introduced in the final good production function discussed in Section 5.3.

also the equilibrium allocation of human capital in research described in equation 5.27 stays constant.

Using this result, it is possible to evaluate the rate at which the flow of abstract knowledge grows in the system:

$$\frac{\dot{A}}{A} = \frac{\dot{A}_i}{A} + \frac{\dot{A}_j}{A} = \delta_i \hat{H}r_i^{1+\phi} \hat{H}r_j d_{ij}^{-\beta_{ij}^{-1}} + \delta_j \hat{H}r_j^{1+\phi} \hat{H}r_i d_{ij}^{-\beta_{ji}^{-1}}$$

which, in equilibrium, can be written as:

$$\frac{\dot{A}}{A} = \delta_j \hat{H}r_i \, d_{ij}^{-\beta_{ji}^{-1}} \, \hat{H}r_j^{\phi} \, \hat{H}r = \delta_i \, \hat{H}r_j \, d_{ij}^{-\beta_{ij}^{-1}} \, \hat{H}r_i^{\phi} \, \hat{H}r \tag{5.28}$$

where $\hat{H}r$ is the equilibrium level of human capital devoted to research activities within the system.

5.5.2 *The Inter-regional Equilibrium in the Final Good Sector*

The equilibrium allocation of unskilled labour and human capital between the two regional final good sectors requires that the wage equalisation conditions for both production factors are solved for simultaneously:

$$\begin{cases} w(L)_i = w(L)_j \\ w(Hq)_i = w(Hq)_j \end{cases}$$

where

$$\begin{aligned} w(L)_i &= \frac{\partial Q_i}{\partial L_i} = \alpha L_i^{\alpha-1} Hq_i^{\eta} \quad Ax_i^{\gamma} Hr_i^{-\lambda L_i} \\ w(L)_j &= \frac{\partial Q_j}{\partial L_j} = \alpha L_j^{\alpha-1} Hq_j^{\eta} \quad Ax_j^{\gamma} Hr_j^{-\lambda L_j} \end{aligned} \tag{5.29}$$

and

$$\begin{aligned} w(Hq)_i &= \frac{\partial Q_i}{\partial Hq_i} = \eta L_i^{\alpha} Hq_i^{\eta-1} \quad Ax_i^{\gamma} Hr_i^{-\lambda L_i} \\ w(Hq)_j &= \frac{\partial Q_j}{\partial Hq_j} = \eta L_j^{\alpha} Hq_j^{\eta-1} \quad Ax_j^{\gamma} Hr_j^{-\lambda L_j}. \end{aligned} \tag{5.30}$$

It is easy to show that the solution to the system is given by:

$$\frac{\hat{L}_i}{\hat{L}_j} = \frac{\hat{H}q_i}{\hat{H}q_j} = \frac{\hat{x}_i(a)}{\hat{x}_j(a)} \tag{5.31}$$

which states that in equilibrium the ratios between the regional endowments of unskilled labour, human and physical capital are the same, and by the additional condition on the external effects:

$$\hat{H}r_i^{\lambda \hat{L}_i} = \hat{H}r_j^{\lambda \hat{L}_j}$$

which states that the extent of these external effects must be the same in the two regions. Taking the logarithmic transformation of both sides, and after simple manipulation, the condition of the equalisation of the external effects becomes:

$$\frac{\hat{L}_j}{\hat{L}_i} = \frac{\ln\left(\frac{\hat{H}r_i}{\hat{H}r_j}\right)}{\ln\left(\hat{H}r_j\right)} + 1 . \tag{5.32}$$

5.5.3 Intra-regional Equilibria for Human Capital

The intra-regional equilibria for human capital require inter-sectoral wage equalisation:

$$\begin{cases} w(Hq)_i = w(Hr)_i \\ w(Hq)_j = w(Hr)_j \end{cases}$$

from which it is immediately possible to obtain:

$$w(\hat{H}q)_i + w(\hat{H}q)_j = 2\, w(\hat{H}r)_j$$

given that in equilibrium the wage rates for researchers are equalised. In Appendix A5.3 it is shown that this equilibrium condition requires the following allocation of human capital between manufacturing and research activities within the system:

$$\hat{H}r = \frac{\gamma(1-\gamma)(1-\Gamma)}{2\sigma\eta} \hat{H}q . \tag{5.33}$$

In equilibrium, therefore, the allocation of the existing stock of human capital depends on the consumers' preferences, via σ and Γ, and on the factors' shares on the product of the final good sector.

5.5.4 The Main Features of the Balanced Growth Equilibrium

It has been shown that the system is characterised by a constant allocation of workers across sectors and regions. In particular, this equilibrium allocation can be summarised by:

$$\begin{cases} \hat{H}r_i = \dfrac{\mu}{1+\mu}\hat{H}r \\ \hat{H}r_j = \dfrac{1}{1+\mu}\hat{H}r \\ \hat{L}_i = \dfrac{\ln \hat{H}r - \ln(\mu+1)}{2\ln \hat{H}r - 2\ln(\mu+1) + \ln\mu} L \\ \hat{L}_j = \dfrac{\ln \hat{H}r - \ln(\mu+1) + \ln\mu}{2\ln \hat{H}r - 2\ln(\mu+1) + \ln\mu} L \\ \hat{H}q_i = \dfrac{\ln \hat{H}r - \ln(\mu+1)}{2\ln \hat{H}r - 2\ln(\mu+1) + \ln\mu} \hat{H}q \\ \hat{H}q_j = \dfrac{\ln \hat{H}r - \ln(\mu+1) + \ln\mu}{2\ln \hat{H}r - 2\ln(\mu+1) + \ln\mu} \hat{H}q \\ \hat{H}r = \dfrac{\gamma(1-\gamma)(1-\Gamma)}{2\sigma\eta + \gamma(1-\gamma)(1-\Gamma)} H \\ \hat{H}q = \dfrac{2\sigma\eta}{2\sigma\eta + \gamma(1-\gamma)(1-\Gamma)} H \end{cases} \tag{5.34}$$

where μ indicates the constant ratio between human capital employed in the two regional research sectors.

Making use of this equilibrium allocation, it has been possible to solve the model for the steady-state equilibrium in which output, consumption, physical capital and abstract knowledge grow at the same constant growth rate. Moreover, it is clear from equations 5.25 and 5.26, for the research sector, and from equations 5.29 and 5.30, for the manufacturing sector, that along this steady-state growth path all wage rates grow at the same constant rate as the other variables, whilst the price of a patent, the price of each intermediate input, the price of the final good and the interest rate stay constant.

To determine the rates at which the regional flows of abstract knowledge grow, it is first necessary to evaluate the equilibrium value of the ratio between the flows of patents created in the two regions:

$$\frac{\dot{A}_i}{\dot{A}_j} = \frac{\delta_i \hat{H}r_i^{1+\phi}\ \hat{H}r_j\ d_{ij}^{-\beta_{ij}^{-1}}}{\delta_j \hat{H}r_j^{1+\phi}\ \hat{H}r_i\ d_{ij}^{-\beta_{ji}^{-1}}} = \frac{\hat{H}r_i}{\hat{H}r_j}\ .$$

It is now possible to work out the asymptotic value of the ratio between the number of patents created in the different regions, that is:

$$\lim_{t\to\infty} \frac{A_i}{A_j}\ .$$

Using L'Hôpital's rule, it is easy to show that the ratio between the number of patents created in the two regions also tends asymptotically to the constant value $\hat{H}r_i / \hat{H}r_j$ and that the ratios between the patents created in region i and j over the total number of patents tend respectively to $\hat{H}r_i / \hat{H}r$ and $\hat{H}r_i / \hat{H}r$. Thus, it is possible to show that the asymptotic growth rate of abstract knowledge will be the same in the two regions and will be:

$$\frac{\dot{A}_i}{A_i} = \frac{A}{A_i} \delta_i\ \hat{H}r_i^{1+\phi} \hat{H}r_j\ d_{ij}^{-\beta_{ij}^{-1}} = \delta_i\ \hat{H}r_i^{\phi} \hat{H}r_j\ d_{ij}^{-\beta_{ij}^{-1}}\ \hat{H}r = \frac{\dot{A}}{A}$$

and:

$$\frac{\dot{A}_j}{A_j} = \frac{A}{A_j} \delta_j\ \hat{H}r_j^{1+\phi} \hat{H}r_i\ d_{ij}^{-\beta_{ji}^{-1}} = \delta_j\ \hat{H}r_j^{\phi} \hat{H}r_i\ d_{ij}^{-\beta_{ji}^{-1}}\ \hat{H}r = \frac{\dot{A}}{A}\ .$$

Appendices

A5.1 The Determination of the Demand for Intermediate Inputs

As seen in Section 5.4, the demand for each intermediate input can be determined starting from the profit maximisation problems faced by final good producers. For a producer of final goods located in region i, the problem can be described as follows:

$$\max_{x} \pi_{\mathrm{FGi}} = \max_{x} \left(\mathrm{Revenues}_{\mathrm{FGi}} - \mathrm{Costs}_{\mathrm{FGi}}\right)$$

where

$$\mathrm{Revenues}_{\mathrm{FGi}} = L_i^{\alpha} Hq_i^{\eta} \left[\int_{A_i} x_i(a_i)^{\gamma}\, da + \int_{A_j} x_i(a_j)^{\gamma}\, da\right] Hr_i^{-\lambda L_i}$$

$$\mathrm{Costs}_{\mathrm{FGi}} = \left[p_i(a_i)\int_{A_i} x_i(a_i)\, da + p_i(a_j)\int_{A_j} x_i(a_j)\, da + w(L)_i L_i + w(Hq)_i Hq_i\right]$$

From the corresponding first-order conditions it is possible to derive the demand functions arising from final good producers located in region i, for intermediate inputs produced in both regions:

$$x_i(a_i) = \gamma^{\frac{1}{1-\gamma}} L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{-\frac{\lambda}{1-\gamma}L_i} p_i(a_i)^{-\frac{1}{1-\gamma}}$$
$$x_i(a_j) = \gamma^{\frac{1}{1-\gamma}} L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{-\frac{\lambda}{1-\gamma}L_i} p_j(a_j)^{-\frac{1}{1-\gamma}}.$$

Analogously, from the profit maximisation problem for final good producers located in region j, it is possible to derive:

$$x_j(a_j) = \gamma^{\frac{1}{1-\gamma}} L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{-\frac{\lambda}{1-\gamma}L_j} p_j(a_j)^{-\frac{1}{1-\gamma}}$$
$$x_j(a_i) = \gamma^{\frac{1}{1-\gamma}} L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{-\frac{\lambda}{1-\gamma}L_j} p_i(a_i)^{-\frac{1}{1-\gamma}}$$

It is now easy to determine the total demand functions faced by intermediate input producers located in region i

$$X(a_i) = \gamma^{\frac{1}{1-\gamma}} \left(L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{\frac{-\lambda L_i}{1-\gamma}} + L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{\frac{-\lambda L_j}{1-\gamma}} \right) p_i(a_i)^{-\frac{1}{1-\gamma}}$$

and in region j

$$X(a_j) = \gamma^{\frac{1}{1-\gamma}} \left(L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{\frac{-\lambda L_i}{1-\gamma}} + L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{\frac{-\lambda L_j}{1-\gamma}} \right) p_j(a_j)^{-\frac{1}{1-\gamma}} .$$

The corresponding prices are therefore:

$$p_i(a_i) = \gamma \left(L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{-\frac{\lambda}{1-\gamma} L_i} + L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{-\frac{\lambda}{1-\gamma} L_j} \right)^{1-\gamma} X(a_i)^{-(1-\gamma)}$$

and

$$p_j(a_j) = \gamma \left(L_i^{\frac{\alpha}{1-\gamma}} Hq_i^{\frac{\eta}{1-\gamma}} Hr_i^{-\frac{\lambda}{1-\gamma} L_i} + L_j^{\frac{\alpha}{1-\gamma}} Hq_j^{\frac{\eta}{1-\gamma}} Hr_j^{-\frac{\lambda}{1-\gamma} L_j} \right)^{1-\gamma} X(a_j)^{-(1-\gamma)} .$$

A5.2 Equilibrium for Human Capital in Research

The wage for human capital employed in region i is:

$$w(Hr)_i = \frac{\partial}{\partial Hr_i} \dot{A}_i \hat{P}(a) , \tag{A5.2.1}$$

where

$$\dot{A}_i = \delta_i Hr_i \, Hr_i^{\phi} \left(Hr_j \, d_{ij}^{-1/\beta_{ij}} \right) A$$

$$\hat{P}(a) = \hat{X}(a) \frac{1-\gamma}{\gamma} .$$

Similarly, the wage rate in region j is:

$$w(Hr)_j = \frac{\partial}{\partial Hr_j} \dot{A}_j \hat{P}(a) \tag{A5.2.2}$$

where

$$\dot{A}_j = \delta_j Hr_j Hr_j^{\phi} \left(Hr_i d_{ij}^{-1/\beta_{ji}} \right) A .$$

As shown in the text, the inter-regional equilibrium in research is achieved when the two regional wages are equalised, that is when:

$$\hat{Hr}_i = \hat{Hr}_j \left[\frac{\delta_i}{\delta_j} d_{ij}^{-\left(\beta_{ij}^{-1} - \beta_{ji}^{-1}\right)} \right]^{\frac{1}{1-\phi}} . \tag{A5.2.3}$$

Since the wage rates for human capital employed in research do not depend on the allocation of the other factors of production, the stability of the inter-regional equilibrium in the research sector can be studied considering the sector in isolation. In order to do this, the differential equations describing the flows of human capital are simplified to:

$$\begin{cases} \dot{Hr}_i = m_H \, BH_{RiRj} \, \hat{Hr} \\ \dot{Hr}_j = m_H \, BH_{RiRj} \, \hat{Hr} \end{cases}$$

but only one of then is required to fully determine the flows of human capital between the two research sectors since in equilibrium the overall level of human capital employed in research is constant. To check the stability of the equilibrium it is necessary to evaluate the partial derivative with respect to Hr_i of $\dot{Hr}_i$ in correspondence of the equilibrium described by (A5.2.3):

$$\left.\frac{\partial \dot{Hr}_i}{\partial Hr_i}\right|_{\dot{Ht}_i=0} = m_{Hr} r^{-1} \hat{Hr} \frac{1-\gamma}{\gamma} X(a)\, A\left(\delta_j \hat{Hr}_j^{\phi} d_{ij}^{-\beta_{ji}^{-1}}\right)^{-1} \left[(\phi-1)\frac{\hat{Hr}_i}{\hat{Hr}_j} + \phi - 1\right].$$

Since $\phi < 1$, the partial derivative has always a negative sign, ensuring that the equilibrium is stable.

A5.3 Inter-sectoral Equilibrium for Human Capital

As shown in the text, the equilibrium condition can be written as

$$w(\hat{Hq})_i + w(\hat{Hq})_j = 2\, w(\hat{Hr})_j . \qquad \text{(A5.3.1)}$$

From the definition of the intermediate goods' price, and given that its equilibrium level is equal to $r\gamma^{-1}$, it is possible the wage rates for human capital employed in manufacturing can be written as:

$$w(\hat{Hq})_i = \eta\, r\, \gamma^{-2} \, Ax_i(a)\, \hat{Hq}_i^{-1}$$

$$w(\hat{Hq})_j = \eta\, r\, \gamma^{-2} \, Ax_j(a)\, \hat{Hq}_j^{-1}$$

whilst the wage rate for human capital employed in research is:

$$w(\hat{Hr})_j = \delta_j \hat{Hr}_j^{\phi} \, \hat{Hr}_i \, d_{ij}^{-\beta_{ji}^{-1}} \, \hat{X}(a)\, \gamma^{-1}(1-\gamma)\, A .$$

The equilibrium condition A5.3.1, thus becomes:

$$\frac{\eta\gamma^{-2}\, r\left[x_i(a)\,\hat{H}q_i^{-1} + x_j(a)\,\hat{H}q_j^{-1}\right] A}{2\gamma^{-1}(1-\gamma)\,\hat{X}(a)\,\delta_j\,\hat{H}r_j^{\phi}\,\hat{H}r_i\,d_{ij}^{-\beta_{ji}^{-1}}\,A} = 1\,.$$

Given that the overall demand faced by intermediate good producers is

$$\hat{X}(a) = \frac{1}{2}\left[\hat{x}_i(a) + \hat{x}_j(a)\right]$$

and that in equilibrium the ratio $\hat{x}_i(a)/\hat{x}_j(a)$ is equal to $\hat{H}q_i/\hat{H}q_j$, after simple manipulation, the equilibrium condition can be re-written as:

$$r\frac{2\eta}{\gamma(1-\gamma)} = \hat{H}q\delta_j\hat{H}r_j^{\phi}\hat{H}r_i\,d_{ij}^{-\beta_{ji}^{-1}}\,.$$

From the consumers' preferences, it has been found that the interest rate is equal to:

$$r = \sigma(1-\Gamma)^{-1}\frac{\dot{C}}{C}\,.$$

As the growth rate of consumption must be equal to the growth rate of abstract knowledge along a steady-state growth path, and given that the latter growth rate can be expressed as:

$$\frac{\dot{A}}{A} = \delta_j\hat{H}r_i\,d_{ij}^{-\beta_{ji}^{-1}}\,\hat{H}r_j^{\phi}\,\hat{H}r\,,$$

it is possible to express the interest rate as:

$$r = \sigma(1-\Gamma)^{-1}\,\delta_j\hat{H}r_i\,d_{ij}^{-\beta_{ji}^{-1}}\,\hat{H}r_j^{\phi}\,\hat{H}r$$

By substituting this expression into the equilibrium condition A5.3.2 it is easy to show that the equilibrium in the market for human capital requires:

$$\hat{H}r = \frac{\gamma(1-\gamma)(1-\Gamma)}{2\ \sigma\eta}\hat{H}q\ .$$

Chapter 6
A Decentralised Model of Endogenous Growth: Spatial Concentration in Research and Income Differentials among Regions

6.1 Differences in Per Capita GDP Levels among Regions

6.1.1 Regional GDP Levels and Growth Rates

Having described the steady-state equilibrium of the model, it is now possible to investigate the levels and growth rates of per capita income in the two regions. In order to do this, it is first necessary to introduce the distinction between regional product, indicated with the letter Q, and regional income or Gross Domestic Product (GDP), indicated with the letter Y. This distinction derives from the fact that part of the intermediate inputs employed in one region are imported; therefore, part of the regional product is used to remunerate the research effort carried out somewhere else. As explained in Appendix A6.1, the level of production in region i is equal to:

$$\hat{Q}_i = w(L)\,\hat{L}_i + w(H)\,\hat{H}q_i + \hat{p}(a)\,A_i\,\hat{x}_i(a_i) + \hat{p}(a)\,A_j\hat{x}_i(a_j)$$

whilst the level of GDP is:

$$\hat{Y}_i = \hat{w}(L)\,\hat{L}_i + \hat{w}(H)\,\hat{H}q_i + \hat{p}(a)\,A_i\,\hat{x}_i(a) + \hat{p}(a)\,A_i\,\hat{x}_j(a)\,.$$

Similarly, it can be immediately shown that the level of GDP in region j is:

$$\hat{Y}_j = \hat{w}(L)\,\hat{L}_j + \hat{w}(H)\,\hat{H}q_j + \hat{p}(a)\,A_j\,\hat{x}_j(a) + \hat{p}(a)\,A_j\,\hat{x}_i(a)\,.$$

Thus, the average level of per capita GDP in region i is:

$$\hat{y}_i = \frac{\hat{w}(L)\,\hat{L}_i + \hat{w}(H)\,\hat{H}q_i + A_i\,\hat{X}(a)\,\hat{p}(a)}{\hat{L}_i + \hat{H}q_i + \hat{H}r_i}$$

and in region j:

$$\hat{y}_j = \frac{\hat{w}(L)\,\hat{L}_j + \hat{w}(H)\,\hat{H}q_j + A_j\,\hat{X}(a)\,\hat{p}(a)}{\hat{L}_j + \hat{H}q_j + \hat{H}r_j}\,.$$

Substituting $\hat{p}(a)$ from equation 5.15, and using equation 5.23, the definition of the interest rate in terms of the consumers' preferences, and the definition of Value

Added for the research sector to derive the equilibrium level $\hat{X}(a)$ as a function of the level of human capital employed in research and the corresponding wage rate, the level of per capita GDP in region i becomes:

$$\hat{y}_i = \frac{\hat{w}(L)\,\hat{L}_i + \hat{w}(H)\,\hat{H}q_i + \hat{w}(H)\,\hat{H}r_i\,\sigma(1-\gamma)^{-1}\,(1-\Gamma)^{-1}}{\hat{L}_i + \hat{H}q_i + \hat{H}r_i}. \qquad (6.1)$$

Similarly, the per capita GDP level in region j is:

$$\hat{y}_j = \frac{\hat{w}(L)\,\hat{L}_j + \hat{w}(H)\,\hat{H}q_j + \hat{w}(H)\,\hat{H}r_j\,\sigma(1-\gamma)^{-1}\,(1-\Gamma)^{-1}}{\hat{L}_j + \hat{H}q_j + \hat{H}r_j} \qquad (6.2)$$

while the ratio between per capita income between regions i and j is:

$$\frac{\hat{y}_i}{\hat{y}_j} = \frac{\hat{w}(L)\,\hat{L}_i + \hat{w}(H)\,\hat{H}q_i + \hat{w}(H)\,\hat{H}r_i\,\sigma(1-\gamma)^{-1}(1-\Gamma)^{-1}}{\hat{w}(L)\,\hat{L}_j + \hat{w}(H)\,\hat{H}q_j + \hat{w}(H)\,\hat{H}r_j\,\sigma(1-\gamma)^{-1}(1-\Gamma)^{-1}}\,\frac{\hat{L}_j + \hat{H}q_j + \hat{H}r_j}{\hat{L}_i + \hat{H}q_i + \hat{H}r_i} \qquad (6.3)$$

6.1.2 Differences in Per Capita GDP Levels between Regions

It is now possible to show that in equilibrium the more innovative region is also the region characterised by a higher level of per capita income. Suppose, without loss of generality, that region i is the more innovative region in the system, that is, $\dot{A}_i / \dot{A}_j > 1$. Using the definitions of the research efforts in the two regions, this implies:

$$\left(\frac{\hat{H}r_i}{\hat{H}r_j}\right)^{\phi} \frac{\delta_i}{\delta_j} d_{ij}^{-(\beta_{ij}^{-1}-\beta_{ji}^{-1})} > 1\,.$$

Substituting the expression for the equilibrium allocation of human capital between the two research sectors given in equation 5.27, it easy to show that $\dot{A}_i / \dot{A}_j > 1$ implies $\hat{H}r_i / \hat{H}r_j > 1$. In other words, the model describes a tendency towards the spatial concentration of the activity of research in the more innovative region.

