Regional Innovation and the Geography of Research Collaboration in Science-based Industries

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Regional Innovation and the Geography of Research Collaboration in Science-based Industries

Regionale innovatie en de
geografie van onderzoekssamenwerking
in science-based sectoren

(met een samenvatting in het Nederlands)

Proefschrift

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Roderik Ponds
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Chapter 1
Introduction

1.1 Knowledge spillovers and geography

The mid-sized city of Vlaardingen, near Rotterdam, is home to one of the largest research centres of multinational Unilever. The main function of this research centre is to develop new innovative consumer products in the field of nutrition. The location in Vlaardingen is mainly a by-product of the historical decision by one of the predecessors of Unilever to move to Rotterdam to take advantage of direct proximity to the seaport. Vlaardingen, however, can neither be considered a high-tech city nor is it close to the most relevant universities. A senior staff member of Unilever, when asked why the research lab of Unilever was still located in Vlaardingen, answered that Vlaardingen is an excellent location due to its proximity to the city of Wageningen. Wageningen is home to the only agricultural university in the Netherlands and a large range of related research institutes focusing on fields of particular interest to the research conducted in Vlaardingen. However, Wageningen is located in the middle of the country and is not, at least in the Netherlands, considered to be proximate to the city of Vlaardingen – certainly not by policymakers in the regional economic development field.

This anecdote shows that the relationship between geographical proximity and knowledge flows is more complex than is often assumed. The notion of geographically localized knowledge spillovers has drawn a lot of attention of researchers in the field of regional economics and economic geography. The presence of localized knowledge spillovers is often regarded as one of the main forces driving the agglomeration of knowledge intensive industries and ultimately regional differences in economic growth. Despite the fact that almost all theoretical contributions emphasize the importance of geographical proximity for knowledge spillovers, empirical studies suffer from a lack of consensus on the size and geographical range of these spillovers. This results from the fact that the empirical evidence for localized knowledge spillovers is merely indirect as no attention has been given to the underlying mechanisms. The geographical dimension of knowledge spillovers is determined by the role of geographical proximity in the different mechanisms through which spillovers occur. In order to understand the geographical dimension of knowledge spillovers, empirical research should focus on these mechanisms. Insights on this are, however, only slowly emerging. This study aims to enhance the understanding of the role of geographical proximity for one mechanism of knowledge spillovers by analysing the geographical dimension of collaborative research and the relationship between collaborative research and innovation in science-based industries in the Netherlands.

1.2 Background and relevance

Since the OECD (1996) introduced the term 'knowledge-based economy' policymakers around the globe have embraced the idea that innovation is critical for future economic growth. While the notion that knowledge is a central element for economic growth is certainly not new in economic theory, the relative importance of knowledge is generally believed to be growing. Based on this idea, ambitious strategies and policy schemes have been launched to stimulate the generation and diffusion of knowledge. At the European level, the Lisbon Agenda of 2000 formulated the challenging goal of creating the most competitive economy in the world. R&D and innovation are considered to be the main drivers. Within the Netherlands, the number of different policy initiatives aimed to stimulate innovation has grown over the last several years. Other countries also have introduced similar policies.

Much attention has also been given to the regional dimension of innovation in different countries. The Netherlands is no exception. Despite the flatness of the country, a glance at several national and regional economic policy documents leaves the reader with the impression that the Netherlands exhibits an astonishingly mountainous landscape. According to the Ministry of Economic Affairs (2004), there are several 'peaks in the Dutch delta' formed by economic core-areas such as the Amsterdam and Eindhoven regions, which need to be stimulated to become even higher peaks. At the same time, several local and regional policymakers emphasize the presence of a large range of valleys. These range from the Energy Valley to the Health Valley and have in common the seeming presence of a cluster of an innovative industry in a region or at least, the desire to have it. In this context, the presence of universities and other public research organisations are often hypothesized as crucial factors for the success of regional innovation strategies. Based on well-known success stories from Silicon Valley and the Cambridge life sciences cluster, universities are increasingly regarded as engines for regional economic development. Nearby firms are assumed to gain from the research conducted at universities due to the presence of localised knowledge spillovers.[1] This notion of localised knowledge spillovers has led to a wide range of policy initiatives, but their success is likely to be dependent on understanding the mechanisms through which knowledge is diffused. Because this understanding is only recently emerging, there could be serious doubts on the effectiveness of policy measures aimed at creating or enhancing clusters.

