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URBAN GRÅSJÖ

Spatial Spillovers of Knowledge Production

- An Accessibility Approach
In memory of Erik and Anders
and to William and Oliver
- my four sons and guiding-stars in heaven and on earth.
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Uddevalla, June, 2006

Urban Gråsjö
Abstract

The main focus of the thesis is on issues concerning production of knowledge. It is a common observation that knowledge activities have a tendency to agglomerate as well as to spill over in space. In order to incorporate geographical proximity, the thesis applies an accessibility approach in which actual travel time distances between locations are used to discount spatial knowledge spillovers. The thesis consists of three individual essays and a joint introduction. The first essay explores to what extent accessibility to R&D conducted at universities and companies can explain the number of patent applications in Swedish municipalities. The second essay analyses the relationship between knowledge accessibility and regional export performance. The knowledge resources used are R&D efforts and university educated labour. Since the distributions of the dependent variables are skewed with a few influential outliers, the estimations are conducted with quantile regressions. The empirical findings indicate that accessibility to university R&D has minor effects on patent production and export performance in Sweden. However, the other used inputs, i.e. accessibility to company R&D and accessibility to university educated labour, are of greater importance. The results also show that knowledge flows transcend municipal borders but that they tend to be bounded within functional regions. The third essay investigates how the inclusion of accessibility variables, i.e. spatially lagged explanatory variables, affects the extent of spatial autocorrelation. The basic proposition is that the inclusion of inputs external to the spatial observation as separate variables reveals spatial dependencies via the parameter estimates. This is confirmed by Monte Carlo simulations. The Monte Carlo Simulations also indicate that problems with spatial autocorrelation and biased parameter estimates are reduced.
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Chapter 1: Introduction and Summary of the Thesis

Urban Gräsjö

1. Introduction

This thesis deals primarily with issues concerning the production of knowledge. Knowledge is a key concept in today’s society and it is easy to understand why. The obvious reason is that investments in knowledge, like education, research and development (R&D), are considered to be crucial tools to spur economic growth etc. As an example, the strategic goal for 2010 set for Europe at the Lisbon European Council in March 2000 is “to become the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion.”

The function that models knowledge production is usually attributed to Griliches (1979). Even though more than 35 years have gone since Griliches modelled the relationship between ‘current level of technological knowledge’ and ‘current and past levels of R&D expenditures’ and much work has been conducted on the subject, there are still many unsolved problems and gaps to fill. Without any attempt to ‘paint the whole picture’ or to cover all aspects of the problems involved, this introductory chapter is set up to introduce the reader to the issues that are addressed in the present thesis.

First, there is a lack of a proper output measure in the knowledge production process. The results of R&D are to a large extent not directly observable. Griliches (1979) discussed the possibility to use patents or publication counts as indices of R&D output and concluded that they are only available for a limited range of sectors and industries. Scholars, however, have

1 Griliches (1979) did not acknowledge that knowledgeable persons and knowledge production activities are spread out in geography and at the same time to a high degree concentrated to agglomerations. However, the original ‘knowledge production function approach’ has later been modified to also accommodate the spatial dimension (Jaffe, 1989; Feldman, 1994; Audretsch & Feldman, 1996)
frequently used these measures in the last decades in their efforts to determine the effects from R&D investments.  

Secondly, knowledge is a phenomenon that has a potential to spill over or flow between agents in an economic system. According to Romer (1990) knowledge spillovers arise because knowledge is a partially excludable and non-rival good. Non-rival in the sense that one agent can use it without limiting its use by others in knowledge production and partially excludable given the possibility to prevent its use in production by others by means of patenting. The non-excludable part of knowledge seems correctly defined if it is assumed to have two portions: a perfectly accessible part consisting of already established knowledge elements (obtainable via scientific publications, patent applications, etc.) and a novel, tacit element, accessible only by interactions among actors in an innovation system. This tacit element of knowledge and the accompanying importance of face-to-face contacts are supported in the growing literature of geographical knowledge spillovers, where it is evident that knowledge is not freely accessible to everybody engaged in research (as stated in Romer, 1990).

In addition, it is a common observation that knowledge activities tend to be agglomerated, i.e. to be clustered and in particular to clusters in large urban regions. Large urban regions offer proximity advantages, which ease knowledge transfusion among economic actors (Vernon, 1962; Glaeser, 1999; Feldman & Audretsch, 1999) and create a proximity-based communication externality (Fujita & Thisse, 2002). As an illustration, Table 1.1 shows the concentration of university educated labour as well as R&D activities to the five largest municipalities in Sweden. From the table it is evident that the knowledge activities (especially R&D) exhibit strong geographical clustering, independently of the distribution of population or employment.

---


3 Polanyi (1966), refers to two types of knowledge: codified knowledge and tacit knowledge.

4 See e.g. Glaeser et al. (1992); Acs, Audretsch, & Feldman (1994); Anselin, Varga, & Acs (1997); Varga (1998, 2000); Breschi & Lissoni (2001 a,b).
Introduction and Summary of the Thesis

Table 1.1: Localisation of knowledge related activities in Sweden, 1999. Concentration to the five largest municipalities in Sweden

<table>
<thead>
<tr>
<th>Activity</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>20.1%</td>
</tr>
<tr>
<td>Employed, by workplace</td>
<td>26.4%</td>
</tr>
<tr>
<td>Labour force with at least three years of university studies</td>
<td>31.3%</td>
</tr>
<tr>
<td>Conducted company R&amp;D</td>
<td>44.2%</td>
</tr>
<tr>
<td>Conducted university R&amp;D</td>
<td>61.6%</td>
</tr>
</tbody>
</table>

*) Source: Statistics Sweden
**) The five largest municipalities by population in Sweden are Stockholm, Göteborg, Malmö, Uppsala and Linköping.
***) R&D is measured in man years

Despite the well-known fact that knowledge tends to spill over in space, there have been very few attempts to model the spillovers in continuous space. The reach of the spillovers from the knowledge source is often modelled with geographical concentric rings with distances reported in kilometres or even simpler with next neighbours. As an alternative, the studies in the present thesis elaborate with an accessibility approach as an instrument to discount the spillover effects spatially. There are several different accessibility approaches and the one chosen can be referred to a class called “gravity-based measures”.