It is also possible to show that the more innovative region is necessarily the one characterised by a superior regional technological competence in research. From the assumption $\dot{A}_i / \dot{A}_j > 1$ it has just been found that $\hat{H}r_i / \hat{H}r_j > 1$ or, equivalently,

$(\hat{H}r_i / \hat{H}r_j)^{1-\phi} > 1$. Taking the logarithmic transformation of both sides, and substituting for the equilibrium allocation of human capital in research:

$$\ln\frac{\delta_i}{\delta_j} - \left(\beta_{ij}^{-1} - \beta_{ji}^{-1}\right)\ln d_{ij} > 0 \tag{6.4}$$

where, according to equations 5.5

$$\beta_{ij}^{-1} - \beta_{ji}^{-1} = \frac{\ln d_{ij}}{\ln d_{ij} + \ln\frac{\delta_{\text{technological leader}}}{\delta_i}} - \frac{\ln d_{ij}}{\ln d_{ij} + \ln\frac{\delta_{\text{technological leader}}}{\delta_j}}.$$

Assuming that region i is the technological leader, so that $\delta_i = \delta_{\text{technological leader}}$, condition 6.4 becomes:

$$\frac{\left(\ln\frac{\delta_i}{\delta_j}\right)^2}{\ln d_{ij} + \ln\frac{\delta_i}{\delta_j}} > 0$$

which is always satisfied, for any value of the cost of the distance d_{ij}. Consider now the case in which region j is the technological leader and $\delta_j = \delta_{\text{technological leader}}$. Under this circumstance, condition 6.4 becomes:

$$\frac{\ln\frac{\delta_i}{\delta_j}\ln\frac{\delta_j}{\delta_i}}{\ln d_{ij} + \ln\frac{\delta_j}{\delta_i}} > 0$$

which is never satisfied given that $\delta_i / \delta_j < 1$. In other words, region i can be the innovative leader if, and only if, it is also characterised by a superior local technological competence in research.

Having shown that research activities tend to cluster within the more innovative region, it is necessary to establish the relative size of the manufacturing sectors to determine the relative size of regional per capita incomes. It has just been shown that the more innovative region is also the region in which research activities tend to cluster. From equation 5.31 and 5.32 it can immediately be shown that:

$$\frac{\hat{H}q_j}{\hat{H}q_i} = \frac{\hat{L}_j}{\hat{L}_i} = \frac{\ln \frac{\hat{H}r_i}{\hat{H}r_j}}{\ln \hat{H}r_j} + 1 . \tag{6.5}$$

The last equation reveals that a ratio $\hat{H}r_i / \hat{H}r_j$ larger than unity, which in turn derives from the assumption $\dot{A}_i > \dot{A}_j$, necessarily implies that manufacturing activities tend to cluster in the less innovative region. To sum up, therefore, if region i is assumed to be the innovative leader, so that $\dot{A}_i > \dot{A}_j$, the solution to the allocation problem for human capital and unskilled labour is characterised by a concentration of research activity in this region. Moreover, to became the innovative leader, region i must have developed a superior level of local technological competence in research and its productive structure must be characterised by a relative specialisation in research activities with respect to the other region.

It is now possible to show that the relative specialisation in research also represents a sufficient condition for a higher level of per capita GDP. Dividing both numerator and denominator in equation 6.3 by $\hat{w}(L)$ and by $\hat{L}_i \hat{L}_j$, and recalling that in equilibrium $\hat{L}_i \, \hat{H}q_j = \hat{L}_j \, \hat{H}q_i = L \, \hat{H}q$, after simplification the ratio between regional per capita GDPs becomes:

$$\frac{\hat{y}_i}{\hat{y}_j} = \frac{\left(1+\hat{w}\frac{\hat{H}q}{L}\right)\left(1+\frac{\hat{H}q}{L}\right) + \hat{w}\zeta\frac{\hat{H}r_i}{\hat{L}_i}\frac{\hat{H}r_j}{\hat{L}_j} + \hat{w}\left(1+\frac{\hat{H}q}{L}\right)\zeta\frac{\hat{H}r_i}{\hat{L}_i} + \left(1+\hat{w}\frac{\hat{H}q}{L}\right)\frac{\hat{H}r_j}{\hat{L}_j}}{\left(1+\hat{w}\frac{\hat{H}q}{L}\right)\left(1+\frac{\hat{H}q}{L}\right) + \hat{w}\zeta\frac{\hat{H}r_i}{\hat{L}_i}\frac{\hat{H}r_j}{\hat{L}_j} + \hat{w}\left(1+\frac{\hat{H}q}{L}\right)\zeta\frac{\hat{H}r_j}{\hat{L}_j} + \left(1+\hat{w}\frac{\hat{H}q}{L}\right)\frac{\hat{H}r_i}{\hat{L}_i}}$$

where $\hat{w} = \hat{w}(H) / \hat{w}(L)$ and $\zeta = \sigma(1\text{-}\gamma)^{-1}(1\text{-}\Gamma)^{-1}$.

From the analysis of the last equation it is clear that the size of the ratio between regional per capita GDPs depends on the ratio

$$\frac{\hat{w}\left(1+\frac{\hat{H}q}{L}\right)\zeta\frac{\hat{H}r_i}{\hat{L}_i} + \left(1+\hat{w}\frac{\hat{H}q}{L}\right)\frac{\hat{H}r_j}{\hat{L}_j}}{\hat{w}\left(1+\frac{\hat{H}q}{L}\right)\zeta\frac{\hat{H}r_j}{\hat{L}_j} + \left(1+\hat{w}\frac{\hat{H}q}{L}\right)\frac{\hat{H}r_i}{\hat{L}_i}}; \tag{6.6}$$

for instance, whenever this ratio is larger than unity, also the ratio between regional per capita GDPs is larger than unity, that is, $\hat{y}_i > \hat{y}_j$. Considering therefore the case in which the ratio in 6.6 is actually larger than unity, it is easy to obtain:

$$\zeta \frac{\hat{w}\left(1+\frac{\hat{H}q}{L}\right)}{1+\hat{w}\frac{\hat{H}q}{L}}\left(\frac{\hat{H}r_i}{\hat{L}_i}-\frac{\hat{H}r_j}{\hat{L}_j}\right) > \left(\frac{\hat{H}r_i}{\hat{L}_i}-\frac{\hat{H}r_j}{\hat{L}_j}\right). \tag{6.7}$$

The first term on the left-hand-side is the constant ζ which depends on the parameters defining the consumers' preferences and on the capital share:

$$\zeta = \sigma(1\text{-}\gamma)^{-1}(1\text{-}\Gamma)^{-1}.$$

Given that the capital share is always lower than unity, the term $(1\text{-}\gamma)^{-1}$ is always greater than unity. Moreover, recall that from the convergence condition in the consumers' utility maximisation problem it must be true that:

$$(1-\sigma)\frac{\dot{C}}{C} < r\Gamma .$$

Substituting the definition of interest rate deriving from the same maximisation problem, this convergence condition becomes:

$$\sigma(1-\Gamma)^{-1} > 1$$

which ensures that the constant ζ is always larger than unity.

As for the second term on the left-hand-side of 6.7, given that in equilibrium $\hat{w} = \hat{w}(H)/\hat{w}(L) > 1$, it is clear that this term is also always larger than unity. As a result, therefore, the case $\hat{y}_i > \hat{y}_j$ requires that:

$$\frac{\hat{H}r_i}{\hat{L}_i} > \frac{\hat{H}r_j}{\hat{L}_j}$$

proving that the more innovative region, being the region relatively more specialised in research, enjoys a permanently higher level of per capita income.

6.1.3 Regional Per Capita GDP Growth Rates

Finally, as far as the growth rate of per capita income is concerned, from equations 6.1 and 6.2 it is possible to derive the proportional growth rates:

$$\frac{\dot{\hat{y}}_i}{\hat{y}_i}=\frac{\frac{\dot{\hat{w}}(L)}{\hat{w}(L)}\frac{1}{\hat{w}(H)}\hat{L}_i+\frac{\dot{\hat{w}}(H)}{\hat{w}(H)}\frac{1}{\hat{w}(L)}\hat{H}q_i+\zeta\frac{\dot{\hat{w}}(H)}{\hat{w}(H)}\frac{1}{\hat{w}(L)}\hat{H}r_i}{\frac{1}{\hat{w}(H)}\hat{L}_i+\frac{1}{\hat{w}(L)}\hat{H}q_i+\zeta\frac{1}{\hat{w}(L)}\hat{H}r_i}$$

and

$$\frac{\dot{\hat{y}}_j}{\hat{y}_j}=\frac{\frac{\dot{\hat{w}}(L)}{\hat{w}(L)}\frac{1}{\hat{w}(H)}\hat{L}_j+\frac{\dot{\hat{w}}(H)}{\hat{w}(H)}\frac{1}{\hat{w}(L)}\hat{H}q_j+\zeta\frac{\dot{\hat{w}}(H)}{\hat{w}(H)}\frac{1}{\hat{w}(L)}\hat{H}r_j}{\frac{1}{\hat{w}(H)}\hat{L}_j+\frac{1}{\hat{w}(L)}\hat{H}q_j+\zeta\frac{1}{\hat{w}(L)}\hat{H}r_j}.$$

Given that all wages grow at the same constant rate at which abstract knowledge grows, it follows immediately from the last two equations that in equilibrium per capita GDP grows in both regions at the same constant rate as all other variables:

$$\frac{\dot{\hat{y}}_i}{\hat{y}_i}=\frac{\dot{\hat{y}}_j}{\hat{y}_j}=\frac{\dot{A}}{A}.$$

6.2 Effects of Integration

In the long-run, the two-region system described above reaches a stable equilibrium in which the more innovative region enjoys a permanently higher level of per capita GDP. An important policy question is whether a process of integration tends to reduce the pre-existing differential between regional per capita incomes. Policies favouring factor mobility, interventions aimed at the reduction of national barriers and, above all, investments in transport infrastructure all have the effect of decreasing the cost of physical distance between locations. Within the framework developed here, therefore, part of the effects of the integration process undergone in the EU in the last decades can be conveniently analysed considering negative variations in the cost of physical distance d_{ij}.

6.2.1 Effect of Integration on the Localisation of Economic Activities

Again assume, without loss of generality, that region i is the more innovative region so that $\delta_i > \delta_j$ and $\delta_{\text{technological leader}} = \delta_i$. The effect of integration on the localisation pattern of research activities can be analysed considering the partial derivative of the equilibrium allocation of human capital in research with respect to the cost of physical distance:

$$\frac{\partial \dfrac{\hat{H}r_i}{\hat{H}r_j}}{\partial d_{ij}} = (1-\phi)^{-1} \frac{\ln \dfrac{\delta_i}{\delta_j}}{\ln \dfrac{\delta_i}{\delta_j} + \ln d_{ij}} d_{ij}^{-(1-\phi)^{-1} \frac{\ln \frac{\delta_i}{\delta_j}}{\ln \frac{\delta_i}{\delta_j} + \ln d_{ij}} - 1} \left(\frac{\delta_i}{\delta_j} \right)^{(1-\phi)^{-1}} \left(\frac{\ln d_{ij}}{\ln \dfrac{\delta_i}{\delta_j} + \ln d_{ij}} - 1 \right).$$

Given that $\delta_i > \delta_j$, the last term of this partial derivative has always a negative sign whilst all the other terms are positive, implying that a reduction in the cost of physical distance produces an increase in the ratio $\hat{H}r_i / \hat{H}r_j$. A process of integration that causes a reduction in the cost of distance will therefore have the effect of favouring the concentration of research activity in the already more innovative region. Moreover, from equation 6.5 it follows that:

$$\frac{\partial \dfrac{\hat{L}_j}{\hat{L}_i}}{\partial d_{ij}} = \frac{\dfrac{\hat{H}r_j}{\hat{H}r_i} \ln \hat{H}r_j \dfrac{\partial \dfrac{\hat{H}r_i}{\hat{H}r_j}}{\partial d_{ij}} + \left(\dfrac{\hat{H}r_i}{\hat{H}r_j} + 1 \right)^2 \hat{H}r_j^{-1} \ln \dfrac{\hat{H}r_i}{\hat{H}r_j} \dfrac{\partial \dfrac{\hat{H}r_i}{\hat{H}r_j}}{\partial d_{ij}}}{\left(\ln \hat{H}r_j \right)^2}$$

which is always negative since the partial derivative of $\hat{H}r_i / \hat{H}r_j$ with respect to d_{ij} is negative. In other words, a reduction in the cost of physical distance between the regions produces an increase in the concentration of manufacturing activities in the less innovative region.

6.2.2 Effect of Integration on Regional Levels of Per Capita GDP

The effect of the integration process on the relative levels of per capita GDP can be analysed through it effects on the inequality in 6.7: since $\hat{w}$, ζ, and $\hat{H}q / \hat{L}$ are independent of d_{ij}, the sign of the effect of a change in the cost of distance can be conveniently evaluated by studying the sign of the effect on the difference

$$\left(\frac{\hat{H}r_i}{\hat{L}_i} - \frac{\hat{H}r_j}{\hat{L}_j} \right);$$

an increase in the above difference necessarily leads to an increase in the ratio $\hat{y}_i / \hat{y}_j$. Since it has just been shown that a reduction in the cost of physical distance increases the relative specialisation in research if the more innovative region it follows that the above difference also increases. This implies that a process of integration that reduces d_{ij} fosters, rather than reduces, the existing differences in per capita GDP levels.

6.2.3 Effect of Integration on the Growth Rate of the System

In a similar fashion, the effect of integration on the growth rate of the system can be determined studying the derivative

$$\frac{\partial \frac{\dot{A}}{A}}{\partial d_{ij}} = \frac{\partial \frac{\dot{A}_i}{A_i}}{\partial d_{ij}} + \frac{\partial \frac{\dot{A}_j}{A_j}}{\partial d_{ij}}$$

which is equal to:

$$\delta_j \left(\frac{\hat{H}r_i}{\hat{H}r_j} + 1 \right)^{-(1-\phi)} \hat{H}r^{2+\phi} d_{ij}^{-\beta_{ij}^{-1}} \left\{ -\beta_{ij}^{-1} \frac{\hat{H}r_i}{\hat{H}r_j} d_{ij}^{-1} + \left[1-(1-\phi) \frac{\hat{H}r_i}{\hat{H}r_j} \left(\frac{\hat{H}r_i}{\hat{H}r_j} + 1 \right)^{-1} \right] \frac{\partial \frac{\hat{H}r_i}{\hat{H}r_j}}{\partial d_{ij}} \right\}.$$

Since the ratio $\hat{H}r_i \big/ \hat{H}r_j$ increases as d_{ij} decreases, the above derivative presents always a negative sign. Consequently, a process of integration that reduces the cost of physical distance between regions has the important effect of boosting the equilibrium growth rate of the system.

To sum up, it has been shown in this section that a process of integration implemented through policies that reduce the cost of people's interactions has the effect of shifting upwards the balanced growth path of the system. This new growth path, however, is characterised by a further concentration of research activities in the more innovative region and of manufacturing activities in the other region which leads to a parallel increase in the existing disparities in regional per capita GDP.

6.3 Generalisation of the Results

The above results are based on the assumption that the levels of technological competence in research across the system remain unaffected by the process of integration. Clearly, a process of integration that reduces the cost of distance between locations and, consequently, increases the probability of fruitful interaction among researchers, might have an influence on the levels of the technological competencies in research. In particular, it is possible that this increase of interaction could enable a speedier and more effective adoption of successful procedures developed in the regions characterised by a superior technological competence in research.[1] If this is the case, a process of integration could modify the ratio between regional competencies in research and hence have important repercussions for the predictions of the model with respect to convergence. As is clear from the analysis carried out in the previous chapter, the prediction that the integration process would determine an increase in the existing disparities in regional per capita incomes is a consequence of the fact that integration leads to a concentration of research activities in the more innovative region. To understand how this result would be affected by the introduction of a relationship between the cost of distance between regions and regional technological competencies in research it is therefore possible to concentrate on equation 5.27 which describes the allocation of human capital among research sectors. Before doing this, however, it is necessary to enrich the model structure by interpreting the cost of distance d_{ij} as an index combining two different dimensions of distance, the physical dimension and the cultural-institutional dimension. Integration could then result from either a reduction of travel distance, t_{ij}, or from an increase in the degree of cultural-institutional homogeneity between the regions, Ω_{ij}, or both. This index could then take on the following functional form:

$$d_{ij} = e^{t_{ij}} - \ln \Omega_{ij} \tag{6.8}$$

so that d_{ij} ranges between 1, in the case of no travel distance and perfect cultural-institutional homogeneity, and infinity when either t_{ij} tends to infinity or the two regions are perfectly heterogeneous or both.