Research on the role and mechanisms of localized knowledge spillovers is embedded in the field of regional and urban economics and economic geography, which are linked by their common interest in the spatial concentration of economic activities. Economic activities are unevenly spread across regions and a large range of studies show that this is even more the case for knowledge intensive industries (e.g. Audretsch and Feldman, 1996; Paci and Usai, 2000). Both urban and regional policymakers and scientists in the field of economics and geography have shown a large interest in the forces that induce this tendency towards concentration. The theoretical argument for the spatial concentration of economic activities is found in the concept of agglomeration economies: spatially bounded

1 In the following, localised knowledge spillovers refer to geographically localised knowledge spillovers (as opposed to other forms of localised knowledge spillovers such as technologically localised knowledge spillovers).

economic externalities resulting from the co-location of firms and other organisations. Regarding innovation, the concept of localised knowledge spillovers is considered to be among the most important forces driving the spatial concentration of innovative activities. Localized knowledge spillovers occur if new knowledge cannot be fully appropriated by the organisation that generated it and 'spills over' to nearby organisations for free or at relatively low costs.[2] The theory holds that knowledge spillovers are localized due to the tacit dimension of knowledge. The exchange of tacit knowledge brings along a need for regular (face-to-face) interactions which are easier and less costly when organisations are located close to each other. Due to the presence of localised knowledge spillovers, the co-location of innovative activities can lead to spatially bounded increasing returns and consequently, a further spatial concentration of specific industries in regions, which are eventually offset by the negative externalities of agglomeration such as congestion or high rents. Universities and other public research organisations are often considered as important sources of knowledge spillovers due to their explicit orientation to the generation and dissemination of scientific knowledge. This is especially the case in science-based industries such as biotechnology and semiconductors, where scientific research is closely related to innovation. Within these industries, firms collaborate intensively with academic research organisations and are often located nearby research universities. It is therefore not surprising that localized knowledge spillovers from universities are often regarded as an important agglomerative force for science-based industries.

Despite Krugman's (1991, p. 153) oft-cited remark that 'knowledge flows are invisible, they leave no paper trail by which they may be measured and tracked,' various studies have tried to analyse the presence and geographical dimension of knowledge spillovers. A large range of econometric studies have found indirect evidence for the presence of knowledge spillovers by relating indicators for knowledge inputs, such as R&D expenditures, to an indicator for innovation, such as patents in a spatial context (e.g. Jaffe, 1989; Audretsch and Feldman, 1996; Anselin et al., 1997). Taken together, these studies conclude that knowledge spillovers from both private and public (e.g. universities) research activities are, to a large extent, localized (for a recent overview, see Döring and Schnellenbach, 2006). However, the conclusions on the magnitude and the spatial range of these spillovers are rather divergent. Apparently, the role of geographical proximity for knowledge spillovers differs across industries and countries. To understand why this is the case, moving beyond the question of whether knowledge spillovers are localized is necessary, and instead, focus must be on the questions of how and why geographical proximity matters for knowledge spillovers. Research on localized knowledge spillovers is increasingly focusing on the underlying mechanisms of knowledge spillovers. In recent, but rapidly growing, literature, three different types of mechanisms are distinguished: labour mobility, entrepreneurship and spin-off dynamics, and knowledge exchange through inter-organisational relationships. Empirical research in this area generally focuses on the role of geographical proximity

2 Note that within the literature, there is no consensus on the definition of knowledge spillovers. The discussion is based on the distinction between pure and pecuniary knowledge spillovers and whether both types can be considered 'real' knowledge spillovers (see for example Breschi and Lissoni, 2001b; Caniels and Romijn, 2003 on this). As discussed in chapter two, the distinction between pecuniary and pure knowledge spillovers is already conceptually difficult, but even harder to maintain within empirical research. In this study, the broad definition of knowledge spillovers, including pure and pecuniary spillovers, is applied.

for these mechanisms based on the notion that knowledge spillovers are geographically localized to the same extent as the underlying mechanisms.

In a related line of research, the role of inter-organisational networks as a mechanism for knowledge spillovers has also received much attention. This partly stems from the notion that processes of knowledge generation are increasingly organised in collaborative networks (Roijakkers and Hagedoorn, 2006), especially in science-based industries where the development of technological knowledge is fast-paced such as biotechnology. The focus in this study is on science-based industries in the Netherlands. Science-based industries are characterised by a high level of innovation, which is largely based on technological development and scientific discoveries (Pavitt, 1984). Within the life sciences, small, dedicated biotechnology firms, pharmaceutical and chemical multinationals, hospitals, and venture capitalists all play pivotal roles in the innovation process (Powell et al., 1996; Cockburn and Henderson, 1998 and Cooke, 2005, 2006). Similar trends are found in other science-based industries like semiconductors, where inter-organisational alliances for research collaboration have become a structural feature in innovation processes (Stuart, 2000). Consequently, inter-organisational research networks are increasingly regarded as the 'locus of innovation' (Powel et al., 1996) in science-based industries. Governments are increasingly aware of the potential value of research collaboration as a mechanism for knowledge spillovers. This is exemplified by the continuously increasing EU budget for collaborative research in the form of different framework programs and, in the Netherlands in 1990s, by the founding of different technology institutes for public-private collaboration. Collaborative research can generate knowledge spillovers in two ways. First, within a collaborative research project, knowledge is exchanged between researchers from different organisations that cannot be specified in formal agreements. Second, research collaboration gives rise to social networks between the researchers involved, and these networks are also likely to be channels through which additional knowledge is exchanged in the future (Breschi and Lissoni, 2003). Science-based industries have a strong tendency towards spatial concentration (Paci and Usai, 2000; Audretsch and Feldman, 2004). Given the importance of collaborative research in science-based industries, localized knowledge spillovers resulting from research collaboration are often considered as an important agglomerative force for these industries. Similarly, cluster policies in science-based industries typically aim to stimulate collaboration and knowledge exchange networks between firms, universities, and other research organisations. However, empirical research on collaborative research suggests that this is not limited to the regional scale. Rather, research collaboration occurs largely at the national or even the international level, implying that subsequent knowledge spillovers are not as localized as often assumed (McKelvey et al., 2003; Hoekman et al., 2008).