Weibull (1976) narrowed down the measurement of accessibility to those that satisfy certain axioms. The accessibility is calculated with the use of an exponential distance-decay function as the discounting factor (see e.g. Martellato, Nijkamp & Reggiani, 1998). The accessibility approach gains another dimension if it is used at different spatial scales. If, for instance, the locations under study are municipalities and the municipalities in such a study can be separated into functional regions which can be approximated with local labour market (LLM) regions, it is possible to define the accessibility on three spatial levels, accessibility (i) within a municipality, (ii) to municipalities within a LLM region and (iii) to municipalities outside the LLM region.

The definition of a functional region is based on the spatial interaction patterns of economic agents in a country. It is characterised by its density of economic activities, social opportunities and interaction options (Ciccone & Hall, 1996; Johansson 1997). Density is a positive factor for the individual firm.

---

5 See e.g. Handy & Niemeier (1997) or Baradaran & Ramjerdi (2001)

6 The accessibility approach has, beside the author, been used and further developed by several scholars at Jönköping International Business School (JIBS), see e.g. Johansson, Klaesson & Olsson (2002, 2003); Andersson & Ejermo (2004 a, b); Andersson & Karlsson (2004, 2005); Karlsson & Pettersson (2005).
since it creates accessibility to suppliers, potential buyers and other actors. Accessibility is obtained by a combination of density and infrastructure, which facilitates particularly high factor mobility within the functional region’s border. What factors will then set the limits of the functional region? Basically it has to do with which primary resource has the largest geographical interaction costs and thereby establishes a geographical border for factor mobility. Disregarding fixed resources such as land and natural resources the major limiting factor normally is the labour force and its propensity to commute. The geographical interaction costs between different market places for work are for households, in principle, equal to the total costs for moving between market places, that is, between different labour markets. According to this conceptualisation, functional regions become equal to local labour markets (Karlsson & Stough, 2002). The functional region is a core concept in all three studies in the present thesis. Earlier studies dealing with spatial knowledge spillovers have normally been based on a division in administrative regions, which do not need to be functional regions.

The title of the first study in the thesis is *Accessibility to R&D and Patent Production*. By using the accessibility approach, it investigates to what extent R&D conducted at universities and companies can explain the number of patent applications in Swedish municipalities. The relationship between patents and R&D has of course been studied by several scholars, but never before with the accessibility approach in combination with municipalities as the research unit.

The second study, *University Educated Labour, R&D and Regional Export Performance*, uses total export value and number of high valued export products in municipalities as output measures in a knowledge production framework. The questions in focus are (i) to what extent R&D efforts and university educated labour affect regional export performance and (ii) is it R&D efforts or university educated labour that best explains the variations in export performance between Swedish municipalities? There is a widespread agreement that knowledge is important for international competitiveness and hence of successful export performance. Therefore, it is strange that there are so few empirical studies where export is used as an output in a knowledge production process in a spatial context.7

In both papers, the estimations are conducted with quantile regressions, since the distributions of the dependent variables are heavily skewed with a few very influential outliers. Furthermore, quantile regression enables an investigation of the whole distribution (at different conditional quantiles) instead of, as in least squares regressions, at a single point (the conditional mean). Despite the appropriateness of quantile regression in studies dealing

---

7 One exception is Breschi & Palma (1999). They evaluate to which extent localised knowledge spillovers can affect trade performance in high technology industries in Italy.
with knowledge and innovation, the empirical examples using this regression technique for estimating knowledge productions functions are few.\textsuperscript{8} 

The third study, \textit{On the Specification of Regression Models with Spatial Dependence - An Application of the Accessibility Concept}, investigates how the inclusion of spatially lagged explanatory variables affects the extent of spatial autocorrelation. The study promotes the use of inputs external to a spatial observation as separate variables, as the first step to reveal spatial dependence and spatial spillovers. In many empirical studies, scholars leave out this first natural step and instead estimate model specifications with spatially lagged dependent variables or spatially lagged errors.

The remainder of this introductory chapter is organized as follows. Section 2 starts with a brief review of the importance of knowledge and knowledge production on economic growth. This is followed by a presentation of the characteristics of knowledge and why it tends to spill over. Then, measurement and modelling issues are discussed. Section 2 ends with estimation considerations. In section 3, the outline of the thesis and the main results of the studies in the thesis are presented.

\section{Knowledge production}

\subsection{The importance of knowledge and human capital for economic growth}

The idea that knowledge and skills have an economic value is not new. Since the time of Adam Smith, economists have known that acquired skills have an effect on productivity, output, wages, etc. One of the first to formalize this notion into a theory of human capital was Schultz (1961). To emphasize the importance of investment in human capital in understanding economic performance, Schultz (1961, p.3) wrote:

\begin{quote}
"This knowledge and skill are in great part the product of investment and, combined with other human investment, predominantly account for the productive superiority of the technically advanced countries. To omit them in studying growth is like trying to explain Soviet ideology without Marx."
\end{quote}