Also the evolution of the regional technological competencies in research must be modelled to take into account the influence of the two dimensions of distance. This can be done by defining the technological competence in research according to the following equation

$$\delta_i = \kappa_i + \left(\kappa_i + \kappa_j\right)\frac{1}{2 - \ln \Omega_{ij}} + \max\left(\kappa_j - \kappa_i, 0\right)\frac{\Omega_{ij}}{1 + t_{ij}} \tag{6.9}$$

where κ_i and κ_j represent the components of regional technological competence in research which are independent of both travel distance and cultural-institutional homogeneity. The second term in the equation represents the component that depends on the degree of cultural-institutional homogeneity within the system. The last term represents the margin of improvement enjoyed by the region that starts with an inferior technological competence in research; this depends on the initial gap, on the degree of cultural-institutional homogeneity and on the travel distance between regions. Clearly, the lower the degree of institutional and cultural heterogeneity within the system and the higher the travel distance, the lower the ability of the region that starts with an inferior technological competence in research to learn from the more advantaged region. In contrast, within a highly homogeneous system whose agents share similar languages, traditions and institutions, and in which travel distances are relatively short, the region that starts with an inferior technological competence is better able to reduce the technological competence gap that separates it from the other region.[2]

The effect of a reduction in the cost of distance on the equilibrium allocation of human capital between the two research sectors and, consequently, on the relative levels of per capita GDP can now be analysed using simulations.[3] The first example corresponds to the case of a system in which the degree of cultural-institutional

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[1] I am indebted to Francesco Pigliaru for suggesting this point.

[2] If one were to account for the different specification of technological competence in research entailed by the evolutionary approach presented in Section 5.2.3, the following definition of the margin of improvement characterising a RIS, χ, should be substituted into equation 5.2:

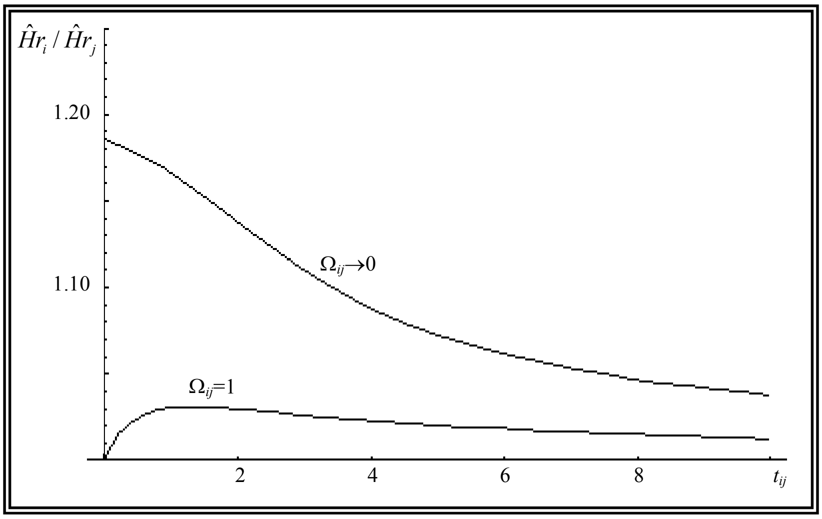
$$\chi_i = \left(\iota_i + \iota_j\right)\frac{1}{1 - \ln \Omega_{ij}} + \max\left(\iota_j - \iota_i, 0\right)\frac{\Omega_{ij}}{1 + t_{ij}}$$

[3] Although it could be possible to present the results of the effects of integration in analytical form, this would be quite difficult and make the presentation extremely heavy. Given the small number of

homogeneity is given and in which integration takes place through a reduction of travel costs. This example is intended to represent the possible consequences of the integration process that has taken place within Europe during the 1980s, in which concrete steps were taken to reduce existing barriers for people and goods travelling across the Union leading to sizeable reductions in travel times between locations, but in which very little was achieved in terms of reducing the degree of heterogeneity characterising the Union from a cultural and institutional point of view.

Figure 6.1 describes the evolution of the allocation of human capital in research for variations in transport costs when $\kappa_i = 0.02$ and $\kappa_j = 0.01$, $\phi = 0.3$, whilst Figure 6.2 considers the case in which $\kappa_i = 0.05$ and $\kappa_j = 0.01$.

Figure 6.1 The Effect of Variations in Transport Costs ($\kappa_i = 0.02$ and $\kappa_j = 0.01$)

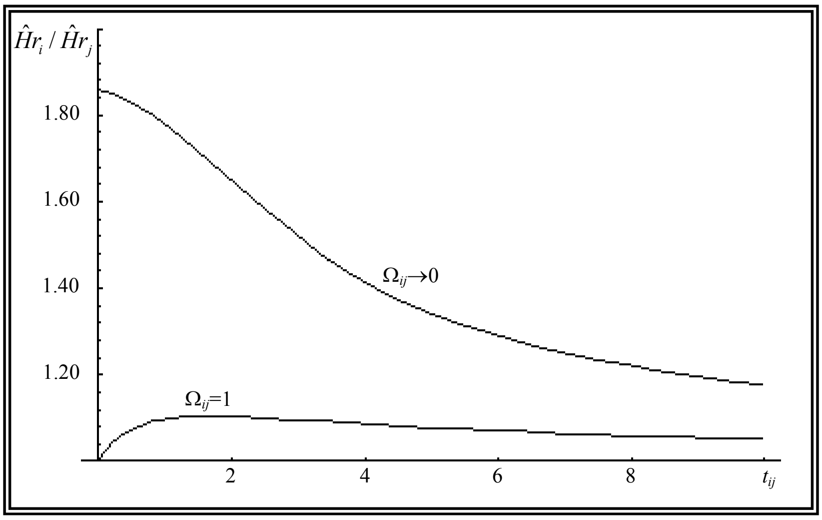


In both figures, the upper curve represents the case in which the system is characterised by absolute heterogeneity from a cultural-institution point of view. In this situation, any reduction of the effective travel distance within the system leads to an increase in the existing regional disparities in per capita income by causing a further concentration of research activities within the more innovative region.

parameters involved, simulation makes it possible to explore the model quite thoroughly and convey the results in a much more intelligible and effective way.

The lower curve represents the alternative case of perfect homogeneity from a cultural-institutional point of view. In such a situation, the overall result of an integration process reducing the effective travel costs is quite different: although the reduction of travel costs might induce an increase in regional disparities when the travel distances are still large, this effect is of limited extent compared to the previous case and, more importantly, is substituted by a convergence process as travel costs are further reduced.

Figure 6.2 The Effect of Variations in Transport Costs (κ_i = 0.05 and κ_j = 0.01):



Within this framework, it is now possible to consider the specific case of the EU, a system characterised by a remarkable heterogeneity of its components. Not only is the Union constituted by Member States characterised by extremely different cultural and institutional identities, but even within each component country there is obvious and extensive cultural and institutional variety. This heterogeneity is so great that individual countries often may appear to represent more as compromises between differences that are deeply rooted in their histories than as homogeneous entities. Therefore, it seems appropriate to describe the European situation as one in which the degree of homogeneity is rather low. The middle curve in Figures 6.3 and 6.4 describes the evolution of the equilibrium allocation of human capital in research for changes in travel costs when the degree of homogeneity in the system is assumed to take on a value of 0.2. A process of integration that reduces travel costs is therefore likely to result in an increase in existing disparities in per capita GDP through an increasing concentration of research in the more advanced region.

Figure 6.3 The European Case (κ_i = 0.02 and κ_j = 0.01)

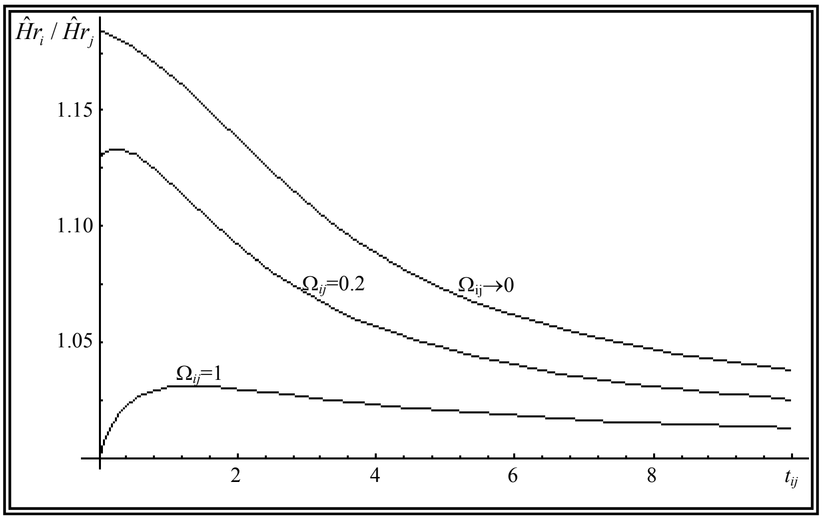
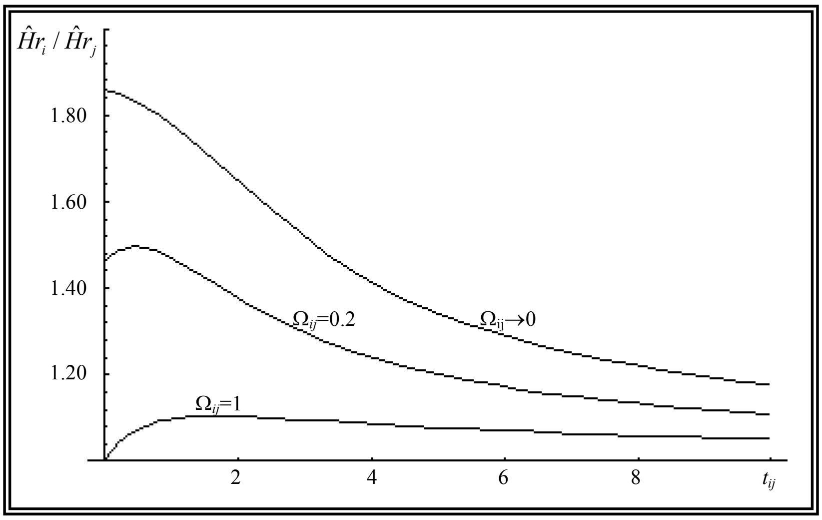


Figure 6.4 The European Case (κ_i = 0.05 and κ_j = 0.01)



The increase in disparities seems noticeable given that the ratio $\hat{H}r_i \big/ \hat{H}r_j$ passes from a value of 1.03 for t_{ij} = 10 to a value of 1.13 for t_{ij} = 0 when κ_i = 0.02; and from a value of 1.11 to a value of 1.46 when κ_i = 0.05. Although the two curves both present a maximum for positive values of t_{ij} (1.13 at t_{ij} = 0.26 when κ_i = 0.02 and

1.50 at $t_{ij} = 0.45$ when $\kappa_i = 0.05$) suggesting the possibility of a convergence process, it is clear that this process is quite limited in scope and confined to low levels of travel cost. In other words, according to the theoretical model developed here, a process of integration that takes the form of a reduction of travel costs within a system characterised by a relatively low degree of cultural and institutional homogeneity, leads to an increase in the growth rate of per capita income for the system as a whole at the expenses of an increase of income disparities across regions.

The way to promote growth while avoiding such an increase in disparities or, depending on the system's features, even reducing them, is by means of a more complex form of integration that not only reduces barriers to mobility but primarily aims at increasing the degree of cultural and institutional homogeneity within the system. Indeed, by increasing the level of Ω_{ij}, it is not only possible to shift the curve describing the equilibrium allocation of human capital in research downwards, but also to change its shape in such a way as to increase the probability that further reductions of travel cost will lead to a reduction, rather than an increase, of existing per capita income disparities. The effects of increases in the degree of cultural-institutional homogeneity on the equilibrium allocation of human capital in research are described in Figures 6.5 and 6.6. Clearly, any increase in the degree of cultural-institutional homogeneity within the system implies a reduction in the level of per capita income disparities through a reduction of concentration of research activities in the more innovative region.

Moreover, the comparison between Figures 6.5 and 6.6 shows that the extent to which an increase in the degree of homogeneity determines a reduction in the concentration of research activities in the leading region and hence promotes a reduction in per capita income disparities significantly depends on the ratio between κ_i and κ_j. Indeed, for κ_i=0.05 and κ_j=0.01, an increase of Ω_{ij} from 0.2 to 0.4 generates a reduction of $\hat{H}r_i \big/ \hat{H}r_j$ from 1.201 to 1.151 (-4.2%); the same increase in the degree of homogeneity when ι_i=0.02 leads to a reduction of $\hat{H}r_i / \hat{H}r_j$ from 1.050 to 1.037 (-1.2%).

Figure 6.5 Variations in Cultural-Institutional Homogeneity (t_{ij}=5;κ_i=0.02;κ_j=0.01)

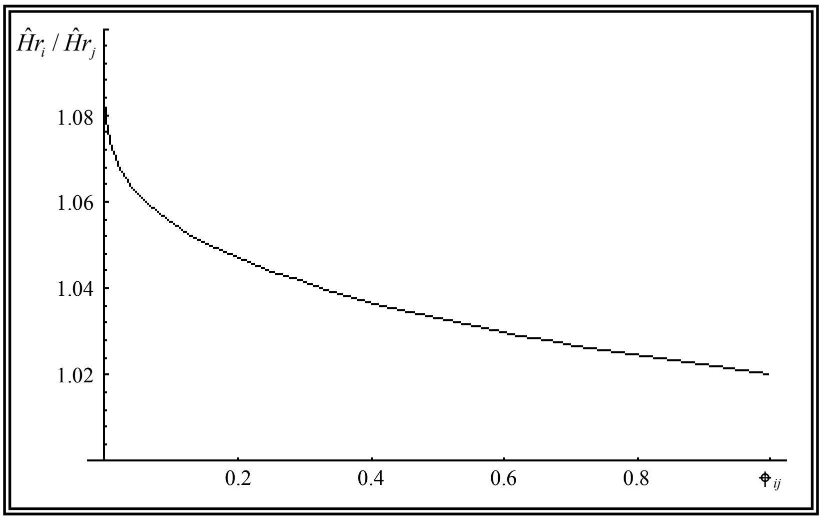
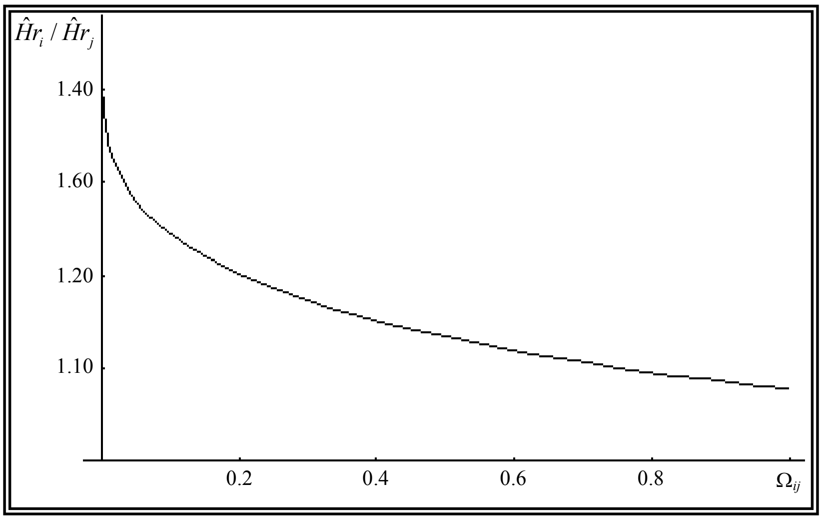
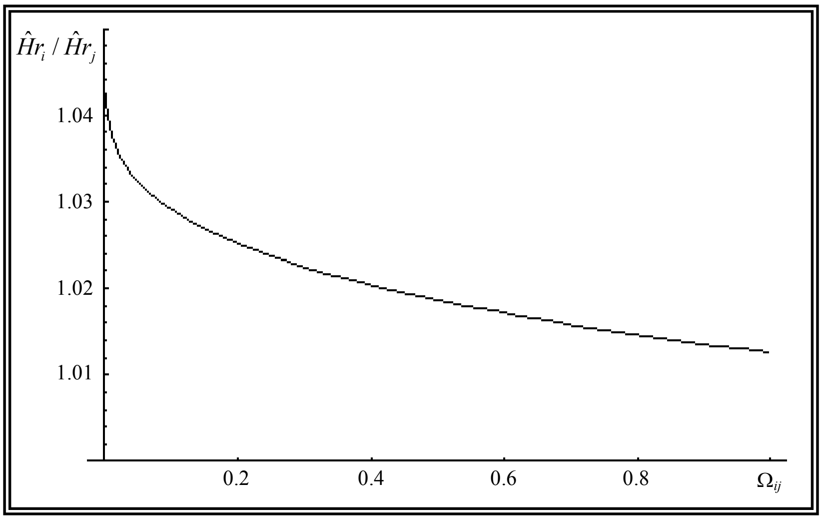


Figure 6.6 Variations in Cultural-Institutional Homogeneity (t_{ij}=5;κ_i=0.05;κ_j=0.01)



Similarly, the extent of the reduction in disparities following an increase in the degree of homogeneity depends on the value of the travel distance. For instance, when t_{ij}=10 and ι_i=0.02, the same increase in Ω_{ij}, that is from 0.2 to 0.4, produces a 0.5% reduction of $\hat{H}r_i / \hat{H}r_j$ from 1.025 to 1.020 (Figure 6.7).

Figure 6.7 Variations in Cultural-Institutional Homogeneity (t_{ij}=10;κ_i=0.02;κ_j=0.01)



6.4 Concluding Remarks

Two basic results of the model should be emphasised. Firstly, even within a system that retains many of the typical neoclassical assumptions, the perfect foresight equilibrium of the model may be characterised by the presence of permanent differences in per capita income levels. By resorting to a definition of research activities that recognises the important role played by spillovers of both tacit and abstract knowledge, the explanation suggested here is that income disparities owe their existence to a process of regional specialisation between 'knowledge creating' and 'knowledge applying' regions.

The ability to innovate within a regional economy depends on the interaction between the macro-economic system and the different factors shaping the RIS. The result is the development of a location-specific ability to innovate which has been referred to as the regional technological competence in research. Those regions which are better able to innovate through the development of a superior technological competence in research will be characterised by a relative specialisation in research activities and thus become ‘knowledge creating’ regions. Since research activities tend to make a more intensive use of human capital than manufacturing activities, the process of concentration of research in one location leads to a parallel concentration of human capital. Moreover, since wages for human capital tend to be higher than wages for unskilled labour, the concentration of human capital in one region implies that the average level of per capita income in this ‘knowledge creating’ region will be higher than that in the ‘manufacturing’ region.

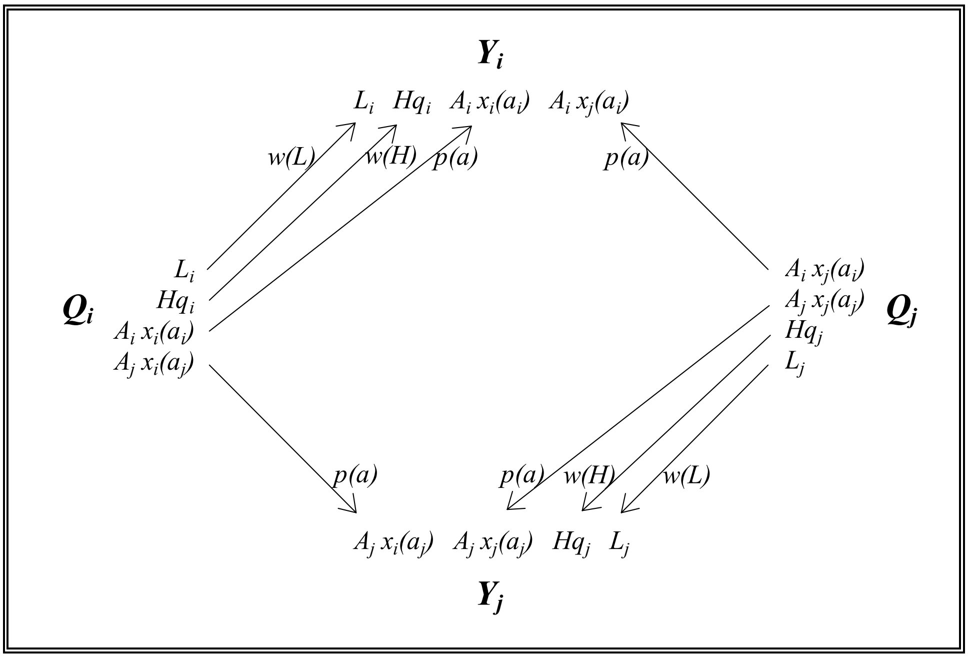
Secondly, the model also offers a possible explanation of the effects of a process of integration on the existing disparities within the EU. Indeed, a process of integration that produces a reduction in the cost of physical distance can improve the rate at which the economic system as a whole grows in the long-run. The price to pay, however, might be represented by an increase in regional differentials. By enhancing the attractiveness to research activities of the more innovative regions, integration might therefore cause a further concentration of research within these regions and exacerbate existing income disparities rather than reduce them. The new steady-state equilibrium growth path is characterised by faster growth, but also by an increased gap in the levels of per capita income. The transition towards this new equilibrium therefore witnesses different regional rates of per capita income growth, with the more innovative regions performing best. In the long-run, regional rates of per capita income growth converge to a common constant rate again and the ratio of regional levels of per capita income stabilises, but to a higher value than the one that existed before integration.