Consequently, science-based industries are characterized, somewhat paradoxically, by a spatial concentration in a limited number of regions on one hand and an increasing importance of collaborative knowledge networks at the national and international scales on the other hand. It has been suggested (see for example Cooke 2001, 2005; Owen-Smith and Powell, 2004 and Gertler and Levitt, 2005) that this can be explained by the simultaneous presence of localised knowledge spillovers (fueled by mechanisms like informal knowledge exchange) and knowledge spillovers between a limited number of regions over longer distances (through collaborative research). To explain the spatial dimension of innovation in science-based industries, it is necessary to have a better understanding of the circumstances under which geographical proximity plays an important role for knowledge spillovers. It is exactly this question of the role of geographical proximity for knowledge spillovers that this study tries to answer more conclusively.

1.3 Aim and research questions of this study

The aim of this study is to determine the role of geographical proximity in collaborative scientific research and the role of collaborative research as a mechanism for knowledge spillovers in science-based industries in the Netherlands. Two main research questions frame this study. The first research question focuses on the geographical dimension of collaborative research and is formulated as follows:

Research question 1: What is the role of geographical proximity in research collaboration in science-based industries in the Netherlands?

Geographical proximity is expected to play a role in research collaboration as it decreases the cost of such collaboration. Indeed, such an effect has been found in earlier studies on research collaboration in the UK (Katz, 1994). Yet, several authors (Boschma, 2005 and Torre and Rallet, 2005) argue that geographical proximity is neither a prerequisite nor sufficient for collaboration to occur and that other forms of proximity might play an important role for knowledge exchange as well. Boschma (2005) introduces four notions of proximity in addition to geographical proximity: cognitive, organisational, social, and institutional proximity. Cognitive proximity is related to technological proximity and refers to the overlap between organisations in knowledge base. A certain level of cognitive proximity is considered to be a prerequisite for inter-organisational knowledge exchange to occur (Nooteboom 2004). The other three forms of proximity are assumed to play an important role in overcoming coordination problems and lowering costs by enhancing mutual trust. Social proximity can be defined as the extent to which researchers have friendly relationships. Organisational proximity is defined as the extent to which two researchers are under common hierarchical control, which can be important to coordinate research activities. Institutional proximity can be defined as the extent to which researchers operate under the same incentive structures, which aligns the objectives of researchers. In the context of this study, the main institutional spheres that are important are universities, industry, and government. The presence of other forms of proximity is assumed to make geographical proximity less important for knowledge exchange. This implies that the geographical dimension of knowledge spillovers is related to the interplay between geographical and other forms of proximity, which might be an explanation why knowledge spillovers through the same mechanism can simultaneously occur at different spatial scales. By analysing one specific mechanism for knowledge spillovers, such as research collaboration, and differentiating between other dimensions of proximity, the effect of geographical proximity can be isolated from other forms of proximity. This can lead to a better understanding of the circumstances under which geographical proximity is more or less important for knowledge spillovers occurring through one specific mechanism.

To answer the first research question, the proximity framework is used to disentangle the role of geographical proximity from other forms of proximity. Different types of collaboration are defined on the basis of the organisations involved. A distinction is made between academic research organisations, governmental organisations, and firms, leading to six different types of collaboration (like academic collaboration or academic-industry collaboration). The role of geographical proximity for these different forms of collaboration is analysed in two chapters focusing on the international and regional dimension of research collaboration, respectively. Research collaboration is measured by co-publications. The appearance of multiple organisations in a scientific publication is considered as an indicator of collaboration in the research leading to the published results in a large range of studies (see for example Cockburn and Henderson, 1998; Zucker et al., 1998a; Wagner-Doebler, 2001). In both chapters, the proximity framework is empirically tested by analysing whether collaboration between different kinds of organisations is geographically more localized than collaboration between similar types of organisations, where localization refers to the national or the regional level, respectively. By distinguishing between geographical and institutional proximity (defined as collaboration between the same types of organisations) and analysing different science-based industries separately, the role of geographical proximity for collaborative research is isolated from cognitive or technological proximity and institutional proximity.[3]

The second research question deals with the role of collaborative research as a mechanism for knowledge spillovers:

Research question 2: Does collaborative research constitute a mechanism for knowledge spillovers in science-based industries in the Netherlands?