\textsuperscript{8}The only example (to my knowledge) of quantile regression in a knowledge production setting is Audretsch, Lehmann & Warning (2005). They use the distance in kilometres of a new firm to the closest university as the endogenous variable in their examination of the impact of university output on locational proximity.
In recent times, human capital theory and neoclassical growth theory, have been brought together to address the issue of externalities related to higher education. The traditional human capital theory has focused on the private rather than social gains from education and has consequently not dealt with externalities. In the same way, the traditional neoclassical growth theory (Solow, 1956) assuming competitive markets, predicts that all factors of production would be rewarded according to their social marginal contribution to production. Hence, private and social returns are always equalized and there is no possibility for externalities. Furthermore, the traditional growth theory only includes capital and homogeneous labour as factors of production, so the role of education in the creation of human capital is not emphasized. The Solow (1956) and Swan (1956) steady state model (no changes in technology) with the input factors, capital \(C\) and labor \(L\) of the production \(Y\) process has the following form:

\[
Y = F(C, L) \quad (2.1)
\]

The function \(F\) is assumed to have constant returns to scale and the technology to be exogenously determined. One of the first to introduce endogenous technical change was Kaldor (1961). He stated the existence of a “technical progress” (learning) function, that per capita income was an increasing function of per capita investment. Thus, “learning” was regarded as a function of the rate of increase in investment. Arrow (1962) had a similar view of the importance of “learning”. But he related the learning function to the absolute level of knowledge already accumulated (and not to the rate of growth in investment). In Arrow’s model workers accumulate knowledge through a learning-by-doing process and knowledge is assumed to be the engine of growth. However, rather than providing a sector where individuals choose their levels of human capital, the model suggests that knowledge is a by-product of capital accumulation. He assumed that the total capital stock in the economy determines the state of the technology \(T\), which in turn affects production in the following manner

\[
Y_i = T(C)F(C_i, L_i) \quad (2.2)
\]

where the index \(i\) stands for firm \(i\). Thus, the total capital stock \(C\) is a productive force external to the firms (i.e. a Marshallian externality) and is assumed to be a free public good.

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See for instance Becker (1964). Becker developed a theoretical model for deciding whether to invest in education. In the model, the direct costs and indirect costs (missed income) are measured against the benefits (the additional earnings resulting from education). Becker also distinguished between general and specific training. General training creates skills and knowledge that are portable; that is, they enhance productivity wherever the worker might go.
Denison (1967) used a production function in order to identify the contribution of different factors to the increase in the gross national product of the United States between 1910 and 1960. Increases in the quantity of labour and physical capital did not explain the increase in gross national product. There was a large “residual factor”. Denison suggested that improvements in the quality of the labour force, including increased education, were important, together with other factors such as technological progress and economies of scale.

The inability of the neoclassical theory to adequately explain the diversity in growth experiences has led to the development of other theories. In Romer’s (1986) equilibrium growth model of endogenous technological change, long-run growth is driven primarily by the accumulation of knowledge (measured by private R&D efforts). Romer’s production function has the following form:

$$Y_i = T(K)F(K, C, L)$$  \hspace{1cm} (2.3)

where $K_i$ stands for the results of private R&D efforts by firm $i$ and $K$ denotes the aggregate stock of research results in the economy. In the neoclassical context, knowledge is considered a public good, perfectly available to everybody in the economy. Romer’s growth theory proposes a positive externality in the production of knowledge because knowledge is assumed not perfectly patented.

With the growth literature following Romer (1986), a new generation of models came to explain growth. Those models used the presence of externalities as the growth engine. Lucas (1988) provided a model where human capital is the growth engine. He assumed that there is a sector for the production of physical capital and a sector for the production of human capital, and that human capital ($H$) and not physical capital (as in Arrow, 1962) is the factor driving technology:

$$Y_i = T(H)F(C, L)$$  \hspace{1cm} (2.4)

Hence, the model suggests that the human capital sector is the source of externalities in the economy.

In Romer (1990), knowledge is thought of as a non-rival and partially excludable good. Non-rival in the sense that knowledge can be “consumed” simultaneously by many economic agents without limitations and partially excludable because the use of new knowledge can be restricted to a patenting firm for a period of time. Hence, new technological knowledge in a specific firm can be used in its production and prevented to be used in other firms’ production. However, the new knowledge can spill over to other firms, for

---

10 This is often referred to as the “Solow residual”.
example by studying the patenting documentation (Romer, 1990), and thereby increases the total stock of knowledge.

An assumption in Romer (1990) is that everybody engaged in research can access the total stock of knowledge freely. This is an assumption that really can be questioned because transferring and absorbing new economic knowledge may require face-to-face contacts since the nature of the new knowledge can be very complex. As a consequence, the geographical proximity to the source of knowledge decides to a large extent the accessibility to the stock of knowledge (Karlsson & Manduchi, 2001). This was established in an early study by Andersson & Mantsinen (1980). They showed that the long-run growth in a multiregional economy depends on the different regions’ accessibility to the knowledge stock in the regions.

2.2 The characteristics of knowledge

Knowledge is a broad concept and the intention here is not to provide a complete description of its many dimensions.\(^\text{11}\) The intention is instead to present some of the characteristics of knowledge that is important for explaining why geographical proximity matters in the spill over process.\(^\text{12}\)

First of all, one has to distinguish between information and knowledge. Knowledge gives its owner the capacity for intellectual or physical action, i.e. a cognitive capability. Information, on the other hand, consists of structured and formatted data that remains passive until used by those with the knowledge needed to interpret and process the information (David & Foray, 2003). While the cost of replicating information is low, reproducing knowledge is a far more expensive process because cognitive capabilities are not easy to express explicitly or to transfer to others (Kobayashi, 1995). Audretsch & Feldman (1996) argue that even though the cost of transmitting information may not change with distance, most likely the cost of transmitting knowledge rises with distance.