Appendix

A6.1 Distinction Between Regional Product and Regional GDP

As shown in Figure A6.1.1, in order to achieve the level of production Q_j in region j, A_i intermediate inputs are imported from region i. In equilibrium, the quantity $\hat{x}_j(a)$ of each of these inputs is imported at the unit price $\hat{p}(a)$. Of the total revenues from the sale of each intermediate input, a part γ is used to remunerate the variable costs of production, while the remaining 1-γ is used to remunerate the fixed cost represented by the development of the relative patent.

Figure A6.1.1 Distinction Between Regional Product and Regional GDP



Similarly, intermediate input producers in region j receive the sum $A_j\,\hat{x}_i(a_j)\,\hat{p}(a)$ a part of which is used to compensate the variable manufacturing costs and the other the research effort.

In more formal terms, the level of GDP of one region is the summation of the Value Added (VA) produced by its three sectors:

$$\text{GDP} = \text{VA}_{\text{Research}} + \text{VA}_{\text{Intermediate Goods}} + \text{VA}_{\text{Final Goods}}$$

Considering, for instance, the case of region i, the Value Added produced by its research sector is just the wage rate multiplied by the level of human capital being employed or, equivalently, the number of patents realised multiplied by the patent's price:

$$\text{VA}_{\text{Research,i}} = w(H)\,\hat{H}r_i = \hat{P}(a)\,\dot{A}_i\,.$$

The Value Added produced by region's i intermediate goods sector is equal to the total value of its output net of the fixed costs of the patents:

$$\text{VA}_{\text{Intermediate Goods,i}} = \hat{p}(a)\,A_i\left[\hat{x}_i(a_i) + \hat{x}_j(a_i)\right] - \hat{P}(a)\,\dot{A}_i\,.$$

Finally, the Value Added of the final goods sector is given by the total value of the output net of the cost of the intermediate goods used in the production:

$$\text{VA}_{\text{Final Goods,i}} = \hat{Q}_i - \hat{p}(a)\,A_i\,\hat{x}_i(a_i) - \hat{p}(a)\,A_j\,\hat{x}_i(a_j)\,.$$

Recalling that the final goods sector is in perfect competition and, therefore, the remuneration of the three production factors exhausts the value of the product,

$$\hat{Q}_i = w(L)\,\hat{L}_i + w(H)\,\hat{H}q_i + \hat{p}(a)\,A_i\,\hat{x}_i(a_i) + \hat{p}(a)\,A_j\hat{x}_i(a_j)$$

it is easy to show that the level of GDP in region i is equal to:

$$\hat{Y}_i = \hat{w}(L)\,\hat{L}_i + \hat{w}(H)\,\hat{H}q_i + \hat{p}(a)\,A_i\,\hat{x}_i(a) + \hat{p}(a)\,A_i\,\hat{x}_j(a)\,.$$

Chapter 7
An Empirical Test of the Main Predictions of the Theoretical Model

7.1 Introduction

In order to guide the empirical analysis, it is useful first to summarise the main predictions of the theoretical model elaborated in the previous chapter. The model presents a stable equilibrium characterised by permanent differences in per capita income levels. By resorting to a definition of research activities that recognises the important role played by spillovers of both tacit and abstract knowledge, it is suggested that regional specialisation between 'knowledge creating' and 'knowledge applying' regions represents an important factor in shaping income disparities across space. The ability to innovate within a regional economy depends on the interaction between the macro-economic system and the different factors shaping the RIS. The result is the development of a location-specific ability to innovate which has been referred to as the regional technological competence in research. Those regions which are better able to innovate through the development of a superior technological competence in research will be characterised by a relative specialisation in research activities and thus become 'knowledge creating' regions. Since research activities tend to make a more intensive use of human capital than manufacturing activities, the process of relative concentration of research in one location leads to a parallel relative concentration of human capital. Moreover, since wages for human capital tend to be higher than wages for unskilled labour, the relative concentration of human capital in one region implies that the average level of per capita income in this 'knowledge creating' regions will be higher than that in 'manufacturing' regions.

The model also offers a possible interpretation of the effects of the process of European integration on disparities in per capita income. Indeed, a process of integration similar to the one that has characterised recent European history, by reducing the cost of physical distance, would produce an increase in the rate at which the European economic system grows in the long-run. At the same time, however, given that the reduction in the cost of distance has been achieved primarily through a reduction of travel time between locations but with little improvement in the degree of cultural and institutional homogeneity of the system, and given the high level of cultural-institutional heterogeneity characterising the European system, the price to pay might be represented by an increase in regional differentials. In such a situation, even though integration may reduce existing gaps in regional levels of technological competence in research, disparities in per capita income are likely to widen (Figures 6.3 and 6.4). In other words, the model would predict that the integration process would produce a new steady-state equilibrium characterised by a further concentration of research activities in the regions which already were relatively more specialised in research. During the transition towards this new equilibrium per capita income growth rates differ across regions. While the adjustment takes place through the reallocation of unskilled labour and human capital, average per capita income in the more innovative, relatively more research-intensive region grows at a faster rate than in the other region.

The aim of the present chapter is to test this prediction. In particular, the growth process of the 122 major European FURs is studied in terms of its fundamental determinants as have been outlined in the previous chapters. In order meaningfully to assess the role of research activity in the growth process it is necessary to consider a fully specified model, capable of accounting for the diverse regional structures.[1] Therefore, alongside variables strictly related to research activities several structural variables appear in the specification. Moreover, some of the structural variables also constitute proxies for factors influencing regional growth prospects through the pattern of evolution of regional competence in research (see Chapter 5 and, in particular, Figure 5.1).

As in the study on convergence presented in Chapter 4, the period covered by the analysis goes from 1979 to 1990. This period conforms to two fundamental requirements. Firstly, as was argued above, the period of analysis is long enough to allow for cyclical movements around the growth trend. Secondly, this is a period in which the European system underwent important steps in its process of economic integration[2].

7.2 The Variables of the Empirical Model

The dependent variable is the growth rate of per capita GDP in each FUR calculated over the period 1979-1990. The formula for the growth rate is the traditional logarithmic transformation of the ratio of regional per capita GDP at the two extremes of the period of analysis:

$$\mathrm{GROWTH}_i = \frac{1}{11}\ln\left(\frac{y_{i,1990}}{y_{i,1979}}\right).$$

The fundamental independent variables of the empirical model relate to the activity of research performed in the regions. Indeed, on the basis of the theoretical analysis it has been emphasised that the regions which are relatively specialised in research activities are expected to grow faster than regions specialised in manufacturing activities. However, according to equation 5.4,

$$\dot{A}_i = \delta_i Hr_i\ Hr_i^{\phi}\left(\ Hr_j\ d_{ij}^{-1/\beta_{ij}}\right)A$$

it is not only the level of research activity carried out within one region that matters but also the level of knowledge spillovers which benefit the region. In particular, three different sources of spillovers have been identified. Whilst all regions take advantage of a-spatial spillovers of abstract technological knowledge, two forms of spatial spillovers benefit the regions in an asymmetric fashion. The level of research activity carried out within the region and the spatial concentration of this activity determines the force of the intra-regional spillover of tacit knowledge. In addition,

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1 A similar point is made by Cheshire and Carbonaro (1995) with respect to the interpretation of the estimated speed of convergence in 'mainstream empirical analyses'.

2 In the evolutionary perspective, this period would correspond to the dominance of the "information based" paradigm, established during the 1970s (Freeman and Perez 1988).

the level of activity in neighbouring regions, together with their physical and technological distances, shapes the strength of inter-regional spillovers of tacit knowledge.

Whilst a-spatial spillovers, accruing to all regions in the same way, are not of interest when the relative performance of the regional economies is concerned, the other forms of spillovers are essentially spatially asymmetric and must be taken into account. An attempt is therefore made here to estimate the total effect of research activity on the growth performance of the region by considering both intra- and inter-regional spillovers of tacit knowledge. Ideally, this would require data for the level of employment in research activities in all the regions at the beginning of the period of analysis as well as data for technological and physical distances. Unfortunately, however, such data are not available and it has been necessary to resort to proxies. In particular, the level of regional research activities is here measured by the number of research and development (R&D) laboratories located in the region at the beginning of the period and belonging to corporations which appear in the Fortune top 500 lists.[3] The data on the laboratories and their location has been collected on the basis of the *Directory of the European Research Centres* published in 1982. To represent relative concentration in research activities within the region, the number of R&D laboratories has been expressed per unit population. As pointed out by Cheshire and Carbonaro (1995 and 1996), who employ similar data for a more recent year, this is only a crude measure of the theoretically appropriate variable. It seems however able to provide a general indication on the role of the relative specialisation in research and on the extent of the spatial spillovers of knowledge.

To obtain an estimate of the parameter ϕ measuring the strength of the intra-regional spillovers, the R&D variable has been divided by the area of the region. As for inter-regional spillovers, the initial step has been the calculation of two matrices of time distances (expressed in minutes) between each pair of FURs. The first matrix reports time distance by road between FURs, whilst the second matrix reports the shortest

[3] Both "the 500 largest industrial corporations in the US" list and "the 500 largest industrials outside the US" have been used for the period 1979-1983.

time distance when a choice between aeroplane and road is available.[4] Given the importance of air transport infrastructure for regions with a stronger commitment to research-intensive activities (emphasised by many empirical studies of European urban regions; see, for example, Andersson *et al* 1990; Batten 1995), this second matrix has then been used in the estimation of the inter-regional spillovers of knowledge. A proxy for the technological distance between pairs of FURs, β_{ij}, has then been calculated on the basis of equation 5.5

$$\beta_{ij} = 1 + \frac{\ln\left(\dfrac{\delta_{\text{technological leader}}}{\delta_i}\right)}{\ln d_{ij}}$$

where the relative levels of technological competence in research have been estimated using data on regional technological creativity for the early 1980s derived by Åke Andersson and reported by Batten (1995).

To sum up, a first set of variables is used in the empirical analysis to account for the role of research activity and spatial spillovers of tacit knowledge. More details on these variables are reported in Table 7.1.

Table 7.1 Research and Development Variables

Variable	Spatial Spillovers	Distance Threshold
R&D	No	-
R&DS1	Yes	90 minutes
R&DS2	Yes	110 minutes
R&DS3	Yes	115 minutes
R&DS4	Yes	120 minutes
R&DS5	Yes	125 minutes
R&DS6	Yes	130 minutes
R&DS7	Yes	150 minutes

The first of this variables, labelled R&D, simply reflects the relative concentration of research without allowing for spatial spillovers. The other variables, R&DS1 to R&DS7, consider both types of these spatial effects and allow for different distance ranges over which inter-regional spillovers are calculated. The *a priori* expectation is that, whilst all variables should be positively related with per capita GDP growth,

4 Details on the calculation of the distances are provided in the Data Appendix.

those allowing for spatial spillovers should be statistically more significant and improve the overall performance of the model. The statistical significance of these variables, together with the measure of fit of the resulting models, will then be used to identify the distance range over which the inter-regional spillovers appear to be strongest.

A second set of variables has been introduced in the empirical analysis in order to reflect the local factors shaping the RIS which in turn determine the regional level of technological competence in research, δ, and, most importantly, its likely evolution. Although not all the factors outlined in Figure 5.1 can be explicitly considered here due to data availability problems, it is nonetheless possible to take into account some of the most relevant ones.

As pointed out in Chapter 5, universities both produce education, and therefore influence the quality of the human capital available to firms, and also engage in research activities and produce knowledge. Universities are therefore an essential feature of the RIS and their influence on the evolution of regional technological competence in research must be accounted for. This is done by considering the number of academic staff employed in universities, higher and further education institutions in the academic year 1976-1977. Clearly, this variable is expected to play a positive role in the economic performance of the region.

Regional performance is influenced by the structure of the local industrial sector. The variables COAL and PORT are intended to account for those industries which are likely to play a particularly negative influence on the growth prospects of the local economies or, in other words, aim to identify "old industrial regions suffering from industrial decline and employment loss" (Objective 2 regions). As pointed out by Cheshire and Carbonaro (1995), the presence of coal mining should adversely affect local growth prospects for a considerable period of time even after this industry has ceased to account for a substantial share of employment. Consequently, the influence of the coal industry is allowed for through a dummy variable related to the coincidence of the area of the FUR with a coalfield as defined in the Oxford Regional Economic Atlas (1971).

The second variable reflects the size of the port industry, as measured by the amount of freight handled in 1978. On the one hand, dramatic developments in transport technology and, particularly, the introduction of containerisation and roll-on roll-off ferries have greatly reduced the attractiveness of port locations for processing activities. This shock therefore should have negatively affected all ports according to their size during the period under analysis. On the other hand, however, the transformation in the industry is likely to have led to a re-organisation of the traffic flows and, therefore, to an increase in the degree of competition among existing ports. Large ports, thanks to their economies of scale, might have been able to take advantage of the process of re-organisation and increased their share of traffic over total flows at the expense of smaller ports. As a result, the relation between port size and growth of per capita income in the region is likely to be quadratic rather than linear.

Another relevant feature of the local industrial structure concerns the relative importance of the service sector due to the role played by the variety of business services in providing firms with market, financial and commercial knowledge. This factor is measured as the percentage share of employment in service activities over employment in services and manufacturing in 1980, and is expected to be positively related to per capita GDP growth.

An interesting issue related to the local industrial structure concerns the question of whether local ability to innovate is promoted by industrial specialisation, thanks to intra-industry spillovers, or rather by industrial diversity and inter-industry spillovers. As explained in Chapter 5, the theoretical model developed here does not provide any indication of the relative importance of these two possibilities, but rather leaves the question open to empirical investigation. The degree of specialisation of the regional economies is then measured on the basis of data on employment for 9 industrial sectors.[5] Employment in each regional sector is expressed as a percentage of total employment in regional industry. After ranking the sectors by size, the index of regional specialisation is calculated as the ratio between the overall percentage share of employment in the smallest four regional sectors, over the overall percentage share of employment in the largest four ones. Thus, if $e_{s,i}$ denotes the share of employment in the s^{th} smallest sector of region i (with $s = 0, \ldots, 9$), the index of industrial specialisation can be expressed as

$$specialisation = \frac{\sum_{s=1}^{4} e_{s,i}}{\sum_{s=6}^{9} e_{s,i}}$$

The index, therefore, ranges between 0 and 1, these two extremes indicating respectively specialisation and diversity in the regional industrial structures.

The variable AGR is the share of employment in agriculture in 1975, in the wider NUTS2 region. This variable therefore focuses on “Objective 5b” and, at least partially, “Objective 1 regions”. Similarly to Cheshire and Carbonaro (1995 and 1996), it is argued that the relation between FUR growth in per capita GDP and specialisation in agriculture in the NUTS2 region should be quadratic. Economic growth in FURs surrounded by regions most specialised in agriculture should be relatively slow because rural-urban migrations of unskilled workers from the countryside are likely to lead to population increasing faster than output and falling average levels of human capital. At the other extreme, FURs located in the most densely urbanised regions would suffer from congestion and other environmentally related problems and therefore could find it difficult to attract human capital.

A second variable that more directly considers the quantity and quality of the local supply of space suitable for economic activities is represented by the density of the population in the FUR area in 1981. Density – other things being equal – could be considered as a proxy for land rent. At the same time, urban areas have witnessed a rapid increase in traffic levels that in many cases has led to acute congestion

5 The breakdown of the sectors is provided in the Data Appendix.

problems. Both factors would suggest population density, measured by the number of habitants per squared kilometre, should be negatively associated with growth.

The variable labelled SDG represents the sum of the difference between the growth rate of a FUR and the growth rates in FURs within a 150 minutes radius. In particular, the variable is calculated as

$$\mathrm{SDG}_i = \sum_j \left(\frac{\frac{\dot{y}_i}{y_i} - \frac{\dot{y}_j}{y_j}}{d_{ij}} \right)$$

where d_{ij} represents the road distance between regions. Moreover, to avoid problems of definitional correlation with the dependent variable, the growth rates are calculated over the period 1979-1985. This variable is introduced in the analysis in order to take into account how spatial adjustment between neighbouring FURs takes place. As explained by Cheshire (1979), adjacent local labour markets tend to interact primarily through adjustment of commuting patterns (see also Evans and Richardson 1981; Burridge and Gordon 1981; Gordon and Lamont 1982; Gordon 1985). As a consequence, a more rapid growth of per capita GDP in one FUR would attract additional in-commuters from surrounding FURs. The effect of such a mechanism is twofold. The first is essentially statistical since the increase in in-commuters changes measured per capita GDP: output, which is measured at workplaces, increases, but resident population does not. The second effect concerns the level of human capital and productivity of the workers employed in the FUR. Since these additional in-commuters are relatively long distance commuters who tend to have higher human capital and productivity, the flow of in-commuters induced by the differential in growth rates is likely to increase the average level of human capital in the recipient FUR. This, in turn, would not only tend to raise output per worker but could have dynamic implications through the intra-regional spillovers of knowledge of the research sector. Because of the combination of both effects, a positive relationship between the growth rate of a FUR and the sum of the differential growth with adjacent FURs is expected.

The variable NFGROWTH reflects the influence of the national macro-economic system. This variable is calculated as the growth rate of per capita GDP in the part of the nation outside its major FURs and takes the place of national dummies in regional 'mainstream empirical analyses' (see, for example Barro and Sala-i-Martin 1991, 1992 and 1995, Sala-i-Martin 1996, and Armstrong 1995a and b). At a sub-national level, empirical analyses have often stressed the specificity of the southern regions of Spain.[6] For instance, in their analysis of the Spanish Provinces, Mas *et al.* (1995) find that growth prospects for the southern agricultural Provinces of Spain are significantly worse than those for northern and eastern part of the country. As a consequence, a dummy variable for the south of Spain is introduced in the model.[7]

7.3 The Results

The empirical model can therefore be summarised as follows:

$$\frac{1}{11}\ln\left(\frac{y_{i,1990}}{y_{i,1979}}\right)=\alpha_0+\alpha\,\mathrm{E}_{i,1979}+\varepsilon_{i,1990} \tag{7.1}$$

where E_{1979} is the vector of explanatory variables just described and ε_{1990} is a vector of random error terms. The results of the OLS cross-sectional estimation of these equations are reported in Table 7.2.

The first version of the model (reported in the first column) makes use of the variable on research activity without considering spatial spillover effects, whilst these effects are instead allowed for in all the other estimated versions. The results appear rather robust in all versions. The $\overline{R}^2$ values range between 0.58 and 0.59, a satisfactory level for a large cross sectional data set. All the expectations on the signs of the coefficients are met, and all coefficients are generally highly significant.

6 A dummy variable for the Italian Mezzogiorno has also been considered. However, the inclusion of this variable has always proven to add no explanatory power to the model.