To analyse whether collaborative research constitutes a mechanism for knowledge spillovers, analysing the effect of research collaboration jointly with other possible mechanisms of spillovers within a single research framework is necessary. This is done in two chapters, which are focused at the level of regions and firms, respectively. At the regional level, the relative importance of collaborative research for knowledge spillovers from academic research is tested in a regional knowledge production framework, while controlling for purely geographically localized spillovers. In doing so, the study presented in chapter six is among the first to include empirical data on spillover mechanisms in a knowledge production framework. At the firm level, the role of collaborative research as a mechanism for knowledge spillovers is compared to informal knowledge exchange. Informal knowledge exchange is considered to be another important mechanism for knowledge spillovers in science-based industries. Since data on informal knowledge exchange is not readily available, data on research collaboration has been combined with data from questionnaires on informal knowledge exchange.[4]

3 Social and organisational proximity are not included in the empirical analyses.

4 Labour mobility and spin-off dynamics are also considered important knowledge spillover mechanisms. As discussed in chapter two, while knowledge spillovers between organisations through inter-organisational relationships can occur sequentially and reciprocally over a longer time period, knowledge spillovers through labour mobility or entrepreneurship are basically occurring at one moment in time. However, both labour mobility and spin-offs are often regarded as important initiating forces for inter-organisational knowledge exchange, be it in the form of research collaboration or informal knowledge exchange.

1.4 Outline of this study

This study contains three parts. The first part places this study within the context of existing literature. Although localized knowledge spillovers were already mentioned as a important agglomerative force by Marshall (1920), renewed interest grew after the rise of endogenous growth models. This has led to a rapidly growing literature in regional economics and economic geography on the geographical dimension of knowledge spillovers and its relationship with the spatial concentration of industries and economic growth. Chapter two will provide an overview of this literature and starts with a short description of the new endogenous growth theory to explain the origins of the renewed interest in knowledge spillovers. Next, the theoretical and empirical contributions to the geographical dimension of knowledge spillovers are discussed. Chapter two ends with a discussion of recent literature that analyses the underlying mechanisms of knowledge spillovers and the role of geographical proximity in these spillovers. The goal is to provide a theoretical background for this study and to position it within the existing literature. The third chapter describes the characteristics of science-based industries, explains the choice for the data, and provides some descriptive insights into the spatial dimension of innovative activities of science-based industries in the Netherlands. The second part of this study focuses on the first research question and addresses the role of geographical proximity for research collaboration. Chapter four consists of the analysis of the international dimension of collaborative research. The regional dimension of research collaboration is analysed in chapter five. The third part of this study deals with the second research question and consists of the analysis of the role of collaborative research as a mechanism for knowledge spillovers. Chapter six

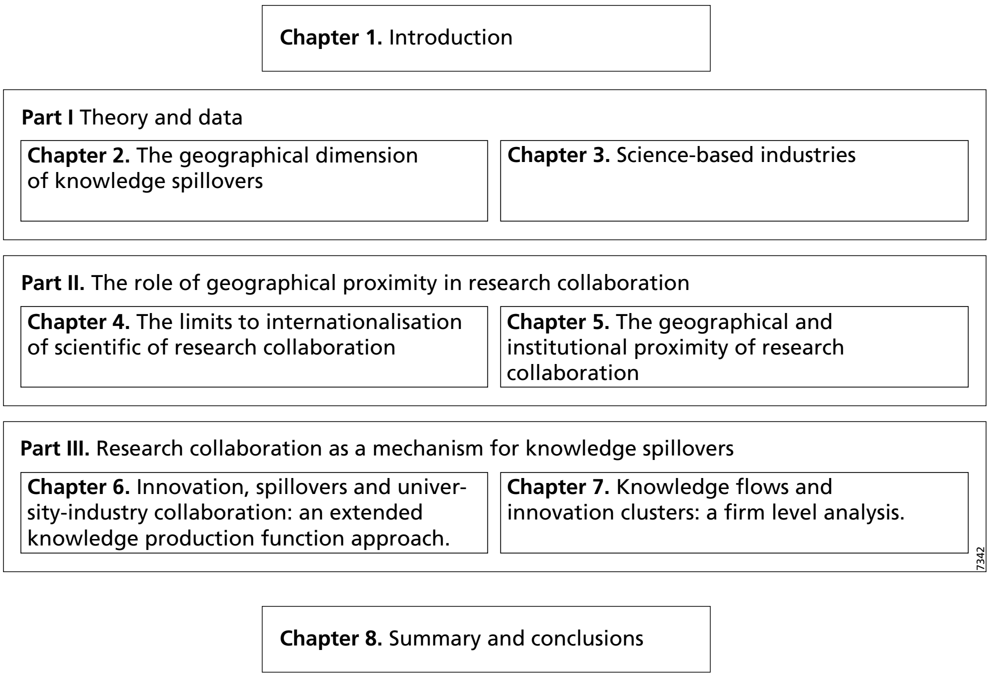

Figure 1.1 - Outline of the study

examines this in a regional knowledge production framework. The comparison between the geographical dimension of informal knowledge exchange and research collaboration and their effect on innovation at the firm level is provided in chapter seven. Chapter eight summarises the most important research findings and presents the conclusions as related to the research questions formulated in this chapter. Furthermore, policy implications and recommendations for further research are given. Figure 1.1 presents a schematic overview of this study.