According to Johansson (2005), knowledge can be transmitted in different ways. First of all, knowledge flows can be purely transaction-based. In this case, there is an explicit agreement of transaction of knowledge between the parties involved. Such transactions can either be monetary payments of knowledge or represent R&D cooperation. Secondly, knowledge may take the form of knowledge spillovers, i.e. unintended side effects of ordinary activities.

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\(^{11}\) See Karlsson & Johansson (2004) for a thorough presentation of knowledge in economic theory.

\(^{12}\) Besides geographical proximity, several authors (Piore and Sabel, 1984) argue that cultural proximity, i.e. the sharing of the same norms and values, is an important factor when sensitive valuable information is exchanged (for instance in a joint innovation project).
Knowledge spillovers can in turn be mediated by market mechanisms or be a pure externality. A pure externality in this context is for example when companies observe and copy techniques from each other.

Models based on theories of localisation suggest that just because knowledge spills over does not mean that it transmits without costs across geographic space. In particular, these theories argue that geographic proximity reduces the cost of accessing and absorbing knowledge spillovers.

Fundamental to the theories of localised spillovers is the distinction between codified and tacit knowledge. According to Polanyi (1966), knowledge can be divided in two categories: codified (explicit) knowledge and tacit (implicit) knowledge. Codified knowledge is transmittable in a formal, systematic way and does not require direct experience of the knowledge that is being acquired. On the other hand, tacit knowledge is context-dependent, often deeply embedded into an ‘organizational culture’, and difficult to codify. Hence, tacit knowledge includes relationships, norms, values, and standard operating procedures. Von Hippel (1994) refers to “sticky knowledge”, when he shows that contextual and uncertain knowledge can only be communicated or transferred through face-to-face contacts and network types of relationships, which require spatial proximity.

Even though codified knowledge may also increase the possibility for a firm to produce new or improved products or processes, it is tacit knowledge that constitutes the competitive edge and the most important basis for innovations. When everyone has relatively easy access to explicit/codified knowledge through modern communication technology, the creation of unique capabilities and products depends on the production and use of tacit knowledge (Maskell & Malmberg 1999). Hence, in the era of information and communication technology, it may be so that spatial proximity as a prerequisite for communicating tacit knowledge is more important than ever.

In the last decades, there have been a number of empirical studies that explore the geographic aspects of knowledge spillovers and the localized relationships between private and university R&D and innovative firms. Jaffe (1989) is generally considered to be the first important study where a geographical dimension was added to the knowledge function approach. The empirical findings in this study indicated that corporate patent activity increase as a result of R&D expenditures undertaken by universities within the same state. Several other studies following Jaffe (1989) confirmed that knowledge spillovers tend to be geographically bounded within the region where the new economic knowledge was created.  

---

2.3 Measuring and modelling knowledge and knowledge spillovers

As described above, the importance of knowledge spillovers is well established and their existence is fundamental to the theory of endogenous growth (Romer, 1986, 1990; Aghion & Howitt, 1998). There are, however, problems associated with measuring spillovers. Griliches (1979, 1992) identified three problems:

1. Distance – spillovers decline with distance (market distance, technological distance, geographical distance)
2. Lag structure – spillovers are not likely to be instant or uniform
3. Incentives to do R&D – spillovers gain competitors.

Of these problems, the present thesis addresses the problem with geographical distance. Most of the current Geographic Information Systems (GIS) functionality assumes that the entities in a spatial system can be expressed as coordinates in a Euclidean plane. That is, they all have coordinates positioning them with respect to a predetermined reference frame. However, representation in a Euclidean space is not always the most appropriate model (e.g. travel time distance and qualitative distances). The majority of the studies in the literature apply distances measured in kilometres in order to discount knowledge flows spatially. However, if data is available, it is always better to use actual travel time between locations (Beckmann, 2000). Time distances take differences in regional infrastructure into account. The inability to reveal such disparities is a major drawback of conventional geographical distance. Time distances are also crucial when it comes to attending to business meetings and to determine the spatial borders of labour markets (Johansson & Klaesson 2001).

One way of modelling spatial knowledge spillovers is to use an accessibility indicator. Accessibility is a concept with many different interpretations, which can be expressed in many different ways. A common feature is that it almost always expresses a “mass of attraction” discounted by the difficulty of reaching it (e.g. in terms of money, time distance or physical distance). The “mass of attraction” in knowledge spillovers is for instance the amount of R&D conducted at a location. Hansen (1959, p.73) argued that accessibility can be seen as the “potential of opportunities for interaction”. A wide variety of ways to measure accessibility can be found in the literature. Most measures can be classified as one of three basic types (Handy and Niemeier 1997)\textsuperscript{14}:

1. **Cumulative opportunities measures** count the number of opportunities reached within a given distance or travel time and give an indication of the range of choices available to individuals.

\textsuperscript{14} This is only one of many classifications that can be found in the literature. See for example Baradaran & Ramjerdi (2001) or Geurs & Ritsema van Eck (2001) for alternatives.
2. **Gravity-based measures** are derived from the denominator of the gravity model used to predict trip distribution; these measures weight the amount of the opportunity at different destinations by the cost, time, or distance to get there.

3. **Utility-based measures** are based on the random utility theory, in which the probability of an individual making a particular choice depends on the utility of that choice relative to the utility of all choices; the accessibility measure comes from the denominator of the model and reflects the total utility of all choices.

Equation (2.5) shows a general form for the gravity-based measures.

\[
A_i = \sum_{j \in L} O_j f(c_{ij}, \beta)
\]  

(2.5)

where \(A_i\) is the accessibility in location \(i\), \(L\) is a set of locations (e.g. a region or a country), \(O_j\) represents the mass of opportunities available (regardless of if they are chosen or not), \(f(c_{ij}, \beta)\) is the distance discounting function (other names are distance decay, impedance or friction function), \(c_{ij}\) is a variable that represents cost (e.g. time distance) between location \(i\) and \(j\), and \(\beta\) is the cost parameter usually estimated from a destination choice model (see Johansson, Klaesson & Olsson, 2002, for the Swedish case).