7 The FURs included in this variable are Alicante, Cordoba, Granada, Malaga, Murcia, and Sevilla.

Table 7.2 The Determinants of per capita GDP Growth in the FURs

	1	2	3	4	5	6	7	8
Constant	0.00718 (0.52)	0.00692 (0.50)	0.00705 (0.51)	0.00743 (0.54)	0.00725 (0.53)	0.00690 (0.50)	0.00713 (0.52)	0.00736 (0.53)
R&D	0.00011 (2.74)	-	-	-	-	-	-	-
R&DS1	-	6.69e-5 (2.81)	-	-	-	-	-	-
R&DS2	-	-	6.02e-5 (2.90)	-	-	-	-	-
R&DS3	-	-	-	5.92e-5 (3.01)	-	-	-	-
R&DS4	-	-	-	-	5.65e-5 (3.00)	-	-	-
R&DS5	-	-	-	-	-	5.19e-5 (3.00)	-	-
R&DS6	-	-	-	-	-	-	4.86e-5 (2.98)	-
R&DS7	-	-	-	-	-	-	-	4.34e-5 (2.95)
University	3.81e-7 (2.22)	4.24e-7 (2.47)	4.23e-7 (2.47)	4.23e-7 (2.48)	4.24e-7 (2.48)	4.17e-7 (2.44)	4.09e-7 (2.40)	4.15e-7 (2.43)
Coal	-0.00296 (-2.31)	-0.00331 (-2.57)	-0.00339 (-2.63)	-0.00336 (-2.62)	-0.00336 (-2.62)	-0.00336 (-2.62)	-0.00339 (-2.64)	-0.00338 (-2.63)
Port	-9.74e-5 (-2.45)	-9.35e-5 (-2.37)	-9.54e-5 (-2.42)	-9.54e-5 (-2.43)	-9.64e-5 (-2.45)	-9.75e-5 (-2.47)	-9.96e-5 (-2.52)	-9.69e-5 (-2.46)
$Port^2$	3.94e-7 (2.20)	3.80e-7 (2.13)	3.89e-7 (2.18)	3.91e-7 (2.20)	3.94e-7 (2.22)	3.97e-7 (2.23)	4.04e-7 (2.26)	3.93e-7 (2.21)
Service	0.01742 (2.21)	0.01726 (2.19)	0.01684 (2.14)	0.01630 (2.07)	0.01655 (2.11)	0.01710 (2.18)	0.01717 (2.19)	0.01682 (2.14)
Specialisation	-0.03957 (-2.53)	-0.04063 (-2.62)	-0.03917 (-2.52)	-0.03907 (-2.52)	-0.03942 (-2.54)	-0.03960 (-2.56)	-0.04015 (-2.60)	-0.04026 (-2.60)
Agriculture	8.99e-4 (4.01)	9.26e-4 (4.09)	9.46e-4 (4.16)	9.55e-4 (4.21)	9.58e-4 (4.21)	9.54e-4 (4.20)	9.50e-4 (4.19)	9.49e-4 (4.18)
$Agriculture^2$	-3.35e-5 (-5.28)	-3.43e-5 (-5.38)	-3.48e-5 (-5.44)	-3.50e-5 (-5.48)	-3.51e-5 (-5.49)	-3.50e-5 (-5.48)	-3.50e-5 (-5.47)	-3.50e-5 (-5.47)
Density	-0.00936 (-3.99)	-0.00952 (-4.06)	-0.00957 (-4.09)	-0.00954 (-4.09)	-0.00957 (-4.10)	-0.00960 (-4.12)	-0.00963 (-4.12)	-0.00959 (-4.11)
SDG	0.19645 (4.93)	0.20122 (5.04)	0.20366 (5.10)	0.20424 (5.13)	0.20538 (5.15)	0.20554 (5.15)	0.20437 (5.13)	0.20251 (5.09)
NFGrowth	1.02707 (6.92)	1.03278 (6.98)	1.03051 (6.98)	1.02832 (6.98)	1.02922 (6.99)	1.03037 (6.99)	1.02888 (6.98)	1.02855 (6.97)
DSE	-0.00936 (-3.99)	-0.00952 (-4.06)	-0.00957 (-4.09)	-0.00954 (-4.09)	-0.00957 (-4.10)	-0.00960 (-4.12)	-0.00963 (-4.12)	-0.00959 (-4.11)
$\overline{R}^2$	0.5812	0.5826	0.5844	0.5866	0.5865	0.5865	0.5860	0.5855

Note: t-ratios are reported within parentheses

The first noticeable result is that all the coefficients for the variables aimed at reflecting the role of R&D activities on per capita GDP growth not only have the expected positive sign but are also highly statistically significant. With all the caveats concerning the measurement of this activity expressed in the previous section, this appears nonetheless a rather encouraging result.

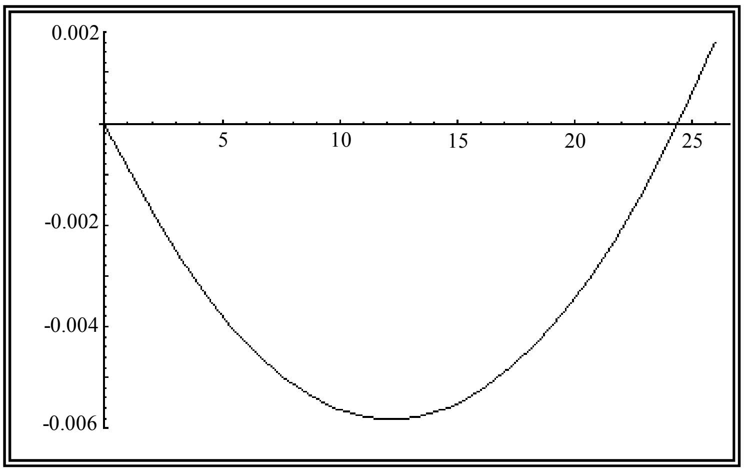
The comparison between the results on the R&D variables for the different models throws light on the role of the spatial knowledge spillovers. Indeed, it is possible to note that the inclusion of the spillovers in the R&D variable generates a generalised improvement in the regression results. Both the $\overline{R}^2$ values and the level of statistical significance of the coefficients for research activities are generally increased when these spatial effects are accounted for. At the same time, the statistical significance of the other variable closely related to innovation activity, the number of university staff, is also substantially improved by the inclusion of these effects. All these results could therefore be interpreted as supporting the view that spatial spillovers of knowledge are an important feature of innovation activities.

Concentrating on those versions of the model that allow for these effects (columns 2-8), it is possible to analyse how the strength of interaction between research sectors of neighbouring FURs is affected by space. As explained in the previous section, these variable are calculated for different inter-regional spillovers distance ranges. These distance ranges vary from a minimum of 90 minutes to a maximum of 150 minutes. The best version of the model, both in terms of the regression $\overline{R}^2$ and of the *t*-ratios for the ‘research activity’ and the ‘university’ variables, corresponds to the R&DS3 variable (column 4), which allows for interaction between regional research sectors located within a range of 115 minutes. In other words, the strength of the inter-regional interaction between researchers appears to reach its strongest level when the researchers are within 115 minutes travelling time. Including the possibility of inter-regional spillover effects for time distances of more than 115 minutes reduces the significance of the variable.

Given these results, attention will be concentrated in what follows on the fourth version of the model. The coefficient for the index of specialisation of the local industrial structure is negative and significant at the 1% level. This suggests that, during the period covered by the analysis, those regions that at the beginning of this period were characterised by a greater degree of specialisation in their industrial structures grew faster, other things being equal. With regard to the nature of the intra-regional spillovers, this result suggests that, in aggregate terms, intra-industry dynamic externalities were more effective than inter-regional dynamic externalities in stimulating per capita GDP growth.

The role of port activities on regional growth according to the estimated coefficients is described in Figure 7.1. As argued in the previous section, it is possible that the relation between port size and regional growth is quadratic, and the regression results seem to support this view. However, a closer look at the figure shows that the minimum point of the curve is reached for an amount of trade just exceeding 120 million tonnes. The only port handling more than 100 million tonnes in 1978 was Rotterdam (with 259 million tonnes). The second port in terms of goods handled was Marseille with 93 million tonnes.

Figure 7.1 The Role of Port Activities



It is therefore likely that the functional form of the influence of port activities on regional growth is conditioned by the observation for Rotterdam. To check for this possibility, two further regressions were run in which the variable for port activity excluded Rotterdam. In the second of these regressions the functional form for the influence of port activity on regional growth was linear; the performance of a quadratic form is compared in the first regression. The results, together with the results of the best version of the previous set of regressions (version 4), are reported in Table 7.3.

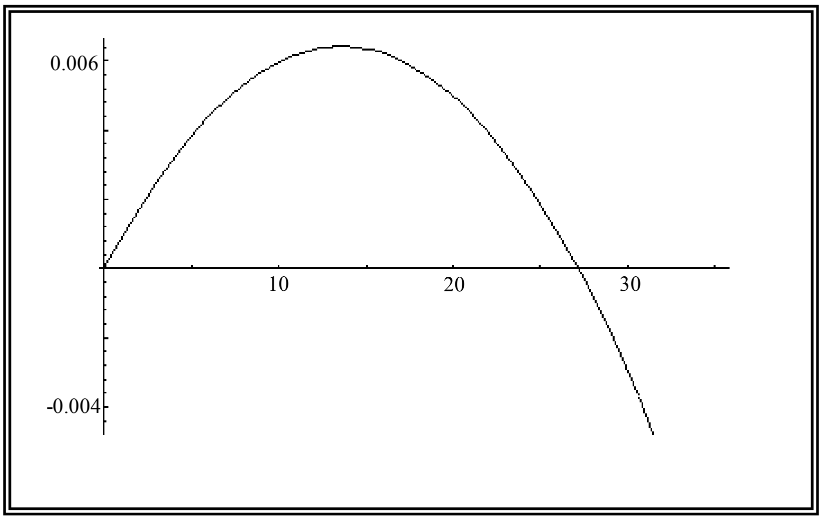
Table 7.3 The Influence of Port Activities

	4	9	10
Constant	0.00743 (0.54)	0.00851 (0.62)	0.00823 (0.60)
R&DS3	5.92e-5 (3.01)	5.72e-5 (2.91)	5.76e-5 (2.97)
University	4.23e-7 (2.48)	4.16e-7 (2.46)	4.16e-7 (2.47)
Coal	-0.00336 (-2.62)	-0.00340 (-2.66)	-0.00340 (-2.67)
Port	-9.54e-5 (-2.43)	-	-
$Port^2$	3.91e-7 (2.20)	-	-
Port2	-	6.15e-4 (-0.82)	7.30e-4 (-2.47)
$Port2^2$	-	1.78e-5 (-0.17)	-
Service	0.01630 (2.07)	0.01649 (2.12)	0.01658 (2.15)
Specialisation	-0.03907 (-2.52)	-0.03979 (-2.59)	-0.03967 (-2.59)
Agriculture	9.55e-4 (4.21)	9.43e-4 (4.19)	9.44e-4 (4.22)
$Agriculture^2$	-3.50e-5 (-5.48)	-3.48e-5 (-5.49)	-3.48e-5 (-5.51)
Density	-0.00954 (-4.09)	-0.00942 (-4.02)	-0.00947 (-4.09)
SDG	0.20424 (5.13)	0.20356 (5.14)	0.20343 (5.16)
NFGrowth	1.02832 (6.98)	1.01503 (6.90)	1.01784 (6.99)
DSE	-0.00954 (-4.09)	-0.00942 (-4.02)	-0.00947 (-4.09)
$\overline{R}^2$	0.5866	0.5873	0.5910

They seem to confirm the impression that the quadratic form is due to the very high leverage on the observation for Rotterdam. The coefficients for "Port2" and "Port2^2", the variables on port activity which exclude the observation for Rotterdam, are both statistically non significant, thus rejecting the hypothesis of a quadratic form for the influence of the other European ports on regional growth. When the relation between port activity and growth is assumed to be linear (version 10), the coefficient is negative and highly significant. In other words, it seems possible to conclude that, generally speaking, port activity had a negative influence on the growth prospects of a region. The most noticeable exception is represented by the port of Rotterdam. The explanation of these results may be outcome of successful port re-structuring in Rotterdam or might be the outcome of other factors specific to the Rotterdam FUR (Cheshire *et al*. 1998).

As for the role of agriculture, the results of the regression confirm the expectation of a quadratic relationship with regional growth. This relationship, which is represented in Figure 7.2, is stable to changes in the port variable. For both version 4 and 10, the curve representing the influence of the share of employment in agriculture, reaches its maximum for a value of 13.6. In contrast to the previous case, almost one sixth of the observations in the database have a value exceeding this maximum.

Figure 7.2 The Role of the Share of Employment in Agriculture



Finally, a set of diagnostics have been performed on version 4 and version 9 of the model. The first test performed was the Kiefer-Salmon test for the normality of the residuals. Heteroscedasticity was tested for with two different diagnostics, the Breusch-Pagan (BP) Lagrange Multiplier test and the Koenker-Bassett (KB) test. However, following the testing procedure in *SpaceStat* (see Anselin 1994) only one test against heteroscedasticity is actually carried out depending on the results of the normality test. When the errors are non-normal (for a probability level of 0.01) the KB test is preferred to the BP test. Ramsey's RESET test is then used to check the functional form. Finally, four separate diagnostic statistics for spatial autocorrelation are produced: Moran's I statistic, Burridge's Lagrange multiplier test, Kelejian and Robinson's test for *spatial error*, and Anselin's test for *spatial lag* (for details see Anselin 1988 and 1994). In each case the tests are based upon both the distance matrices used in the derivation of the variables of the model. All diagnostics excluded the presence of specification problems with either of the two preferred versions of the model. The full results of these tests are reported in appendices A7.1 and A7.2.

7.4 Conclusions

The results of the regression analysis carried out in this chapter lend support to the main predictions of the theoretical model developed here. These results can be summarised as follows. Firstly, innovation activities appear to play an important role in the process of regional growth. The coefficients for the variables measuring regional research efforts are always positive and highly significant. Secondly, by considering different specifications of the spatial interaction between researchers, it has been possible to find evidence supporting the existence of spatial spillovers of knowledge. The effects of inter-regional spillovers of knowledge are maximised if interactions are assumed to extend to a distance determined by about 2 hours travelling time. Thirdly, several factors affecting the regional growth rate of per capita GDP by shaping the local level of technological competence in research have been identified. One of these factors appears to be the existence of universities.

These contribute to the regional research effort both directly, in their role of centres of research, and indirectly, as that part of the regional infrastructure that provides new human capital. Data limitations do not allow these effects to be analysed separately. Nonetheless, the empirical analysis suggests the conclusion that one or both of these effects have a significant positive impact on regional growth. Finally, another interesting outcome concerns the controversy on the relative importance of intra-industry and inter-industry dynamic spillovers in promoting growth. An index of the degree of sectoral specialisation of regional industrial specialisation has been used to shed light on this issue which has been the subject or considerable debate. The results indicate that, during the period 1979-1990, European urban regions characterised by a higher degree of sectoral specialisation grew faster than regions with a more diverse industrial structure. In other words, intra-regional dynamic spillovers appear to have been more successful than inter-regional dynamic spillovers in fostering regional economic growth.

Finally, a note of caution is in order because data limitations have, in some instances, lead to the use of only proxies or rather crude measures of the variables indicated by the theoretical model. In particular, this appears to be the case for the variable related to research activity. Although the lack of spatially disaggregated data on employment in research forced the adoption of the rather crude measure employed here, this measure appears nonetheless capable of providing a first indication of the influence of research activities on regional growth.

A7.1 Results of the Tests Performed on Version 4

REGRESSION DIAGNOSTICS

TEST ON NORMALITY OF ERRORS

TEST	DF	VALUE	PROB
Kiefer-Salmon	2	7.108340	0.028605

DIAGNOSTICS FOR HETEROSKEDASTICITY
RANDOM COEFFICIENTS

TEST	DF	VALUE	PROB
Breusch-Pagan test	13	18.625927	0.135166

DIAGNOSTICS FOR SPATIAL DEPENDENCE

FOR WEIGHTS MATRIX F130RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.003168	0.085446	0.931907
Lagrange Multiplier (error)	1	0.000393	0.984179
Lagrange Multiplier (lag)	1	0.020451	0.886286

FOR WEIGHTS MATRIX F230RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.007166	0.013735	0.989041
Lagrange Multiplier (error)	1	0.001991	0.964407
Lagrange Multiplier (lag)	1	0.020028	0.887458

FOR WEIGHTS MATRIX F160RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.022743	-0.203553	0.838703
Lagrange Multiplier (error)	1	0.058113	0.809503
Lagrange Multiplier (lag)	1	1.233002	0.266824

FOR WEIGHTS MATRIX F260RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.035732	-0.343618	0.731134
Lagrange Multiplier (error)	1	0.137195	0.711085
Lagrange Multiplier (lag)	1	1.225475	0.268289

FOR WEIGHTS MATRIX F190RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006766	-0.008885	0.992911
Lagrange Multiplier (error)	1	0.005972	0.938403
Lagrange Multiplier (lag)	1	0.472763	0.491719

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FOR WEIGHTS MATRIX   F290RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)          -0.017684    -0.138635    0.889739
Lagrange Multiplier (error)        1     0.037993    0.845458
Lagrange Multiplier (lag)          1     0.467350    0.494209

FOR WEIGHTS MATRIX  F1120RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)          -0.023929    -0.237845    0.812001
Lagrange Multiplier (error)        1     0.083228    0.772970
Lagrange Multiplier (lag)          1     0.417711    0.518082

FOR WEIGHTS MATRIX  F2120RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)          -0.030404    -0.308386    0.757788
Lagrange Multiplier (error)        1     0.122282    0.726572
Lagrange Multiplier (lag)          1     0.404376    0.524838

FOR WEIGHTS MATRIX  F1150RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)           0.029794     0.529942    0.596152
Lagrange Multiplier (error)        1     0.175176    0.675552
Lagrange Multiplier (lag)          1     0.009645    0.921766

FOR WEIGHTS MATRIX  F2150RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)           0.020596     0.361050    0.718062
Lagrange Multiplier (error)        1     0.070835    0.790125
Lagrange Multiplier (lag)          1     0.009947    0.920557

FOR WEIGHTS MATRIX  F1180RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)           0.059865     1.376976    0.168520
Lagrange Multiplier (error)        1     1.308550    0.252657
Lagrange Multiplier (lag)          1     1.186654    0.276006

FOR WEIGHTS MATRIX  F2180RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)           0.057895     1.184493    0.236218
Lagrange Multiplier (error)        1     0.986340    0.320638
Lagrange Multiplier (lag)          1     1.165200    0.280390

FOR WEIGHTS MATRIX  F1210RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)          -0.016850    -0.286931    0.774165
Lagrange Multiplier (error)        1     0.262761    0.608229
Lagrange Multiplier (lag)          1     0.190863    0.662199

FOR WEIGHTS MATRIX  F2210RS (row-standardized weights)
TEST                          MI/DF        VALUE        PROB
Moran's I (error)          -0.022690    -0.410405    0.681509
Lagrange Multiplier (error)        1     0.340394    0.559602
Lagrange Multiplier (lag)          1     0.171619    0.678677
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FOR WEIGHTS MATRIX  F1240RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)             0.007297     0.919765     0.357695
Lagrange Multiplier (error)          1     0.110515     0.739559
Kelejian-Robinson (error)           14     6.231491     0.960315
Lagrange Multiplier (lag)            1     0.000003     0.998706

FOR WEIGHTS MATRIX  F2240RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)             0.000052     0.341831     0.732478
Lagrange Multiplier (error)          1     0.000003     0.998572
Kelejian-Robinson (error)           14     6.231491     0.960315
Lagrange Multiplier (lag)            1     0.001561     0.968479

FOR WEIGHTS MATRIX  F1270RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)             0.002440     0.988686     0.322817
Lagrange Multiplier (error)          1     0.021403     0.883685
Kelejian-Robinson (error)           14     4.060956     0.995088
Lagrange Multiplier (lag)            1     0.001361     0.970568

FOR WEIGHTS MATRIX  F2270RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            -0.004566     0.186052     0.852404
Lagrange Multiplier (error)          1     0.034337     0.852991
Kelejian-Robinson (error)           14     4.060956     0.995088
Lagrange Multiplier (lag)            1     0.000669     0.979365

FOR WEIGHTS MATRIX  F1300RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)             0.000282     0.901872     0.367125
Lagrange Multiplier (error)          1     0.000331     0.985490
Kelejian-Robinson (error)           14     5.276781     0.981576
Lagrange Multiplier (lag)            1     0.276855     0.598770