Chapter 2

The geographical dimension of knowledge spillovers

2.1 Introduction

This chapter provides an overview of the relevant theoretical and empirical contributions on knowledge spillovers, geography, and innovation. Since the introduction of knowledge spillovers within the new endogenous growth theory, knowledge-related externalities are regarded as key to explaining differences in regional growth. Research on the geographical dimension of knowledge spillovers emphasizes that knowledge does not diffuse automatically between places. This is considered to be the result of specific characteristics of knowledge, which accompanies barriers to diffusion of newly generated knowledge. These barriers are often related to geographical distance, leading to geographically localized knowledge spillovers. The presence of geographically localized knowledge spillovers can generate positive returns to scale within a region, leading to an increasing concentration of industries in specific regions and persistent growth differentials. Understanding of the mechanisms of knowledge spillovers and the geographical dimension of these mechanisms is rapidly increasing, but several unanswered questions remain. The goal of this chapter is to review the literature on the geographical dimension of knowledge spillovers. It becomes clear that several directions in research remain relatively unexplored and these form the basis for the following empirical chapters.

The second section of this chapter provides a short overview of the new endogenous growth literature that brought the concept of knowledge spillovers to the forefront of research in regional differences in economic growth. The third section explains why knowledge spills over imperfectly and why there is a geographical dimension to it. Moreover, an overview of the empirical literature on localized knowledge spillovers is given. Section four describes the different mechanisms through which knowledge spillovers occur. Geographical proximity will be shown to play an indirect role regarding the presence and magnitude of knowledge spillovers. Different views have developed regarding how this might occur. Two of the most promising views are discussed in sections five and six. Section seven concludes.

2.2 The source of interest in knowledge spillovers

Interest in localized knowledge spillovers has been growing rapidly in the past few decades, especially in the field of regional and urban economics and economic geography. This is related to the development of new ideas concerning the role of knowledge and technological change in economic growth in the 1980s and 1990s. Economic growth has traditionally attracted much attention from researchers (see, for one of the many overviews of this literature, Verspagen, 2005). Schumpeter already pointed to the crucial role of innovation in processes of economic development. This was also acknowledged in traditional neo-classical growth theories in the 1950s and 1960s (based on Solow, 1956) even though technological development was treated as an exogenous factor. The increasing attention on technological progress as an important determinant of economic growth accumulated in the new endogenous growth theory, where R&D, knowledge spillovers, and technological change were crucial elements.

The most important element in all new endogenous growth models is the notion that knowledge has some characteristics of a public good, which leads to knowledge spillovers. Arrow (1959) is often considered to be one of the first to point to the presence of knowledge spillovers. He argued that firms face difficulties in appropriating the full value of information and inventions. Although patent laws are designed to assign property rights to new inventions, Arrow (1959) points to the fact that only a limited range of information and inventions can actually be patented. Additionally, he also notes that newly generated information is likely to be used for further development of inventions by other firms. According to Arrow (1959), the appropriation of knowledge used as input for research is even more difficult than the appropriation of knowledge used in commodities. With attention for the presence of non-appropriable parts of information and invention, Arrow was among the first to argue that knowledge generation is likely to generate externalities or spillovers.

The incorporation of these spillovers in growth models came with the rise of the so-called new endogenous growth models. Within these models, knowledge accumulation and technological change are considered to form the most important determinants of long-run economic growth. The assumption of knowledge spillovers is crucial. Technological change drives economic growth and results from deliberate investments by firms in the generation of new knowledge through R&D with the goal of producing new products or improving existing production processes.[5] R&D investments generate knowledge externalities or spillovers, which can be used by other firms to develop new products or better production methods. The mere existence of knowledge spillovers is typically explained from the public good characteristics of knowledge. In line with Arrow (1959), knowledge is (implicitly) assumed to be a non-rival and non-excludable good, resulting in firms' free use of knowledge generated by another firm. The presence of these spillovers between individual firms leads to increasing returns to scale at the aggregate level and consequently, to different growth rates between the units of aggregation.

Within the various models of new endogenous growth theory, how these spillovers enter the economy is specified differently. The most important contributions are Romer (1986, 1990), Lucas (1988), Grossman and Helpman (1991) and Aghion and Howitt (1992). A detailed survey of the differences and similarities between these models can be found in Verspagen (1992). According to Acs and Varga (2002), the work of Romer (1990, 1994) is a key contribution to research on the relationship between knowledge spillovers and economic growth differentials. Whereas earlier contributions (Romer, 1986; Lucas, 1988) did not elaborate much on the definition of the characteristics of knowledge, Romer (1990)

5 Note that the assumption of perfect competition is abandoned here in favour of the assumption of monopolistic competition. The formulation of monopolistic competition by Dixit and Stiglitz (1977) is often considered as an important impulse for the development of the new endogenous growth theory.

was the first to formulate knowledge as a non-rival and only partial excludable good. The distinction between appropriable and non-appropriable parts of knowledge is fundamental. Firms have an incentive to invest in knowledge generation only with the presence of an appropriable or excludable part of knowledge, which is used to produce new goods or improve production methods. If new technological knowledge is purely a public good, all new technological knowledge would spill over and consequently no firm would invest in its generation. In Romer's (1990) formulation, only part of the knowledge is excludable for the firm that generated it, whereas the other part spills over to other firms. These knowledge spillovers are assumed to add to a publicly available stock of knowledge available to other firms. Depending on the formulation of the model, this stock of available technological knowledge enters the economy directly by enhancing the productivity of R&D (see e.g. Romer, 1990), or indirectly in the form of higher quality of the capital goods supplied (as in Aghion and Howitt, 1992).