The studies in the present thesis apply the accessibility approach in Equation (2.5). The set \(L\), i.e. Sweden, is divided into several subsets, i.e. local labour market (LLM) regions. The location \(i\) is a municipality and every municipality belongs to a LLM-region. The opportunities \(O_j\) are university R&D, company R&D or university educated labour in municipality \(j\). The distance discounting function, \(f(c_{ij}, \beta)\), is a negative exponential function and \(c_{ij}\) is travel time between municipality \(i\) and \(j\).\(^{15}\) With the negative exponential form of the distance decay in Equation (2.5), it can be shown that this accessibility also is an example of an utility-based measure (see Andersson & Gråsjö, 2006).\(^{16}\)

There are several advantages of using an accessibility measure like the one in Equation (2.5) to model knowledge flows. Accessibility provides a connection

\(^{15}\) The negative exponential function, \(e^{-\beta c}\), of distance or travel time is closely tied to the travel behaviour theory and often produces good results when compared with other measures (Handy and Niemeier, 1997; Kwan, 1998; Song, 1996). Several other forms of distance decay functions have been used in accessibility studies. An inverse power function, \(c^{-\alpha}\), has for example been used by Hansen (1959). Ingram (1971) used a modified version of the Gaussian function, \(e^{-d^{2}/\nu}\).

\(^{16}\) Andersson & Gråsjö (2006) is also the third study in the present thesis.
between the functional and the spatial component of an urban system (Bertuglia & Occelli, 2000). It defines the range and temporal organization of economic opportunities available in space as well as the cost of overcoming space in order to explore the opportunities in different locations. Accessibility accounts for the size of an opportunity in a location and discounts the value of the opportunity with time distance in a way that reflects the willingness to explore that opportunity given its size and distance. Accessibility is also a robust operational measurement tool which makes spatial proximity operational (Karlsson & Manduchi, 2001).

Besides calculating accessibility values between different municipalities, it is also possible to express an intra-municipal (local) accessibility with travel time $c_r$. The cost parameter $\beta$ takes three different values ($\beta_L$, $\beta_R$ and $\beta_X$) depending on the spatial level:

(i) L - intra-municipal (local), within municipality $i$
(ii) R - intra-regional, between municipality $i$ and $r$ within LLM-region $R$
(iii) X - inter-regional, between municipality $i$ and $k$, with $k$ located outside $R$

For a municipality $i$ in LLM-region $R$ we have the following total accessibility

$$A_i = O_i e^{-\beta_L c_{ii}} + \sum_{r \in R, k \neq i} O_i e^{-\beta_R c_{ir}} + \sum_{k \in R} O_k e^{-\beta_X c_{ik}}$$  \hspace{1cm} (2.6)

If the three terms in (2.6) are used separately in a knowledge production function as explanatory variables, it is possible to identify potentially important local, intra-regional and inter-regional knowledge flows. This way of handling knowledge spillovers, with spatially lagged explanatory variables, is an example where the effects are modelled.

Following Anselin (2003), the spatial effects can be either (i) unmodelled, (ii) modelled or (iii) both unmodelled and modelled. If the spatial externalities are global, i.e. every location is correlated with every other location, but the correlations decrease with distance, the inclusion of a spatial multiplier effect of the form $(I - W)'$ models the spatial effects. Equation (2.7) - (2.9) show the three structural forms.

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17 Johansson, Klaesson & Olsson (2003) estimated these cost (or time sensitivity) parameters by using data on commuting flows within and between Swedish municipalities in 1990 and 1998.
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Unmodelled effects:  
\[ y = x\beta + (I - \lambda W)^{-1}u \]  
(2.7)

Modelled effects:  
\[ y = (I - \lambda W)^{-1}x\beta + u \]  
(2.8)

Both effects:  
\[ y = (I - \hat{\lambda} W)^{-1}x\beta + (1 - \hat{\lambda} W)^{-1}u \]  
(2.9)

with \((I - \hat{\lambda} W)^{-1} = I + \hat{\lambda} W + \hat{\lambda}^2 W^2 + \ldots \) and \(|\hat{\lambda}| < 1\)

where \(y\) is the dependent variable, \(W\) is a spatial weight matrix, \(\lambda\) is a spatial autoregressive parameter, \(x\) is a matrix of independent variables, \(\beta\) is a vector of regression parameters and \(u\) is a vector of independent disturbance terms, \(u \sim N(0,\sigma^2)\).

The question is then which model to choose. The answer depends very much on the case under study. Let us follow an example, where the objective is to determine to what extent R&D can account for the variations in municipalities’ patent production.

- If the interest is limited to the local effects of R&D, i.e. how R&D conducted in municipality \(i\) affects patent production in municipality \(i\), then the answer is unmodelled effects.
- If the interest is to find both the local effects and the spatial spillovers of R&D, i.e. how patent production in municipality \(i\) is affected by R&D efforts in municipality \(i, j, k, \ldots\), then the answer is modelled effects.
- If the interest is to estimate local effects of R&D and spatial dependencies of patent production, i.e. how patent production in municipality \(i\) is affected by R&D efforts in municipality \(i\) and patent production in municipality \(j, k, \ldots\), then the answer is both effects.