FOR WEIGHTS MATRIX  F2300RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            -0.004996     0.173621     0.862163
Lagrange Multiplier (error)          1     0.046791     0.828744
Kelejian-Robinson (error)           14     5.276781     0.981576
Lagrange Multiplier (lag)            1     0.170899     0.679314

FOR WEIGHTS MATRIX  F1330RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            -0.003612     0.570877     0.568083
Lagrange Multiplier (error)          1     0.061687     0.803849
Kelejian-Robinson (error)           14     5.082037     0.984638
Lagrange Multiplier (lag)            1     0.041686     0.838219

FOR WEIGHTS MATRIX  F2330RS (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            -0.008600    -0.030271     0.975851
Lagrange Multiplier (error)          1     0.153928     0.694810
Kelejian-Robinson (error)           14     5.082037     0.984638
Lagrange Multiplier (lag)            1     0.515926     0.472585
```

FOR WEIGHTS MATRIX F1360RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.005477	0.471050	0.637605
Lagrange Multiplier (error)	1	0.168304	0.681624
Kelejian-Robinson (error)	14	4.857498	0.987699
Lagrange Multiplier (lag)	1	0.049515	0.823909

FOR WEIGHTS MATRIX F2360RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.009313	-0.075151	0.940094
Lagrange Multiplier (error)	1	0.201611	0.653424
Kelejian-Robinson (error)	14	4.857498	0.987699
Lagrange Multiplier (lag)	1	0.553368	0.456945

FOR WEIGHTS MATRIX F1390RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.003626	0.895656	0.370437
Lagrange Multiplier (error)	1	0.078845	0.778868
Kelejian-Robinson (error)	14	4.324638	0.993175
Lagrange Multiplier (lag)	1	0.486565	0.485464

FOR WEIGHTS MATRIX F2390RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.007870	0.013170	0.989492
Lagrange Multiplier (error)	1	0.151161	0.697428
Kelejian-Robinson (error)	14	4.324638	0.993175
Lagrange Multiplier (lag)	1	0.808130	0.368674

FOR WEIGHTS MATRIX F1420RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006614	0.356989	0.721100
Lagrange Multiplier (error)	1	0.272125	0.601910
Kelejian-Robinson (error)	14	5.353990	0.980251
Lagrange Multiplier (lag)	1	0.120982	0.727972

FOR WEIGHTS MATRIX F2420RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.010052	-0.128935	0.897409
Lagrange Multiplier (error)	1	0.254174	0.614151
Kelejian-Robinson (error)	14	5.353990	0.980251
Lagrange Multiplier (lag)	1	0.593564	0.441044

FOR WEIGHTS MATRIX F1450RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006026	0.495565	0.620201
Lagrange Multiplier (error)	1	0.229246	0.632083
Kelejian-Robinson (error)	14	4.321070	0.993204
Lagrange Multiplier (lag)	1	0.068588	0.793404

FOR WEIGHTS MATRIX F2450RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.009423	-0.090125	0.928188
Lagrange Multiplier (error)	1	0.225819	0.634642
Kelejian-Robinson (error)	14	4.321070	0.993204
Lagrange Multiplier (lag)	1	0.568900	0.450696

```
FOR WEIGHTS MATRIX  F1480RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.006314     0.440219     0.659778
Lagrange Multiplier (error)          1     0.252832     0.615088
Kelejian-Robinson (error)           14     4.634865     0.990274
Lagrange Multiplier (lag)            1     0.052092     0.819462

FOR WEIGHTS MATRIX  F2480RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.009465    -0.092862     0.926013
Lagrange Multiplier (error)          1     0.228496     0.632642
Kelejian-Robinson (error)           14     4.634865     0.990274
Lagrange Multiplier (lag)            1     0.566764     0.451548

FOR WEIGHTS MATRIX  F1510RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.005955     0.525324     0.599358
Lagrange Multiplier (error)          1     0.225279     0.635047
Kelejian-Robinson (error)           14     4.571112     0.990932
Lagrange Multiplier (lag)            1     0.046376     0.829494

FOR WEIGHTS MATRIX  F2510RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.009302    -0.081883     0.934740
Lagrange Multiplier (error)          1     0.220927     0.638334
Kelejian-Robinson (error)           14     4.571112     0.990932
Lagrange Multiplier (lag)            1     0.560992     0.453861

FOR WEIGHTS MATRIX  F1ALLRS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.006110     0.490855     0.623529
Lagrange Multiplier (error)          1     0.237168     0.626259
Kelejian-Robinson (error)           14     4.623888     0.990389
Lagrange Multiplier (lag)            1     0.038771     0.843903

FOR WEIGHTS MATRIX  F2ALLRS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.009375    -0.086659     0.930942
Lagrange Multiplier (error)          1     0.224424     0.635690
Kelejian-Robinson (error)           14     4.623888     0.990389
Lagrange Multiplier (lag)            1     0.554746     0.456385
```

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FOR WEIGHTS MATRIX  D130S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.321934     2.152379     0.031367
Lagrange Multiplier (error)          1     4.282971     0.038496
Lagrange Multiplier (lag)            1     0.034254     0.853167

FOR WEIGHTS MATRIX  D130S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.346507     2.280787     0.022561
Lagrange Multiplier (error)          1     4.820800     0.028118
Lagrange Multiplier (lag)            1     0.039110     0.843232
```

FOR WEIGHTS MATRIX D130S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.364812	2.354560	0.018545
Lagrange Multiplier (error)	1	5.145123	0.023312
Lagrange Multiplier (lag)	1	0.042494	0.836681

FOR WEIGHTS MATRIX D160S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.054698	0.769927	0.441343
Lagrange Multiplier (error)	1	0.445178	0.504634
Lagrange Multiplier (lag)	1	0.621777	0.430388

FOR WEIGHTS MATRIX D160S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.087776	1.123494	0.261228
Lagrange Multiplier (error)	1	1.022813	0.311853
Lagrange Multiplier (lag)	1	0.540843	0.462084

FOR WEIGHTS MATRIX D160S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.112168	1.326153	0.184789
Lagrange Multiplier (error)	1	1.476679	0.224295
Lagrange Multiplier (lag)	1	0.482115	0.487466

FOR WEIGHTS MATRIX D190S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.054698	0.769927	0.441343
Lagrange Multiplier (error)	1	0.445178	0.504634
Lagrange Multiplier (lag)	1	0.621777	0.430388

FOR WEIGHTS MATRIX D190S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.087776	1.123494	0.261228
Lagrange Multiplier (error)	1	1.022813	0.311853
Lagrange Multiplier (lag)	1	0.540843	0.462084

FOR WEIGHTS MATRIX D190S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.112168	1.326153	0.184789
Lagrange Multiplier (error)	1	1.476679	0.224295
Lagrange Multiplier (lag)	1	0.482115	0.487466

FOR WEIGHTS MATRIX D1120S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.001651	0.135573	0.892159
Lagrange Multiplier (error)	1	0.000566	0.981022
Lagrange Multiplier (lag)	1	1.017326	0.313154

FOR WEIGHTS MATRIX D1120S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.028374	0.484574	0.627979
Lagrange Multiplier (error)	1	0.142843	0.705471
Lagrange Multiplier (lag)	1	0.927122	0.335612

FOR WEIGHTS MATRIX D1120S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.053173	0.756611	0.449283
Lagrange Multiplier (error)	1	0.430429	0.511779
Lagrange Multiplier (lag)	1	0.845141	0.357931

```
FOR WEIGHTS MATRIX D1150S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.010413     0.286864     0.774217
Lagrange Multiplier (error)          1     0.029125     0.864491
Lagrange Multiplier (lag)            1     0.330436     0.565402

FOR WEIGHTS MATRIX D1150S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.045518     0.784211     0.432916
Lagrange Multiplier (error)          1     0.452109     0.501335
Lagrange Multiplier (lag)            1     0.277111     0.598601
FOR WEIGHTS MATRIX D1150S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.074639     1.105782     0.268821
Lagrange Multiplier (error)          1     1.001057     0.317055
Lagrange Multiplier (lag)            1     0.229136     0.632165

FOR WEIGHTS MATRIX D1180S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.013599     0.381832     0.702586
Lagrange Multiplier (error)          1     0.059973     0.806538
Lagrange Multiplier (lag)            1     0.372168     0.541825

FOR WEIGHTS MATRIX D1180S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.048922     0.910128     0.362755
Lagrange Multiplier (error)          1     0.615064     0.432887
Lagrange Multiplier (lag)            1     0.309470     0.578006

FOR WEIGHTS MATRIX D1180S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.079226     1.253392     0.210063
Lagrange Multiplier (error)          1     1.296659     0.254824
Lagrange Multiplier (lag)            1     0.255434     0.613275

FOR WEIGHTS MATRIX D1210S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.013009     0.407937     0.683320
Lagrange Multiplier (error)          1     0.065451     0.798079
Lagrange Multiplier (lag)            1     0.003979     0.949705

FOR WEIGHTS MATRIX D1210S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.051633     1.026886     0.304474
Lagrange Multiplier (error)          1     0.782894     0.376258
Lagrange Multiplier (lag)            1     0.000065     0.993572

FOR WEIGHTS MATRIX D1210S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.083907     1.392317     0.163826
Lagrange Multiplier (error)          1     1.598490     0.206117
Lagrange Multiplier (lag)            1     0.001941     0.964858

FOR WEIGHTS MATRIX D1240S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.000475     0.185003     0.853227
Lagrange Multiplier (error)          1     0.000103     0.991919
Lagrange Multiplier (lag)            1     0.032060     0.857896
```

FOR WEIGHTS MATRIX D1240S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.037509	0.846146	0.397471
Lagrange Multiplier (error)	1	0.467061	0.494342
Lagrange Multiplier (lag)	1	0.057856	0.809918

FOR WEIGHTS MATRIX D1240S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.069427	1.237816	0.215784
Lagrange Multiplier (error)	1	1.196811	0.273960
Lagrange Multiplier (lag)	1	0.088496	0.766098

FOR WEIGHTS MATRIX D1270S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.005611	0.058191	0.953597
Lagrange Multiplier (error)	1	0.013985	0.905863
Lagrange Multiplier (lag)	1	0.231732	0.630243

FOR WEIGHTS MATRIX D1270S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.032523	0.771700	0.440292
Lagrange Multiplier (error)	1	0.356222	0.550612
Lagrange Multiplier (lag)	1	0.306100	0.580083

FOR WEIGHTS MATRIX D1270S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.064663	1.195309	0.231966
Lagrange Multiplier (error)	1	1.074060	0.300030
Lagrange Multiplier (lag)	1	0.384005	0.535468

FOR WEIGHTS MATRIX D1300S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.007676	0.000392	0.999687
Lagrange Multiplier (error)	1	0.032508	0.856918
Lagrange Multiplier (lag)	1	0.309820	0.577791

FOR WEIGHTS MATRIX D1300S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.026985	0.704592	0.481064
Lagrange Multiplier (error)	1	0.278462	0.597711
Lagrange Multiplier (lag)	1	0.389351	0.532640

FOR WEIGHTS MATRIX D1300S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.056476	1.095928	0.273110
Lagrange Multiplier (error)	1	0.881666	0.347746
Lagrange Multiplier (lag)	1	0.471923	0.492104

FOR WEIGHTS MATRIX D1360S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.002197	0.273729	0.784293
Lagrange Multiplier (error)	1	0.003078	0.955756
Kelejian-Robinson (error)	14	28.581440	0.011900
Lagrange Multiplier (lag)	1	0.106516	0.744146

```
FOR WEIGHTS MATRIX D1360S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.034254     0.911796     0.361876
Lagrange Multiplier (error)          1     0.518808     0.471351
Kelejian-Robinson (error)           14    28.581440     0.011900
Lagrange Multiplier (lag)            1     0.157976     0.691027

FOR WEIGHTS MATRIX D1360S_3 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.061484     1.258123     0.208347
Lagrange Multiplier (error)          1     1.198542     0.273613
Kelejian-Robinson (error)           14    28.581440     0.011900
Lagrange Multiplier (lag)            1     0.217804     0.640718

FOR WEIGHTS MATRIX D1420S_1 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)            -0.000621     0.243759     0.807418
Lagrange Multiplier (error)          1     0.000367     0.984711
Kelejian-Robinson (error)           14    23.898679     0.047130
Lagrange Multiplier (lag)            1     0.092722     0.760744

FOR WEIGHTS MATRIX D1420S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.025335     0.843955     0.398695
Lagrange Multiplier (error)          1     0.378695     0.538302
Kelejian-Robinson (error)           14    23.898679     0.047130
Lagrange Multiplier (lag)            1     0.159197     0.689897

FOR WEIGHTS MATRIX D1420S_3 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.049727     1.173911     0.240430
Lagrange Multiplier (error)          1     0.970237     0.324621
Kelejian-Robinson (error)           14    23.898679     0.047130
Lagrange Multiplier (lag)            1     0.238643     0.625188

FOR WEIGHTS MATRIX D1480S_1 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.026092     1.265210     0.205796
Lagrange Multiplier (error)          1     0.794832     0.372643
Kelejian-Robinson (error)           14    18.331578     0.192094
Lagrange Multiplier (lag)            1     1.254627     0.262671

FOR WEIGHTS MATRIX D1480S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.048128     1.513027     0.130273
Lagrange Multiplier (error)          1     1.544889     0.213892
Kelejian-Robinson (error)           14    18.331578     0.192094
Lagrange Multiplier (lag)            1     1.449503     0.228608

FOR WEIGHTS MATRIX D1480S_3 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.069937     1.638801     0.101255
Lagrange Multiplier (error)          1     2.061317     0.151080
Kelejian-Robinson (error)           14    18.331578     0.192094
Lagrange Multiplier (lag)            1     1.651051     0.198816
```

FOR WEIGHTS MATRIX D1600S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.000753	0.417976	0.675965
Lagrange Multiplier (error)	1	0.000994	0.974848
Kelejian-Robinson (error)	14	14.421689	0.418790
Lagrange Multiplier (lag)	1	0.340138	0.559750

FOR WEIGHTS MATRIX D1600S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.022146	0.924402	0.355277
Lagrange Multiplier (error)	1	0.408915	0.522521
Kelejian-Robinson (error)	14	14.421689	0.418790
Lagrange Multiplier (lag)	1	0.520884	0.470465

FOR WEIGHTS MATRIX D1600S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.044286	1.180916	0.237636
Lagrange Multiplier (error)	1	0.940038	0.332268
Kelejian-Robinson (error)	14	14.421689	0.418790
Lagrange Multiplier (lag)	1	0.721127	0.395774

FOR WEIGHTS MATRIX D1800S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.002348	0.740153	0.459207
Lagrange Multiplier (error)	1	0.015543	0.900784
Kelejian-Robinson (error)	14	6.961055	0.936203
Lagrange Multiplier (lag)	1	0.000780	0.977714

FOR WEIGHTS MATRIX D1800S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.022683	1.074472	0.282611
Lagrange Multiplier (error)	1	0.526151	0.468230
Kelejian-Robinson (error)	14	6.961055	0.936203
Lagrange Multiplier (lag)	1	0.019126	0.890005

FOR WEIGHTS MATRIX D1800S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.044720	1.265891	0.205552
Lagrange Multiplier (error)	1	1.057027	0.303894
Kelejian-Robinson (error)	14	6.961055	0.936203
Lagrange Multiplier (lag)	1	0.091531	0.762240

FOR WEIGHTS MATRIX D11000S1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.022260	1.114591	0.265026
Lagrange Multiplier (error)	1	0.554214	0.456601
Kelejian-Robinson (error)	14	3.460835	0.997931
Lagrange Multiplier (lag)	1	2.262098	0.132574

FOR WEIGHTS MATRIX D11000S2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.042733	1.247942	0.212052
Lagrange Multiplier (error)	1	1.012772	0.314240
Kelejian-Robinson (error)	14	3.460835	0.997931
Lagrange Multiplier (lag)	1	2.480946	0.115233

```
FOR WEIGHTS MATRIX D11000S3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.042733     1.247942     0.212052
Lagrange Multiplier (error)          1     1.012772     0.314240
Kelejian-Robinson (error)           14     3.460835     0.997931
Lagrange Multiplier (lag)            1     2.480946     0.115233

FOR WEIGHTS MATRIX D11800S1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.001710     1.145298     0.252086
Lagrange Multiplier (error)          1     0.013598     0.907170
Kelejian-Robinson (error)           14     5.727350     0.972903
Lagrange Multiplier (lag)            1     0.647077     0.421160

FOR WEIGHTS MATRIX D11800S2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.020088     1.102505     0.270242
Lagrange Multiplier (error)          1     0.504082     0.477712
Kelejian-Robinson (error)           14     5.727350     0.972903
Lagrange Multiplier (lag)            1     1.739397     0.187215

FOR WEIGHTS MATRIX D11800S3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.041172     1.231931     0.217975
Lagrange Multiplier (error)          1     0.974311     0.323607
Kelejian-Robinson (error)           14     5.727350     0.972903
Lagrange Multiplier (lag)            1     2.237388     0.134708

FOR WEIGHTS MATRIX D1ALLS_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.001385     1.130154     0.258411
Lagrange Multiplier (error)          1     0.009044     0.924237
Kelejian-Robinson (error)           14     4.623888     0.990389
Lagrange Multiplier (lag)            1     0.504660     0.477460

FOR WEIGHTS MATRIX D1ALLS_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.020104     1.105844     0.268794
Lagrange Multiplier (error)          1     0.506643     0.476596
Kelejian-Robinson (error)           14     4.623888     0.990389
Lagrange Multiplier (lag)            1     1.724505     0.189114

FOR WEIGHTS MATRIX D1ALLS_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.041134     1.231461     0.218150
Lagrange Multiplier (error)          1     0.973217     0.323879
Kelejian-Robinson (error)           14     4.623888     0.990389
Lagrange Multiplier (lag)            1     2.234838     0.134931
```

A7.2 Results of the Tests Performed on Version 10

REGRESSION DIAGNOSTICS

TEST ON NORMALITY OF ERRORS

TEST	DF	VALUE	PROB
Kiefer-Salmon	2	6.349938	0.041795

DIAGNOSTICS FOR HETEROSKEDASTICITY

RANDOM COEFFICIENTS

TEST	DF	VALUE	PROB
Breusch-Pagan test	12	17.587217	0.128811

DIAGNOSTICS FOR SPATIAL DEPENDENCE

FOR WEIGHTS MATRIX F130RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.001970	0.059797	0.952318
Lagrange Multiplier (error)	1	0.000152	0.990162
Lagrange Multiplier (lag)	1	0.001366	0.970518

FOR WEIGHTS MATRIX F230RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.012532	-0.010365	0.991730
Lagrange Multiplier (error)	1	0.006090	0.937796
Lagrange Multiplier (lag)	1	0.001254	0.971752

FOR WEIGHTS MATRIX F160RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.025388	-0.238418	0.811557
Lagrange Multiplier (error)	1	0.072412	0.787857
Lagrange Multiplier (lag)	1	1.360511	0.243449

FOR WEIGHTS MATRIX F260RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.038761	-0.381747	0.702649
Lagrange Multiplier (error)	1	0.161441	0.687833
Lagrange Multiplier (lag)	1	1.352918	0.244769

FOR WEIGHTS MATRIX F190RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.009442	-0.045314	0.963857
Lagrange Multiplier (error)	1	0.011629	0.914125
Lagrange Multiplier (lag)	1	0.548430	0.458960