However, the implicit assumption of aggregated non-excludable parts of knowledge as a pure public good implies that long-term growth differences between countries would not exist. Countries would easily catch up due to the immediate contribution of newly generated knowledge in a specific country to the stock of knowledge available to all other countries. To analyse convergence-divergence processes, Romer (1994) relaxed this assumption and introduced country-specific stocks of knowledge. As a result, differences in growth rates between countries could be explained within the framework of endogenous growth models. Economic growth is assumed to depend, among other things, on the size and the increase of the publicly available knowledge, which in turn is a function of the size of the spillovers from investments in new knowledge.

The insights derived from the new endogenous growth models also have important policy implications. If the R&D of individual firms generates spillovers that are beneficial for other firms, this implies that the benefits for society as whole exceed the aggregated benefits for individual firms that perform R&D. Consequently, the actual amount of aggregated R&D expenditures might be lower than the optimal amount from a welfare perspective. Based on this idea, many countries have implemented policies to stimulate R&D, for example, in the form of subsidies or lower taxes. Concerning scientific research, the excludable part of knowledge development is often considered to be relatively small, leading to private investments in fundamental research far below the social optimum (Arrow 1959). At the same time, fundamental scientific research is often considered to function as the basis for more applied research, which can lead to a broad range of innovations. This has often been used as the rationale for public funding of research within organisations, such as universities, that are explicitly oriented towards the dissemination of knowledge.

The crucial role of innovation and technological change for economic development is also emphasized in the field of evolutionary economics (Nelson and Winter, 1982). Nonetheless, some fundamental differences exist. The new endogenous growth theory implicitly assumes a rather deterministic relationship between R&D, innovation, and economic growth. The evolutionary approach, on the other hand, argues that this relationship is rather complex due to fundamental uncertainties regarding the outcomes of R&D processes and the cumulative character of knowledge.[6] Evolutionary economists focus, among other things, on processes of path-dependency, historical accidents, and the institutional context. This has logically led to more heterogeneous models and concepts compared to the new endogenous growth models. Altogether, the evolutionary approach can be considered as analysing the process of innovation in a more realistic way at the costs of having less theoretical and analytical consistency in modeling the relationship between knowledge spillovers and economic growth. Similarly, the models in the new endogenous growth theory are arguably more theoretically and analytically consistent with the cost of less realistic assumptions regarding processes of innovation. Over time, it seems that some evolutionary insights have been incorporated into the new endogenous growth approach, for example, in models focusing on the role of general-purpose technologies (Helpman, 1998). Within these models, the relationship between R&D, innovation, and economic growth is less deterministic, but has a more cyclic structure, which is more in line with the evolutionary view on how technological change evolves.

2.3 Knowledge spillovers and the geography of innovation

2.3.1 Costs of knowledge transmission

The assumption of knowledge spillovers adding to a publicly available stock of knowledge forms an important element of new endogenous growth theory. Although extremely useful for aggregate modeling, within the endogenous growth literature, it was already acknowledged that it is rather unrealistic and not very helpful for a deeper exploration of the concept of knowledge spillovers. As discussed previously, this assumption was relaxed by Romer (1994) with the introduction of country-specific knowledge levels, suggesting that knowledge does not spill over for free around the world. Although Arrow (1962a) argues that the presence of knowledge spillovers is related to relatively low transmission costs, different individuals and nations do not have access to the same amount of knowledge (Arrow 1962b). This is related to the idea that the costs of knowledge transmission might be relatively low, but also differ across transmission channels. For example, international knowledge transmission involves higher costs than transmission between individuals within the same country, which might form an explanation for differences between countries in the size of the accessible knowledge. Although the model aims to explain economic growth of nations while considering externalities of human capital, Lucas (1988) notes that the nation is a rather arbitrary level of aggregation regarding the scope of externalities stemming from technological development. He argues that the external effects of technological development – in the form of human capital externalities – can sometimes be internalised within small groups of people like firms, but in other cases, it

6 The reasons for these differences are in the underlying micro-economic assumptions. An important difference is in the role of uncertainty in R&D processes. New endogenous growth theory acknowledges the fact that R&D investments do not automatically lead to innovation and assumes that the relationship between R&D and innovation follows a probability distribution. Firms can evaluate the probabilities on success (innovation) and firms base decisions on R&D investments on these estimations. Following Knight (1921), the evolutionary approach argues that firms cannot know and cannot estimate this probability function because the possible outcomes of R&D are not known, consequently making identifying a probability function for these outcomes impossible. The decisions and outcomes in innovation processes are assumed to be much more guided by common practices, past experiences, and accident.

more or less directly becomes common property to the society as a whole. He notes that the scope of these externalities is typically between these two extremes and often limited to a specific sector or region. Interestingly enough, Lucas (1988, pp. 37-38) argues that the geographically limited scope of human capital externalities might be an important force behind the mere existence of cities, while referring to Jacobs (1969). So, it was already acknowledged within the literature of endogenous growth theory that the assumption of zero transmission costs of non-excludable parts of knowledge at the aggregate level does not hold.