Hence, if the objective is to estimate the importance of spatial spillovers of explanatory variables, then the first choice has to be ‘modelled effects’. If the chosen spatial weight structure is the right one and if all explanatory variables are found, then there is no problem with spatial autocorrelation. Problems only arise if the there is an unobserved latent explanatory variable, say \(z\). Omitting such a variable causes a misspecified model, no matter if \(z\) is spatially dependent or not. If \(z\) is spatially dependent, then the true model is

\[ y = (I - \lambda W)^{-1}x\beta + (I - \lambda W)^{-1}z\gamma + u^*, \quad u^* \sim N(0,\sigma^2). \]  
(2.10)
Estimating Equation (2.8) if Equation (2.10) is the true model is only correct if $z$ has no systematic effect on $y$, that is if $\gamma = 0$. This is apparent if one combines (2.8) with (2.10):

$$u = (I - \lambda W)^{-1} z \gamma + u^*$$  \hspace{1cm} (2.11)

and $E[u] \neq 0$

If tests show omitted spatially lagged variables and if it is impossible to get data of these variables, then the alternative is ‘both unmodelled and modelled effects’, i.e. Equation (3). Estimating Equation (2.9) if Equation (2.10) is the true model gives the following relation between the errors:

$$(I - \lambda W)^{-1} u = u^*$$  \hspace{1cm} (2.12a)

$$u = (I - \lambda W)u^*$$  \hspace{1cm} (2.12b)

and $E[u] = 0$

Consequently, statistical reasons may force you to avoid a model like ‘modelled effects’ although economic theory may tell you otherwise. This is of course always the last way out but reviewing the literature gives by hand too many examples of the opposite. A common way of handling spatial effects is to refer to Anselin (1988a) and the two traditional spatial models: spatial lag and spatial error, and to run Lagrange Multiplier tests (see e.g. Anselin, 1998b) to be guided in which model to choose and then estimate the chosen model with Maximum Likelihood. This is a strange way of handling these problems. Instead, the natural first step ought to be to model the spatial dependencies with spatially lagged explanatory variables and then in a next step test for any remaining unmodelled spatial effects. This is especially true if the underlying economic theory suggests existence of externalities, which is the case in studies of innovation, R&D and knowledge (see e.g. Audretsch, 2003).

2.4 Estimation considerations

There are many things to consider before deciding what estimation procedure to choose. When dealing with knowledge production and data on for example R&D and patents, there are often statistical problems that have to be dealt with such as heteroscedastic disturbances, collinear data, distributions that are
skewed, censored and/or heterogenous. In many of these situations, least squares regressions are not adequate and another regression technique is required. One alternative, that solves many of these problems, is quantile regression introduced in Koenker & Bassett (1978). The regression technique may be viewed as a natural extension of least squares estimation of conditional mean models, to the estimation of a group of models for conditional quantile functions. The simplest case is the median regression estimator that minimizes a sum of absolute residuals. The other conditional quantile functions are estimated by minimizing an asymmetrically weighted sum of absolute residuals. The group of estimated conditional quantile functions offers together a much more complete view of the effect of covariates on the location, and the scale and shape of the distribution of the response variable (Koenker & Hallock, 2001).

An important motivation for quantile regression has been its inherent robustness to outlying observations in the response variable. The quantile regression estimator gives less weight to outliers of the dependent variable than least squares estimators, or to put it differently and to quote Koenker & Hallock (2000, p.17):

“While mean regression tends to follow a single outlier like a rat behind the Pied Piper, the influence of an outlying observation on $\hat{\beta}(\tau)$ is bounded. Indeed, moving observations away from the quantile regression in the y-direction has no effect whatsoever on the fit. This insensitivity has been occasionally misinterpreted, but it is fundamental to the nature of the quantiles. As in mean regression, outlying x observations can be highly influential in quantile regression, but the problem is not quite so severe.”

Thus, every observation of the dependent variable can be made arbitrarily big or small without changing the results. Besides being robust to outliers, the technique is also robust to potential heteroscedasticity. This is achieved because the parameter estimates for the marginal effects of the explanatory variables are allowed to differ across the quantiles of the dependent variable. Furthermore,

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8 According to Silverberg & Verspagen (2004), it has been recognized in the literature for some time that the highly skewed and possibly fat-tailed distribution of returns from R&D projects poses a tricky problem for the management of innovation (see e.g. Scherer and Harhoff, 2000).

9 In contrast, least-squares regression assumes that the covariates affect only the location of the conditional distribution of the response, and not its scale or any other aspect of its distributional shape.

10 $\hat{\beta}(\tau)$ is the parameter estimate at the $\tau^{th}$ quantile.
when the error terms are non-normal, quantile regression estimators may be more efficient than least squares estimators. The main advantage, though, is the semi-parametric nature of the approach, which relaxes the restrictions on the parameters to be constant across the entire distribution of the dependent variables. Much of applied statistics may be viewed as an elaboration of the linear regression model and related estimation methods of least squares. When describing these techniques, Mosteller & Tukey (1977) comment:

“What the regression curve does is give a grand summary for the averages of the distributions corresponding to the set of x’s. We could go further and compute several different regression curves corresponding to the various percentage points of the distributions and thus get a more complete picture of the set. Ordinarily this is not done, and so regression often gives a rather incomplete picture. Just as the mean gives an incomplete picture of a single distribution, so the regression curve gives a correspondingly incomplete picture for a set of distributions.”

The first two studies in the present thesis use quantile regression in order to overcome some of the problems described above and to take advantage of the appealing features of the technique when dealing with conditional heterogeneous distributions.

3. Outline of the thesis and summary of the papers

Chapter 2 - Accessibility to R&D and Patent Production - investigates to what extent accessibility to university R&D and company R&D can explain patent production in Swedish municipalities. Knowledge production functions are estimated for all industrial sectors together and for different industrial sectors separately with the number of patent applications as dependent variable and local, intra-regional and inter-regional accessibility to R&D (company and university) as explanatory variables. The results from the regressions on an aggregated level indicate that investments in company R&D have a positive impact on the patenting capacity in a municipality, while there is no evidence that university R&D affects patent production. In accordance with the literature, the results show that spatial proximity matters for establishing a productive link between R&D efforts and the number of patent applications.