FOR WEIGHTS MATRIX F290RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.020606	-0.176342	0.860025
Lagrange Multiplier (error)	1	0.051585	0.820328
Lagrange Multiplier (lag)	1	0.542983	0.461199

```
FOR WEIGHTS MATRIX  F1120RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)            -0.027024     -0.281982     0.777957
Lagrange Multiplier (error)          1      0.106150     0.744570
Lagrange Multiplier (lag)            1      0.498660     0.480090

FOR WEIGHTS MATRIX  F2120RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)            -0.033907     -0.354968     0.722613
Lagrange Multiplier (error)          1      0.152081     0.696554
Lagrange Multiplier (lag)            1      0.484631     0.486332

FOR WEIGHTS MATRIX  F1150RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.022008      0.412015     0.680328
Lagrange Multiplier (error)          1      0.095586     0.757193
Lagrange Multiplier (lag)            1      0.018832     0.890848

FOR WEIGHTS MATRIX  F2150RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.012472      0.249608     0.802890
Lagrange Multiplier (error)          1      0.025974     0.871964
Lagrange Multiplier (lag)            1      0.019351     0.889365

FOR WEIGHTS MATRIX  F1180RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.050908      1.201300     0.229635
Lagrange Multiplier (error)          1      0.946264     0.330672
Lagrange Multiplier (lag)            1      1.323061     0.250044

FOR WEIGHTS MATRIX  F2180RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.048445      1.018130     0.308616
Lagrange Multiplier (error)          1      0.690625     0.405952
Lagrange Multiplier (lag)            1      1.302306     0.253792

FOR WEIGHTS MATRIX  F1210RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)            -0.017783     -0.317661     0.750742
Lagrange Multiplier (error)          1      0.292652     0.588526
Lagrange Multiplier (lag)            1      0.213016     0.644414

FOR WEIGHTS MATRIX  F2210RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)            -0.024430     -0.459365     0.645972
Lagrange Multiplier (error)          1      0.394579     0.529902
Lagrange Multiplier (lag)            1      0.193955     0.659645

FOR WEIGHTS MATRIX  F1240RS (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.005099      0.798285     0.424705
Lagrange Multiplier (error)          1      0.053961     0.816309
Kelejian-Robinson (error)           13      6.516618     0.925317
Lagrange Multiplier (lag)            1      0.000437     0.983318
```

FOR WEIGHTS MATRIX F2240RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.002640	0.236562	0.812997
Lagrange Multiplier (error)	1	0.008168	0.927990
Kelejian-Robinson (error)	13	6.516618	0.925317
Lagrange Multiplier (lag)	1	0.000347	0.985141

FOR WEIGHTS MATRIX F1270RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.001742	0.929440	0.352661
Lagrange Multiplier (error)	1	0.010903	0.916838
Kelejian-Robinson (error)	13	4.232480	0.988458
Lagrange Multiplier (lag)	1	0.003034	0.956075

FOR WEIGHTS MATRIX F2270RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.005901	0.120486	0.904098
Lagrange Multiplier (error)	1	0.057340	0.810751
Kelejian-Robinson (error)	13	4.232480	0.988458
Lagrange Multiplier (lag)	1	0.000036	0.995182

FOR WEIGHTS MATRIX F1300RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.000311	0.844939	0.398145
Lagrange Multiplier (error)	1	0.000400	0.984042
Kelejian-Robinson (error)	13	5.557139	0.960798
Lagrange Multiplier (lag)	1	0.286449	0.592505

FOR WEIGHTS MATRIX F2300RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006132	0.113617	0.909542
Lagrange Multiplier (error)	1	0.070480	0.790639
Kelejian-Robinson (error)	13	5.557139	0.960798
Lagrange Multiplier (lag)	1	0.180832	0.670659

FOR WEIGHTS MATRIX F1330RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.003673	0.563926	0.572805
Lagrange Multiplier (error)	1	0.063778	0.800621
Kelejian-Robinson (error)	13	5.201735	0.970479
Lagrange Multiplier (lag)	1	0.025928	0.872075

FOR WEIGHTS MATRIX F2330RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.009221	-0.067701	0.946024
Lagrange Multiplier (error)	1	0.176973	0.673988
Kelejian-Robinson (error)	13	5.201735	0.970479
Lagrange Multiplier (lag)	1	0.463161	0.496151

FOR WEIGHTS MATRIX F1360RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.005867	0.408258	0.683084
Lagrange Multiplier (error)	1	0.193162	0.660297
Kelejian-Robinson (error)	13	4.955696	0.976155
Lagrange Multiplier (lag)	1	0.034207	0.853267

FOR WEIGHTS MATRIX F2360RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.010274	-0.135352	0.892334
Lagrange Multiplier (error)	1	0.245361	0.620361
Kelejian-Robinson (error)	13	4.955696	0.976155
Lagrange Multiplier (lag)	1	0.504792	0.477402

FOR WEIGHTS MATRIX F1390RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.004078	0.811114	0.417300
Lagrange Multiplier (error)	1	0.099734	0.752149
Kelejian-Robinson (error)	13	4.421103	0.985832
Lagrange Multiplier (lag)	1	0.445606	0.504429

FOR WEIGHTS MATRIX F2390RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.008875	-0.051455	0.958963
Lagrange Multiplier (error)	1	0.192242	0.661058
Kelejian-Robinson (error)	13	4.421103	0.985832
Lagrange Multiplier (lag)	1	0.755094	0.384868

FOR WEIGHTS MATRIX F1420RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006916	0.293791	0.768917
Lagrange Multiplier (error)	1	0.297600	0.585391
Kelejian-Robinson (error)	13	5.481404	0.963013
Lagrange Multiplier (lag)	1	0.105674	0.745124

FOR WEIGHTS MATRIX F2420RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.010941	-0.187897	0.850958
Lagrange Multiplier (error)	1	0.301137	0.583170
Kelejian-Robinson (error)	13	5.481404	0.963013
Lagrange Multiplier (lag)	1	0.552652	0.457236

FOR WEIGHTS MATRIX F1450RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006239	0.448123	0.654065
Lagrange Multiplier (error)	1	0.245729	0.620098
Kelejian-Robinson (error)	13	4.470973	0.985073
Lagrange Multiplier (lag)	1	0.062450	0.802664

FOR WEIGHTS MATRIX F2450RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.010249	-0.145429	0.884372
Lagrange Multiplier (error)	1	0.267140	0.605257
Kelejian-Robinson (error)	13	4.470973	0.985073
Lagrange Multiplier (lag)	1	0.534984	0.464519

FOR WEIGHTS MATRIX F1480RS (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	-0.006516	0.394542	0.693181
Lagrange Multiplier (error)	1	0.269243	0.603840
Kelejian-Robinson (error)	13	4.748911	0.980313
Lagrange Multiplier (lag)	1	0.048155	0.826306

```
FOR WEIGHTS MATRIX  F2480RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.010269    -0.146909     0.883204
Lagrange Multiplier (error)          1     0.269009     0.603997
Kelejian-Robinson (error)           13     4.748911     0.980313
Lagrange Multiplier (lag)            1     0.534858     0.464571

FOR WEIGHTS MATRIX  F1510RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.006169     0.476327     0.633842
Lagrange Multiplier (error)          1     0.241739     0.622953
Kelejian-Robinson (error)           13     4.702167     0.981178
Lagrange Multiplier (lag)            1     0.042645     0.836396

FOR WEIGHTS MATRIX  F2510RS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.010111    -0.136244     0.891629
Lagrange Multiplier (error)          1     0.261028     0.609415
Kelejian-Robinson (error)           13     4.702167     0.981178
Lagrange Multiplier (lag)            1     0.529444     0.466841

FOR WEIGHTS MATRIX  F1ALLRS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.006327     0.441072     0.659161
Lagrange Multiplier (error)          1     0.254315     0.614053
Kelejian-Robinson (error)           13     4.751905     0.980256
Lagrange Multiplier (lag)            1     0.035352     0.850859

FOR WEIGHTS MATRIX  F2ALLRS (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.010185    -0.141136     0.887762
Lagrange Multiplier (error)          1     0.264904     0.606771
Kelejian-Robinson (error)           13     4.751905     0.980256
Lagrange Multiplier (lag)            1     0.523356     0.469413
```

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FOR WEIGHTS MATRIX  D130S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.311820     2.105663     0.035234
Lagrange Multiplier (error)          1     4.018101     0.045014
Lagrange Multiplier (lag)            1     0.013031     0.909115

FOR WEIGHTS MATRIX  D130S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.336562     2.237566     0.025249
Lagrange Multiplier (error)          1     4.548036     0.032957
Lagrange Multiplier (lag)            1     0.016118     0.898976

FOR WEIGHTS MATRIX  D130S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.354973     2.313870     0.020675
Lagrange Multiplier (error)          1     4.871341     0.027306
Lagrange Multiplier (lag)            1     0.018352     0.892240

FOR WEIGHTS MATRIX  D160S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.051915     0.716287     0.473814
Lagrange Multiplier (error)          1     0.401040     0.526553
Lagrange Multiplier (lag)            1     0.654777     0.418410
```

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FOR WEIGHTS MATRIX  D160S_2 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.083179     1.045588     0.295751
Lagrange Multiplier (error)          1     0.918496     0.337870
Lagrange Multiplier (lag)            1     0.572132     0.449413

FOR WEIGHTS MATRIX  D160S_3 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.106783     1.242347     0.214108
Lagrange Multiplier (error)          1     1.338282     0.247337
Lagrange Multiplier (lag)            1     0.511810     0.474356

FOR WEIGHTS MATRIX  D190S_1 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.051915     0.716287     0.473814
Lagrange Multiplier (error)          1     0.401040     0.526553
Lagrange Multiplier (lag)            1     0.654777     0.418410

FOR WEIGHTS MATRIX  D190S_2 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.083179     1.045588     0.295751
Lagrange Multiplier (error)          1     0.918496     0.337870
Lagrange Multiplier (lag)            1     0.572132     0.449413

FOR WEIGHTS MATRIX  D190S_3 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.106783     1.242347     0.214108
Lagrange Multiplier (error)          1     1.338282     0.247337
Lagrange Multiplier (lag)            1     0.511810     0.474356

FOR WEIGHTS MATRIX D1120S_1 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)            -0.007928    -0.007282     0.994190
Lagrange Multiplier (error)          1     0.013051     0.909046
Lagrange Multiplier (lag)            1     1.146297     0.284326

FOR WEIGHTS MATRIX D1120S_2 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.017874     0.340448     0.733519
Lagrange Multiplier (error)          1     0.056682     0.811820
Lagrange Multiplier (lag)            1     1.050066     0.305492

FOR WEIGHTS MATRIX D1120S_3 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.042015     0.615193     0.538427
Lagrange Multiplier (error)          1     0.268733     0.604183
Lagrange Multiplier (lag)            1     0.962174     0.326640

FOR WEIGHTS MATRIX D1150S_1 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.002575     0.153333     0.878135
Lagrange Multiplier (error)          1     0.001781     0.966338
Lagrange Multiplier (lag)            1     0.439643     0.507295

FOR WEIGHTS MATRIX D1150S_2 (row-standardized weights)
TEST                           MI/DF         VALUE         PROB
Moran's I (error)             0.036397     0.646610     0.517885
Lagrange Multiplier (error)          1     0.289067     0.590819
Lagrange Multiplier (lag)            1     0.377734     0.538818
```

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FOR WEIGHTS MATRIX D1150S_3 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.064546     0.968744    0.332673
Lagrange Multiplier (error)         1     0.748624    0.386912
Lagrange Multiplier (lag)           1     0.321209    0.570882

FOR WEIGHTS MATRIX D1180S_1 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.005163     0.225503    0.821588
Lagrange Multiplier (error)         1     0.008646    0.925917
Lagrange Multiplier (lag)           1     0.518329    0.471555

FOR WEIGHTS MATRIX D1180S_2 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.039288     0.753653    0.451058
Lagrange Multiplier (error)         1     0.396679    0.528810
Lagrange Multiplier (lag)           1     0.443827    0.505281

FOR WEIGHTS MATRIX D1180S_3 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.068642     1.100568    0.271085
Lagrange Multiplier (error)         1     0.973348    0.323847
Lagrange Multiplier (lag)           1     0.378394    0.538464

FOR WEIGHTS MATRIX D1210S_1 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.006366     0.271589    0.785938
Lagrange Multiplier (error)         1     0.015671    0.900376
Lagrange Multiplier (lag)           1     0.026365    0.871012

FOR WEIGHTS MATRIX D1210S_2 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.043543     0.885823    0.375713
Lagrange Multiplier (error)         1     0.556777    0.455562
Lagrange Multiplier (lag)           1     0.011604    0.914215

FOR WEIGHTS MATRIX D1210S_3 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.074712     1.253267    0.210108
Lagrange Multiplier (error)         1     1.267365    0.260262
Lagrange Multiplier (lag)           1     0.003105    0.955561

FOR WEIGHTS MATRIX D1240S_1 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)           -0.004935     0.061680    0.950818
Lagrange Multiplier (error)         1     0.011066    0.916222
Lagrange Multiplier (lag)           1     0.007569    0.930670

FOR WEIGHTS MATRIX D1240S_2 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.030425     0.713030    0.475827
Lagrange Multiplier (error)         1     0.307287    0.579350
Lagrange Multiplier (lag)           1     0.021907    0.882335

FOR WEIGHTS MATRIX D1240S_3 (row-standardized weights)
TEST                            MI/DF        VALUE        PROB
Moran's I (error)            0.061134     1.105545    0.268924
Lagrange Multiplier (error)         1     0.927988    0.335386
Lagrange Multiplier (lag)           1     0.041911    0.837790
```

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FOR WEIGHTS MATRIX D1270S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.010657    -0.055780    0.955517
Lagrange Multiplier (error)          1     0.050440    0.822299
Lagrange Multiplier (lag)            1     0.144760    0.703594

FOR WEIGHTS MATRIX D1270S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.025772     0.643769    0.519726
Lagrange Multiplier (error)          1     0.223674    0.636254
Lagrange Multiplier (lag)            1     0.204053    0.651469

FOR WEIGHTS MATRIX D1270S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.056703     1.066134    0.286363
Lagrange Multiplier (error)          1     0.825892    0.363463
Lagrange Multiplier (lag)            1     0.268045    0.604646

FOR WEIGHTS MATRIX D1300S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.011813    -0.105197    0.916220
Lagrange Multiplier (error)          1     0.077001    0.781403
Lagrange Multiplier (lag)            1     0.210739    0.646188

FOR WEIGHTS MATRIX D1300S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.020989     0.582725    0.560079
Lagrange Multiplier (error)          1     0.168470    0.681476
Lagrange Multiplier (lag)            1     0.277256    0.598505

FOR WEIGHTS MATRIX D1300S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.049183     0.972669    0.330718
Lagrange Multiplier (error)          1     0.668646    0.413524
Lagrange Multiplier (lag)            1     0.347490    0.555537

FOR WEIGHTS MATRIX D1360S_1 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)            -0.002629     0.145644    0.884203
Lagrange Multiplier (error)          1     0.004409    0.947061
Kelejian-Robinson (error)           13    29.763783    0.005093
Lagrange Multiplier (lag)            1     0.045879    0.830396

FOR WEIGHTS MATRIX D1360S_2 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.027647     0.770716    0.440875
Lagrange Multiplier (error)          1     0.337966    0.561006
Kelejian-Robinson (error)           13    29.763783    0.005093
Lagrange Multiplier (lag)            1     0.081782    0.774897

FOR WEIGHTS MATRIX D1360S_3 (row-standardized weights)
TEST                           MI/DF        VALUE        PROB
Moran's I (error)             0.053642     1.118663    0.263284
Lagrange Multiplier (error)          1     0.912309    0.339502
Kelejian-Robinson (error)           13    29.763783    0.005093
Lagrange Multiplier (lag)            1     0.126458    0.722133
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FOR WEIGHTS MATRIX D1420S_1 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)            -0.003888     0.131230     0.895594
Lagrange Multiplier (error)          1     0.014382     0.904542
Kelejian-Robinson (error)           13    24.591618     0.026104
Lagrange Multiplier (lag)            1     0.067326     0.795270

FOR WEIGHTS MATRIX D1420S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.019994     0.707559     0.479219
Lagrange Multiplier (error)          1     0.235869     0.627206
Kelejian-Robinson (error)           13    24.591618     0.026104
Lagrange Multiplier (lag)            1     0.125846     0.722779

FOR WEIGHTS MATRIX D1420S_3 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.042983     1.037213     0.299637
Lagrange Multiplier (error)          1     0.724934     0.394530
Kelejian-Robinson (error)           13    24.591618     0.026104
Lagrange Multiplier (lag)            1     0.197652     0.656623

FOR WEIGHTS MATRIX D1480S_1 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.022444     1.132419     0.257458
Lagrange Multiplier (error)          1     0.588081     0.443162
Kelejian-Robinson (error)           13    18.255192     0.148068
Lagrange Multiplier (lag)            1     1.143421     0.284931

FOR WEIGHTS MATRIX D1480S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.042346     1.359729     0.173916
Lagrange Multiplier (error)          1     1.195978     0.274127
Kelejian-Robinson (error)           13    18.255192     0.148068
Lagrange Multiplier (lag)            1     1.332369     0.248384

FOR WEIGHTS MATRIX D1480S_3 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.062671     1.488546     0.136607
Lagrange Multiplier (error)          1     1.655256     0.198245
Kelejian-Robinson (error)           13    18.255192     0.148068
Lagrange Multiplier (lag)            1     1.527139     0.216542

FOR WEIGHTS MATRIX D1600S_1 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)            -0.000777     0.343123     0.731506
Lagrange Multiplier (error)          1     0.001058     0.974048
Kelejian-Robinson (error)           13    14.582683     0.334124
Lagrange Multiplier (lag)            1     0.335993     0.562151

FOR WEIGHTS MATRIX D1600S_2 (row-standardized weights)
TEST                           MI/DF        VALUE         PROB
Moran's I (error)             0.018205     0.803129     0.421900
Lagrange Multiplier (error)          1     0.276319     0.599124
Kelejian-Robinson (error)           13    14.582683     0.334124
Lagrange Multiplier (lag)            1     0.514883     0.473032
```

FOR WEIGHTS MATRIX D1600S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.038623	1.053324	0.292193
Lagrange Multiplier (error)	1	0.715010	0.397786
Kelejian-Robinson (error)	13	14.582683	0.334124
Lagrange Multiplier (lag)	1	0.713177	0.398391

FOR WEIGHTS MATRIX D1800S_1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.001306	0.666369	0.505175
Lagrange Multiplier (error)	1	0.004810	0.944707
Kelejian-Robinson (error)	13	6.981616	0.903096
Lagrange Multiplier (lag)	1	0.001962	0.964669

FOR WEIGHTS MATRIX D1800S_2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.019120	0.950727	0.341743
Lagrange Multiplier (error)	1	0.373828	0.540925
Kelejian-Robinson (error)	13	6.981616	0.903096
Lagrange Multiplier (lag)	1	0.014610	0.903793

FOR WEIGHTS MATRIX D1800S_3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.039416	1.139644	0.254435
Lagrange Multiplier (error)	1	0.821153	0.364843
Kelejian-Robinson (error)	13	6.981616	0.903096
Lagrange Multiplier (lag)	1	0.081277	0.775574

FOR WEIGHTS MATRIX D11000S1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.019009	0.995905	0.319296
Lagrange Multiplier (error)	1	0.404165	0.524946
Kelejian-Robinson (error)	13	3.549433	0.995109
Lagrange Multiplier (lag)	1	2.194781	0.138479

FOR WEIGHTS MATRIX D11000S2 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.037689	1.124653	0.260736
Lagrange Multiplier (error)	1	0.787799	0.374767
Kelejian-Robinson (error)	13	3.549433	0.995109
Lagrange Multiplier (lag)	1	2.426478	0.119301

FOR WEIGHTS MATRIX D11000S3 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.037689	1.124653	0.260736
Lagrange Multiplier (error)	1	0.787799	0.374767
Kelejian-Robinson (error)	13	3.549433	0.995109
Lagrange Multiplier (lag)	1	2.426478	0.119301

FOR WEIGHTS MATRIX D11800S1 (row-standardized weights)

TEST	MI/DF	VALUE	PROB
Moran's I (error)	0.000784	1.036574	0.299934
Lagrange Multiplier (error)	1	0.002862	0.957333
Kelejian-Robinson (error)	13	5.969260	0.947265
Lagrange Multiplier (lag)	1	0.618952	0.431437

```
FOR WEIGHTS MATRIX D11800S2 (row-standardized weights)
TEST                            MI/DF        VALUE         PROB
Moran's I (error)             0.016613     0.966781     0.333653
Lagrange Multiplier (error)          1     0.344737     0.557108
Kelejian-Robinson (error)           13     5.969260     0.947265
Lagrange Multiplier (lag)            1     1.678244     0.195158

FOR WEIGHTS MATRIX D11800S3 (row-standardized weights)
TEST                            MI/DF        VALUE         PROB
Moran's I (error)             0.035927     1.101101     0.270853
Lagrange Multiplier (error)          1     0.741878     0.389060
Kelejian-Robinson (error)           13     5.969260     0.947265
Lagrange Multiplier (lag)            1     2.182529     0.139585

FOR WEIGHTS MATRIX D1ALLS_1 (row-standardized weights)
TEST                            MI/DF        VALUE         PROB
Moran's I (error)             0.000447     1.017774     0.308785
Lagrange Multiplier (error)          1     0.000942     0.975510
Kelejian-Robinson (error)           13     4.751905     0.980256
Lagrange Multiplier (lag)            1     0.481880     0.487572

FOR WEIGHTS MATRIX D1ALLS_2 (row-standardized weights)
TEST                            MI/DF        VALUE         PROB
Moran's I (error)             0.016639     0.970245     0.331924
Lagrange Multiplier (error)          1     0.347043     0.555792
Kelejian-Robinson (error)           13     4.751905     0.980256
Lagrange Multiplier (lag)            1     1.664839     0.196951

FOR WEIGHTS MATRIX D1ALLS_3 (row-standardized weights)
TEST                            MI/DF        VALUE         PROB
Moran's I (error)             0.035891     1.100643     0.271052
Lagrange Multiplier (error)          1     0.740953     0.389356
Kelejian-Robinson (error)           13     4.751905     0.980256
Lagrange Multiplier (lag)            1     2.180181     0.139798
```

Chapter 8
Conclusions

The central theme of this work has been the relationship between economic growth, and technological change. In particular, the role of human capital in innovative activities and, therefore, as a determinant of technological progress has been interpreted as the central element in an explanation of how regional economies grow and why their levels of per capita income differ.