Building on insights from several earlier studies (Nelson, 1959, 1982; Rosenberg, 1982; Pavitt, 1987), Von Hippel (1994) introduces the term 'stickiness' to refer to transmission costs of a specific unit of knowledge. If these costs are high, the stickiness of knowledge is high. A high level of stickiness implies that this specific unit of knowledge is relatively difficult and costly to exchange and consequently, in the terminology of Lucas (1988), the scope of externalities is rather low. Von Hippel (1994) distinguishes two factors affecting the costs of knowledge transmission: the attributes of the knowledge being transmitted and the attributes of the senders and receivers of the knowledge.

Regarding the nature of transferred knowledge, the distinction between tacit and codified knowledge is crucial. Polanyi (1966) introduced this distinction to refer to the fact that some knowledge is encoded in a rather explicit way, whereas other forms of knowledge are more tacit. Tacit knowledge refers to the notion that 'we can know more than we can tell' (Polanyi, 1966, as cited by Gertler, 2003 p. 77). A large part of skills and expertise of individuals is based on unarticulated rules and manners not observable for others and not easy to specify. Tacit knowledge is therefore assumed to be highly contextual and difficult to codify. Gertler (2003) argues that tacit knowledge can only be exchanged by frequent interaction through demonstration, practice, and meetings, which requires frequent face-to-face contacts and mutual understanding. Consequently, knowledge transmission with a strong tacit dimension involves higher costs than the transmission of codified knowledge, which is assumed to be relatively easy.

The cost of knowledge transmission is also affected by characteristics of senders and receivers, which is related to the cumulative character of knowledge. New knowledge builds largely on existing knowledge, implying that new knowledge can often only be understood in combination with prior knowledge on the subject or having specific skills. Consequently, the knowledge transmission costs are also related to both the receiver and sender's knowledge. Transmission costs are relatively high if receiving organisations have to acquire related knowledge and skills to understand or use received knowledge. Alternatively, sending organisations can face large transmission costs if it has to specially transform knowledge so that the receiver can understand it. Cohen and Levinthal (1990) introduce 'absorptive capacity' to refer to the ability of organisations to learn and use new knowledge. The absorptive capacity of organisations is determined by prior knowledge related to new knowledge and can be influenced by investments in R&D or training. As a result, the transmission costs of the same 'piece of knowledge' can strongly differ between different pairs of organisations, depending on their absorptive capacity.

2.3.2 Tacit knowledge, geography and localized knowledge spillovers

Knowledge transmission involves costs, which implies that knowledge spills over in a far from perfect way. Jacobs' (1969) observation that cities form important engines for economic growth was related to the notion that geographical proximity might play an important role in knowledge exchange. This implies that the costs of knowledge transmission are related to geographical distance, which begs the question of what the geographical dimension of these spillovers is and to what extent knowledge spills over to other economic agents in different countries or regions. Jacobs (1969) distinguished between knowledge and information in relation to the economic functioning of cities. Information is assumed to have a familiar meaning around the world, such as the price of specific share on a stock exchange. Knowledge is assumed to be more specific to context and location and consequently, it is more difficult to exchange, especially over longer distances. The differentiation between knowledge and information rather closely resembles Polanyi's (1966) tacit-codified distinction. It is not a coincidence that the tacit dimension of knowledge has been a central element in the literature on localized knowledge spillovers. This results from the notion that frequent interaction and face to-face contacts are required for the exchange of tacit knowledge. Face-to-face contacts require physical co-location, which imply that the costs of exchanging tacit knowledge rise rapidly with geographical distance. Furthermore, Von Hippel (1994) emphasizes that a minimum level of mutual understanding and trust is necessary for the exchange of tacit knowledge. A common language, shared values, and a similar cultural background greatly enhance the creation of this understanding and trust. Because these elements are, according to some (e.g. Gertler, 2003), geographically defined, this provides another reason for the role of geographical proximity in tacit knowledge exchange. Given that newly generated technological knowledge is, at least temporally, largely tacit, the spillovers associated with it are also often assumed to be largely localized (see Audretsch, 1998).