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21 The text is quoted from Koenker & Hallock (2001, p. 154). Buchinsky (1994, p.453) has also said “'On the average' has never been a satisfactory statement to conclude a study on heterogeneous populations".
By using the accessibility concept on the three spatial levels, it is clear that local accessibility dominates the other two accessibilities. The local effects are statistically significant for municipalities with a patent production above the median. The results also indicate that investments in R&D have a greater impact on patent production in municipalities with high patenting activity. Knowledge flows within a functional region, measured by intra-regional accessibility to R&D, are also of some importance. The population size of a municipality plays also a role explaining patent production. Big municipalities in Sweden with large populations produce, ceteris paribus, more patents than smaller ones. The regression results show that it requires a lot of R&D and/or infrastructural improvements to accomplish patent applications. Nevertheless, there are municipalities that perform better than others do and concentrated investments could be worthwhile. A conclusion is that concentrated R&D investments in companies situated in municipalities with a high patenting activity would not only gain the municipalities themselves, but also the patent production in other municipalities in the functional region.

The third chapter – *University Educated Labour, R&D and Regional Export Performance* – focuses on how knowledge and knowledge diffusion affect exports at the regional level. This is done by estimating knowledge production functions with total export value and number of high valued export products in Swedish municipalities as outputs. In order to account for spatial proximity, the explanatory variables are expressed as accessibilities to R&D and university educated labour at three spatial levels (local, intra-regional and inter-regional). Although multicollinearity problems make it difficult to separate the effects of the explanatory variables, the empirical findings indicate that accessibility to university educated labour is the factor that drives the export performance the most. Accessibility to university R&D seems to have very little impact on exports. The total value of exported products is mainly affected by local accessibility to university educated labour (and company R&D). The intra-regional and to some extent the inter-regional knowledge flows play a more important role when the output is the number of high valued export products in Swedish municipalities.

The econometrical issues addressed in chapter 2 and 3 are similar. When dealing with innovation indicators at the regional or the municipal level there are often problems with spatial autocorrelation and heteroscedasticity. The data of the dependent variables also often contains a few very influential observations (outliers). The findings in chapter 2 and 3 indicate that the use of the accessibility concept enables estimations without getting spatially autocorrelated error terms. The decomposition of the total accessibility into three spatial levels and the inclusion of these separated accessibilities, i.e. spatially lagged explanatory variables, in the regressions is a successful approach to handle knowledge spillovers. The estimations in chapter 2 and 3 are conducted with quantile regressions with a bootstrap procedure to avoid problems with too small standard errors.
The final chapter - *On the Specification of Regression Models with Spatial Dependence - An Application of the Accessibility Concept* - investigates how the inclusion of spatially discounted variables on the ‘right-hand-side’ (RHS) in empirical spatial models affects the extent of spatial autocorrelation. The basic proposition is that the inclusion of inputs external to the spatial observation in question as a separate variable reveals spatial dependence via the parameter estimate. One of the advantages of this method is that it allows for a direct interpretation. Monte Carlo simulations applied on the model specifications in Anselin (2003) show that the coefficient estimates of the accessibility variables are significantly different from zero in the case of ‘modelled effects’. The rejection frequencies of three typical tests (Moran’s $I$, $LM$-lag and $LM$-err)$^{22}$ are significantly reduced when these additional variables are included in the model. When the coefficient estimates of the accessibility variables are statistically significant, it suggests that problems of spatial autocorrelation are significantly reduced. Simulation results also imply that the bias of the parameter estimates is reduced when accessibility variables are incorporated into the model. Thus, by including spatially lagged explanatory variables on the RHS, the problem with biased parameter estimates is reduced even if the underlying spatial structure is spatially lagged dependent variables (both unmodelled and modelled effects). In addition, the parameter estimates are much more efficient when the accessibility variables are included in the regressions. The findings also support the use of the accessibility concept for spatial weights.

In summation, this thesis contributes to the research field focusing on the spatial extent of knowledge spillovers and it extends the literature in this field in four dimensions:

1. *Application of a regionally varying accessibility measure.*

   This thesis promotes the use of an accessibility measure that discounts the knowledge spillovers with actual time distances. The accessibility concept used in the thesis has several advantages. Firstly, it incorporates “global” knowledge spillovers and does not only account for the impact from neighbours or locations within a certain (Euclidean) distance band. Secondly, the separation of the total effect into local, intra-regional and inter-regional spillovers captures potential productive knowledge flows between locations and makes the inferential aspects more clear. Thirdly, distance is often measured by physical distance, but a better way to measure it is to use the time it takes to travel between different locations.

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$^{22}$ See e.g. Cliff & Ord (1972); Burridge (1980); Anselin, (1988b); Anselin & Florax (1995)
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2. *Estimating the effect of knowledge inputs to regional export.*
   This thesis promotes the use of exports as an output measure of a knowledge production process. In spite of theoretical advances regarding knowledge and international competitiveness, still very few empirical works exist attempting to verify the relationship between localised knowledge spillovers and regional export performance.

3. *Providing a Monte Carlo study on the effect of spatially lagged explanatory variables on spatial error and lag dependencies.*
   This thesis promotes the use of a model with spatially lagged explanatory variables (accessibility variables) to explain the effects of knowledge spillovers. Spatial dependence is not only an econometrical issue it is also evidence of spatial spillovers. A model with spatially lagged explanatory variables captures and reveals spillover effects and allows for a direct interpretation.