Clearly, the relation between economic growth and technological progress is not a new issue. Apart from classical economists, like Smith and Marx, who extensively discussed this question, the work of Schumpeter, and his *Theory of Economic Development*, is often cited as the seminal contribution to the understanding of technological progress. More or less at the same time, Harrod and Domar tried to integrate the elements of economic growth with Keynesian analysis. Writing in the period between the Great Depression and World War II, these authors shared the widespread belief that the capitalist system was inherently unstable. The period of stable growth that followed determined a profound revision of this belief and the traditional neoclassical model set out by Solow, Swan and many others reflected this change. This model predicted the existence of a unique and stable growth path determined by the exogenous rates of technological progress and labour force growth.

Recently, the interest in the relationship between economic growth and innovation has resurfaced within different streams of theoretical work. Whilst all traditions place the process of technological change at the centre of their explanations of economic growth, the way in which this is done differs profoundly in fundamental features. At one extreme, the evolutionary tradition provides insights into the nature of the process of technological change. Much of the theoretical work within this tradition, however, relies primarily on appreciative theory, that is on less abstract, more descriptive modelling. At the other end of the spectrum, interest in economic growth recently rekindled within mainstream economics when a solution was found to the treatment of the relationship between the endogenous nature of technological change and the public good aspect of technological change. This recent work on endogenous growth tries to codify some of the elements emphasised by evolutionary theorists by employing the formal, more abstract modelling tools of the mainstream economic tradition. Within both frameworks, technological progress is either seen as the by-product of other economic activities or the intentional result of research efforts carried out by profit seeking agents.

Of particular interest for the present work is the relationship between technological progress, knowledge spillovers and space. This aspect has been investigated by evolutionary theorists but essentially ignored by endogenous growth theorists; in many of the existing endogenous growth models, the flow of knowledge cannot be separated from the flow of intermediate goods whilst in others knowledge spillovers are exogenously limited by national boundaries, regardless of the trade regime. Evolutionary theorising, instead, draws a distinction between abstract and tacit knowledge; whilst the first is public and ubiquitous, the second, being the non-written personal heritage of individuals or groups, is naturally concentrated in space. It therefore offers a framework within which to analyse the geographical dimension of these spillovers. Chapters 5 and 6 present the development of an abstract model of economic growth that tries to incorporate these features.

Before proceeding to do that, however, the main empirical works on growth and technological change have been analysed to provide empirical guidance for the model building phase. One basic result of the existing analyses of growth is that the mainstream empirical approach to the convergence issue, namely cross-sectional regressions of growth rates over initial levels, appears inadequate to shed light on the cross-sectional distributional dynamics. As a result an alternative methodology was developed building on the recent contributions of Quah. This was presented in Chapter 4. The analysis uses a Markov chain approach in which particular attention has been devoted to the development of an adequate methodology to treat the problem of the definition of a discrete income space. The choice of the income class size has then been made by following a procedure that guides the selection among a set of possibilities obtained from different optimising criteria. The transition probability matrix determined in this way made it possible to analyse not only the one-period dynamics and the resulting ergodic distribution, but also transitional dynamics as well as the calculation of the speed at which the steady-state is approached.

The other major issue emphasised Chapter 4 concerns the definition of regions and their impact on the empirical results. In particular, it has been argued that administrative criteria for the definition of regions – which bear little relation to the regional socio-economic sphere – are inadequate. Therefore, the analysis adopted a set of 122 major European Functional Urban Regions (FURs). The Markov chain analysis employed points to the conclusion that the process of regional economic growth at work in the EU over the period 1979-1990 was characterised by a tendency towards divergence. In particular, six of the European functionally defined regions: Düsseldorf, Hamburg, Stuttgart, München, Paris, and Frankfurt, showed a tendency to grow away from the others. The other regions exhibited a bimodal distribution within the stationary cross-sectional distribution, suggesting a further distinction between poor regions and middle-income regions.

These conclusions are then considered in the subsequent chapters (5 and 6) while developing an endogenous growth model in the tradition of Romer (1990a and b), Rivera-Batiz and Romer (1991a and b) and Rivera-Batiz and Xie (1993), but which also tries to accommodate the influence of space by taking inspiration from some evolutionary ideas. Two basic results of the model can be emphasised. Firstly, even within a system that retains many of the typical neoclassical assumptions, the perfect-foresight equilibrium of the model is characterised by the presence of permanent differences in per capita income levels. By resorting to a definition of research activities that recognises the important role played by spillovers of both tacit and abstract knowledge, the explanation suggested here is that income disparities owe their existence to a process of regional specialisation between 'knowledge creating' and 'knowledge applying' regions. The ability to innovate within a regional economy depends on the interaction between the macro-economic system and the different factors shaping the regional innovation system. The result is the development of a location-specific ability to innovate which has been referred to as the regional technological competence in research. Those regions which are better able to innovate through the development of a superior technological competence in research will be characterised by a relative specialisation in research activities and thus become 'knowledge creating' regions. Since research activities tend to make a more intensive use of human capital than manufacturing activities, the process of research concentration in one location leads to a parallel concentration of human capital. Moreover, since wages for human capital tend to be higher than wages for unskilled labour, the concentration of human capital in one region implies that the average level of per capita income in this 'knowledge creating' region will be higher than that in the 'manufacturing' region.

Secondly, the model also offers a possible explanation of the effects of a process of integration on the existing regional disparities within the EU. The results support the idea that a process of integration that produces a reduction in the cost of physical distance can increase the rate at which the economic system as a whole grows in the long-run. There is, however, a price to pay. The model implies that increased integration of this type also tends to increase regional differentials. By enhancing the attractiveness to research activities of the more innovative regions, integration of this type causes a further concentration of research within these regions and exacerbates the existing income disparities rather than reduces them. The new steady-state equilibrium growth path is characterised by faster growth, but also by an increased gap in the levels of per capita income. The transition towards this new equilibrium therefore witnesses different regional rates of per capita income growth, with the more innovative regions performing best. In the long-run, regional rates of per capita income growth converge to a common constant rate again and the ratio of regional levels of per capita income stabilises, but to a higher value than the one that existed before integration. An alternative form of integration, represented in the model as greater cultural and institutional homogeneity, would not involve these costs of increased disparities.

The main predictions of the theoretical model were empirically tested in Chapter 8. The results of the cross-sectional regression analysis presented in this chapter lend some support to the ideas put forward in the model, particularly with regard to human capital and innovation, the key elements in the theoretical explanation. They can be summarised as follows. Firstly, innovation activities appear to play an important role in the process of regional growth. The coefficients for the variables measuring regional research efforts are always positive and highly significant. Secondly, by considering different specifications of the spatial interaction between researchers, it was possible to find evidence supporting the existence of spatial spillovers of knowledge. The influence if inter-regional spillovers of knowledge appears to be maximised if interactions are assumed to extend to about 2 hours of travelling time. Thirdly, several factors affecting the regional growth rate of per capita GDP by shaping the local level of technological competence in research have been identified. One of these factors appears to be the existence of universities. Universities it was argued contribute to the regional research effort both directly, in their role as centres of research, and indirectly, as that part of the regional infrastructure that provides new human capital. Data limitations do not allow these effects to be analysed separately. Nonetheless, the results provide support to the conclusion that some combination of these effects has a significant positive impact on regional growth. Finally, another interesting outcome concerns the controversy on the relative importance of intra-industry and inter-industry dynamic spillovers in promoting growth. An index of the degree of sectoral specialisation of regional industrial specialisation has been used to shed light on this issue. The results indicate that, during the period 1979-1990, European regions characterised by a higher degree of sectoral specialisation have grown faster than regions with a more diverse industrial structure. In other words, intra-regional dynamic spillovers appear to have been more influential than inter-regional dynamic spillovers in fostering regional economic growth.

Data Appendix

Definition of the FURs

The present analysis adopts functionally defined regions centred on the spatial sphere of socio-economic influence of its urban core. In general, functional definitions follow two main models. The first one is represented by the Standard Metropolitan Statistical Areas (SMSAs), defined by the United States Bureau of the Census since 1940. SMSAs are derived from county-level data on the basis of a two-step procedure: firstly, a 'central city' of at least 50.000 inhabitants is identified. Secondly, contiguous counties evincing socio-economic integration with the 'central city' – at least 15% of the resident workers commute to the 'central city' – and a 'metropolitan character' – at least 75% of total employment is 'non-agricultural'; population density is at least 150 persons per square mile – are added to the 'central city'.

The second model, the Daily Urban System (DUS) adopted by Berry (1973) in his analysis of the changes in the American urban system during the 60's, is slightly different. On the one hand, the concept of DUS extends even further the emphasis placed on daily commuting. On the other hand, it overcomes the strict core-hinterland distinction of SMSAs for a more complex notion of self-containment with regard to labour and housing markets.

Within Europe, Hall and Preston (1973) and Drewett *et al*. (1976) made the first important attempt to apply the concepts of SMSA and DUS on the basis, respectively, of 1961 and 1966 British Census data. The resulting sets of Standard Metropolitan Labour Areas (SMLA) and Metropolitan Economic Labour Areas (MELA) share a common feature that distinguishes them from their American models: the cores are defined in terms of employment concentration – 20.000 jobs – rather than in terms of population. This feature is also common to the system of European regions derived by Hall and Hay (1980) for 1971, and adopted by Cheshire and Hay (1989) in their analysis of urban problems in Europe between 1951 and 1981, and by Cheshire and Carbonaro (1995 and 1996). Each of these regions, termed Functional Urban Regions (FURs), is derived from a two-step procedure. Firstly, a core is defined by identifying an urban centre with 20,000 jobs or more, and adding all those contiguous surrounding areas – at the lowest level of disaggregation available – which have a density of 12.35 jobs per hectare or greater. Secondly, to each core are added all those contiguous administrative areas from which more workers commuted to the core in question than to any other core. As for the calculation of the GDP series, this is based on the data provided by the Community Statistical Office for NUTS 3 regions, which made it possible to derive a consistent time series for the 122 largest FURs[1] from 1979 to 1991.

The FURs are:

Belgium	Antwerpen, Bruxelles-Brussel, Chaleroi, Liège;
Denmark	Århus, Københavns;
Germany	Aachen, Augsburg, Berlin, Bielefeld, Bochum, Bonn, Braunschweig, Bremen, Dortmund, Düsseldorf, Duisburg, Essen, Frankfurt, Hamburg, Hannover, Karlsruhe, Kassel, Köln, Krefeld, Mannheim, Mönchengladbach, München, Münster, Nürnberg, Saarbrücken, Stuttgart, Wiesbaden, Wuppertal;
Greece	Athinai, Thessaloniki;
Spain	Alicante, Barcelona, Bilbao, Cordoba, Gijon/Aviles, Granada, La Coruña, Madrid, Malaga, Murcia, Palma de Mallorca, Sevilla, Valencia, Valladolid, Vigo, Zaragoza;
France	Bordeaux, Clermont-Ferrand, Dijon, Grenoble, Le Havre, Lille, Lyon, Marseille, Montpellier, Mulhouse, Nancy, Nantes, Nice, Orléans, Paris, Rennes, Rouen, St. Etienne, Strasbourg, Toulon, Toulouse, Valenciennes
Ireland	Dublin;

[1] Defined as those with a core city greater than or equal to 200,000 inhabitants and a total population greater than or equal to a third of a million inhabitants.

Italy	Bari, Bologna, Brescia, Cagliari, Catania, Firenze, Genova, Messina, Milano, Napoli, Padova, Palermo, Roma, Taranto, Torino, Venezia, Verona;
Netherlands	Amsterdam, Rotterdam, S-gravenhage, Utrecht;
Portugal	Lisboa, Porto;
UK	Belfast, Birmingham, Brighton, Bristol, Cardiff, Coventry, Derby, Edinburgh, Glasgow, Hull, Leeds, Leicester, Liverpool, London, Manchester, Newcastle, Nottingham, Plymouth, Portsmouth, Sheffield, Southampton, Stoke, Sunderland, Teeside.

Per Capita GDP

Almost all available data on per capita GDP for the European regions are supplied by the latest version of the REGIO Databank (RD), the database published by the European Community Statistical Office. This data base, supplied by Eurostat, represents the main source of regional statistics for the Member States of the European Union, covering the principal aspects of the economic and social life of the Community. In particular, the database offers information concerning 7 statistical domains – Demography, Economic accounts, Registered unemployment, Community labour force sample survey, Industry and services, Agriculture, Transport – according to the regional breakdown defined by the NUTS classification.

As far as GDP data are concerned, RD provides annual series starting from 1975 for NUTS 2 and from 1977 for NUTS 3 regions. Member States GDPs are broken down in accordance with the regional distribution of gross value added at factor cost, except in the case of Portugal where gross value added at market prices has been used. The data are expressed in Purchasing Power Parities (PPPs) on European Currency Units (ECU), making therefore allowance for differences in the prices of goods and services in different Member States.

At present, data on GDP are not available for the former East Germany, whilst time series are not complete for all countries. At NUTS 3 level, the level used to calculate FURs' series, GDP data are available from 1977 only for Denmark and Luxembourg, from 1979 for Greece, from 1980 for Belgium, Germany – excluding the new East German *Länder* – and Spain – Ceuta and Melilla excluded – and from 1981 to 1994 for Italy. The Dutch regions are included in the data set from 1982 or 1986 in some cases. Observations relative to several years within the period covered by the data set are missing for France, United Kingdom, Ireland and Portugal in which cases complete time series are available only from 1986 for France – with the exclusion of the two Corsican regions and of the *départments d'outre-mer* – and from 1987 for the UK.

The method followed in the estimation of data required by FURs' calculation, makes use of the regional distribution of per capita GDP in the nearest year available. In particular, per capita GDPs at the lowest available hierarchical level are broken down in accordance with the distribution of per capita GDP amongst NUTS 3 regions for the nearest year available. Obviously, this implies that, within each NUTS 2 region, the ratio between per capita GDPs of different NUTS 3 has remained unchanged in these particular years. More generally, if NUTS 3 belonging to different NUTS2 regions are considered, the ratio between levels of per capita GDP in these NUTS 3 regions varies according to the change in the ratio between per capita GDPs of the corresponding NUTS2 regions.

University

The variable reflects the number of (full-time plus part-time) academic staff employed in universities, higher and further education institutions during the 1976-1977 academic year. The sources of data on employment are:

> The International Association of Universities, *International Handbook of Universities*, (7th edition), London: The Macmillan Press, 1978.
>
> Association of Commonwealth Universities, *Commonwealth University Yearbook 1979*, (55th edition), London: The Association of Commonwealth Universities, 1978.
>
> The World of Learning 1978-1979, (29th edition), London: Europa Publications, 1978.

Due to the different national education systems, it has been necessary to identify comparable institutions on the basis of:

The British Council, *International Guide to Qualifications in Education*, (2nd edition), London: Mansell Publishing, 1990.

Coal

The influence of the coal industry is accounted for through a dummy variable related to the presence of coalfields in the FURs' territory. The localisation of the coalfields is derived from the

Oxford Regional Economic Atlas, London: Oxford University Press, 1971.

Port

The variable measures the amount of freight handled (measured in million tonne) in 1978 by European large ports according to the:

Handbuch Der Europäischen Seehäfen, *Die Seehäfen an der Deutschen Nordseeküste – Band III*, Hamburg: Verlag Weltarchiv, 1980.

Services

The variable measures the relative importance of the service sector in 1980. It is calculated as the ratio between the level of employment in service activities and the level of employment in manufacturing and services. The data on employment are derived from the REGIO Databank (Eurostat).

Degree of Industrial Specialisation

The index of specialisation is calculated on the basis of data on employment for 9 industrial NACE classes. In particular, the employment in each regional sector is expressed as a percentage of the total industrial employment in the region. After having ranked the sectors by size, the index of regional specialisation is calculated as the ratio between the total percentage share of employment in the smallest four regional sectors, over the total percentage share of employment in the largest four ones. Thus, if $e_{s,i}$ denotes the share of employment in the s^{th} smallest sector of region i (with $s = 0, \ldots, 9$), the index of industrial specialisation can be expressed as

$$specialisation = \frac{\sum_{s=1}^{4} e_{s,i}}{\sum_{s=6}^{9} e_{s,i}}$$

The index, therefore, ranges between 0 and 1, these two extremes indicating respectively specialisation and diversity in the regional industrial structures. The data on employment 1980 are derived from the REGIO Databank (Eurostat). In the case of Greece and Portugal this source has been complemented by the respective national statistical offices. The 9 sectors considered in the analysis are:

Table DA1 Index of Industrial Specialisation: NACE Classes

	Sector denomination	NACE Classes
1	Energy and Water	1
2	Extraction and Preparation of Metalliferous Ores;	21
	Production and Preliminary Processing of Metals;	22
	Extraction of Minerals other than Metalliferous and Energy-Producing minerals, Peat Extraction;	23
	Manufacture of Non-Metallic Mineral Products.	24
3	Chemical Industry;	25
	Man-Made fibres Industry.	26
4	Metals Manufacture: Mechanical, Electrical and Instrument Engineering.	3
5	Food, Drink and Tobacco Industry.	41, 42
6	Textile Industry;	43
	Leather and Leather Goods Industry;	44
	Footwear and Clothing Industry;	45
	Processing of Rubber and Plastics;	48
	Other Manufacturing Industries.	49
7	Timber and Wooden Furniture Industries.	46
8	Manufacture of Paper and Paper Products, Printing and Publishing.	47
9	Building and Civil Engineering	5

Agriculture

This variable measures the share of total regional employment in agriculture in 1980. As with the other variables calculated from employment data, the source is represented by the REGIO Databank (Eurostat).

Matrices of distances between FURs

Two matrices of distances between pairs of FURs have been produced. The first one reports time distance (measured in minutes) by road calculated using the *Microsoft Automap Road Atlas*. This software takes into account important factors such as varying travel speeds according to different road types, level of congestion and time duration of ferry trips. The second matrix reports the shortest time distance when a choice between airplane and road is available. In this case, the shortest time distance via airplane is computed considering the road distance to the closest airports and the average flight time between airports, and allowing 60 minutes for check-in and other controls for domestic flights and 90 minutes for international flights.

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