4. *Focusing on the problems with influential outliers and skewed distributions.*
   This thesis promotes the use of quantile regression as an alternative to OLS. Quantile regression is recommendable when the dependent variable has influential outliers and a skewed distribution. However, it is a suitable regression technique also when the research unit is heterogeneous with respect to the explanatory variables and an investigation over the entire conditional distribution is desired. In addition, quantile regression is an appropriate method when there is a heteroscedastic error structure, since the dependent variable is investigated, and the marginal effects are estimated, at different conditional quantiles. Despite the fact that many innovation indicators, such as R&D expenditure, patents etc., are far from being homogenous on firm or regional level, very few (if any) empirical studies estimating knowledge production functions have used quantile regressions.

The general conclusions that can be extracted from the empirical parts of the thesis are:

- R&D conducted at universities has only minor (direct) effects on patent production and export performance in Sweden. The other applied measures (accessibility to company R&D and accessibility to university educated labour) are of greater importance.
- The reach of beneficiary knowledge flows depends on the output measure used in the analysis. The total export value in Swedish municipalities is only affected by intra-municipal (local) knowledge flows. The number of patent applications and the number of high
valued export products are influenced by local and intra-regional accessibility to the knowledge source.

It could be the case that university R&D affects the investigated outputs indirectly through its feasible impact on conducted company R&D. The relation between university and company R&D and their combined effect on the knowledge output needs further study and is a question for future research. Furthermore, the supply of students and graduates that constitutes the base of the university educated labour is certainly large in regions where university R&D is large. Recent studies (c.f. Faggian & McCann, 2006) also indicate that university R&D is mainly accessed indirectly via labour-market transactions.

One dimension that has not been taken into consideration in the present thesis is the potential impact from abroad. However, due to lack of data it has not been possible to include international accessibility to R&D in the analysis. One way to account for the impact from foreign countries is to include import flows in the analysis. For instance, accessibility to high valued import products or to special import groups could be useful measures that affect the knowledge production. This is a natural extension of the work presented in this thesis.
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Chapter 2: Accessibility to R&D and Patent Production

Urban Gråsjö

Abstract

The main purpose in this paper is to study to what extent accessibility to R&D can explain patent production. Therefore a knowledge production function is estimated both on an aggregated level and for different industrial sectors. The output of the knowledge production is the number patent applications in Swedish municipalities from 1994 to 1999. In order to account for the importance of proximity, the explanatory variables are expressed as accessibilities to university and company R&D. The total accessibility is then decomposed into local, intra-regional and inter-regional accessibility to R&D. As often is the case with R&D outputs, the regional distribution of patents is highly skewed with influential outliers. The estimations are therefore conducted with quantile regressions. The main results on an aggregated level indicate that high accessibility (local) to company R&D has the greatest positive effects on patent production. The effects are statistically significant for municipalities with a patent production corresponding to the median and to quantiles above the median. Local accessibility to university R&D is only of importance for certain industrial sectors and not on an aggregated level. There is also evidence that intra-regional accessibility to company R&D affects patent production positively. A conclusion is that concentrated R&D investments in companies situated in municipalities with a high patenting activity would not only benefit the municipalities themselves, but also the patent production in other municipalities in the functional region.

Keywords: innovations, patents, R&D, knowledge production
Chapter 3: University Educated Labour, R&D and Regional Export Performance

Urban Gråsjö

Abstract

The main purpose of the study in this paper is to establish to what extent accessibility to R&D and university educated labour can explain regional export performance. This is done by estimating knowledge production functions, with total export value and number of high valued exports in Swedish municipalities from 1997 to 1999 as outputs. In order to account for geographical proximity, the explanatory variables are expressed as accessibilities to R&D and university educated labour. The total accessibility is divided into three geographical levels; local (within the municipality), intra-regional and inter-regional accessibility to R&D and university educated labour. R&D conducted at universities and in companies is measured in man-years and university educated labour is measured by the numbers of people with at least three years of university studies. The estimations are conducted with quantile regressions since the distributions of the dependent variables are highly skewed with a few very influential outliers. The results in the paper indicate that accessibility to university educated labour has the greatest positive effects. The value of exported products is mainly affected by local accessibility to university educated labour (and company R&D). The intra- and inter-regional accessibilities play a more important role when the number of high valued export products in Swedish municipalities is the output.

JEL Classification: C14, O18, R11

Keywords: knowledge production, R&D, exports, quantile regression
Chapter 4: On the Specification of Regression Models with Spatial Dependence – An Application of the Accessibility Concept

Martin Andersson & Urban Gräsjo

Abstract

Using the taxonomy by Anselin (2003), this paper investigates how the inclusion of spatially discounted variables on the ‘right-hand-side’ (RHS) in empirical spatial models affects the extent of spatial autocorrelation. The basic proposition is that the inclusion of inputs external to the spatial observation in question as a separate variable reveals spatial dependence via the parameter estimate. One of the advantages of this method is that it allows for a direct interpretation. The paper also tests to what extent significance of the estimated parameters of the spatially discounted explanatory variables can be interpreted as evidence of spatial dependence. Additionally, the paper advocates the use of the accessibility concept for spatial weights. Accessibility is related to spatial interaction theory and can be motivated theoretically by adhering to the preference structure in random choice theory. Monte Carlo Simulations show that the coefficient estimates of the accessibility variables are significantly different from zero in the case of modelled effects. The rejection frequency of the three typical tests (Moran’s I, LM-lag and LM-err) is significantly reduced when these additional variables are included in the model. When the coefficient estimates of the accessibility variables are statistically significant, it suggests that problems of spatial autocorrelation are significantly reduced. Significance of the accessibility variables can be interpreted as spatial dependence.

JEL Classifications: R15, C31, C51

Keywords: accessibility, spatial dependence, spatial econometrics, Monte Carlo simulations, spatial spillovers
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