With the growth of new endogenous growth theory, interest in the role of knowledge spillovers in relation to patterns of spatial agglomeration and regional differences in economic growth also rose. If knowledge spillovers are largely localized, regional differences in knowledge generation form an important explanation for the spatial concentration of industries and regional differences in economic growth. The idea that localized knowledge spillovers are relevant for the spatial concentration of industries was already mentioned by Marshall (1920). Marshall (1920 p. 225) noted that 'when an industry has thus chosen for a location for itself, it is likely to stay there long, so great are the advantages....'. The spatial concentration of an industry within a specific location can lead to increasing returns external to individual firms in that location. Marshall (1920) distinguished between three different forces leading to these increasing returns at the aggregated level, which have been considered to be the major sources of spatial concentration of industries since. The first is based on the advantages of a pooled labour market resulting from the aggregated labour demand of firms. A better matching between the supply and demand of labour leads to lower costs for firms looking for employees with relevant skills or experience. The second is related to how the pooled aggregated demand for intermediate goods leads to the presence of specialised suppliers, which in turn leads to a higher variety of inputs at lower costs. The third is related to the presence of information or technological knowledge spillovers between firms, leading to higher productivity and a faster development of new products and goods. Marshall (1920, p. 225) describes that 'the mysteries of trade become no mysteries, but are as it were in the air, and children learn many of them, unconsciously'. Marshall's account of spatially bounded externalities from the concentration of a specific industry has become a well-known research topic under the heading of agglomeration economies in regional and urban economics, regional science, and economic geography.

2.3.3 The geography of innovation

Within research on agglomeration economies in the field of regional and urban economics, localized knowledge spillovers has gained considerable attention especially during the last two decades. The 'geography of innovation' literature (for an overview see Acs, 2002 and Audretsch and Feldman, 2004) views the presence of localized knowledge spillovers as the main driving force in spatial agglomerations of industries and regional differences in economic growth. Conceptually, this line of literature can be considered to be based on a regionalized version of the new endogenous growth theory (see also Nijkamp and Poot, 1998 for a regional perspective on economic growth theories). The costs of tacit knowledge exchange rise with geographical distance, leading to geographically localized knowledge spillovers. Firms located near to knowledge spillovers generating organisations, such as universities and other firms performing R&D, are assumed to be more innovative[7] and consequently perform better than firms located at longer distances. The presence of localized knowledge spillovers offers an incentive for firms to locate in the geographical proximity of knowledge sources so that they can benefit from these spillovers. The combination of better performing firms within a region and relocation patterns can lead to a further concentration of industries in specific areas. This increasing concentration induces a further increase of localized knowledge spillovers, given the increase of the aggregated sum of the R&D activities of individual firms. Whereas an individual firm might be facing decreasing returns on its investment in knowledge generation, the presence of knowledge spillovers can generate increasing returns at the aggregate level of agglomerations, only to be offset by negative externalities such as higher rents. The presence of increasing returns to scale is assumed to be an important explanation for the spatial concentration of industries and persistent differences in economic growth between regions.[8] Several empirical studies show that industries with relatively high knowledge intensities and high levels of innovation tend to agglomerate (see for example Audretsch and Feldman, 1996 and Brouwer et al., 1999). Low-tech activities, where knowledge spillovers are assumed to be less important, tend to be more spread out and located in more peripheral regions. Within the geography of innovation literature, there is a wide variety of approaches addressing the issue of knowledge spillovers (see for example the special issue in Papers

7 Or innovate at lower costs.

8 Note that there is no consensus in the field of regional and urban economics on the relative importance of knowledge spillovers as agglomeration force compared to other forces. Whereas the geography of innovation literatures sees localized knowledge spillovers as main cause for the presence of agglomeration, 'the new economic geography' (based on the work of Krugman, 1991) argues that the main agglomerating forces are related to transport costs and the first two Marshallian externalities, advantages from labour market pooling and presence of specialized suppliers. Within the strand of literature that assumes an important role for localized knowledge spillovers, the issue of if specialization, diversity, or related variety is most beneficial is the subject of intense debate. Given the focus of this study on the geographical dimension of knowledge spillovers, a discussion of the extensive literature on the sources and mechanisms of agglomeration economies would be beyond the goal of this chapter. Van Oort (2004) and Rosenthal and Strange (2004), provide thorough overviews of this literature.

in Regional Science by De Groot et al., 2001). The two main empirical approaches are discussed here: first, the knowledge production function approach and second, studies on the geographical dimension of knowledge flows measured by patent citations.[9]

The application of production functions in relation to knowledge and innovation was initiated by Griliches (1979). Within the 'knowledge production function' approach, knowledge inputs, typically measured in R&D expenditures, are related to knowledge outputs such as patents. The knowledge production function has been applied at aggregate levels of countries (Griliches, 1984) and industries (Scherer, 1982). The most innovative countries and industries were found to also have the largest R&D expenditures. These results are consistent with the underlying logic of a production function: a higher input leads to a higher output. The relationship between knowledge inputs and innovation output turned out to be less clear at the more micro-economic level of the firm or plant (Acs and Audretsch, 1988). The observation that the knowledge production function model seems to better capture the relationship between knowledge inputs and innovation at the aggregated level than at the level of firms suggests the presence of externalities. This was further strengthened by the notion that small firms were responsible for a large portion of innovations but only for a relatively small portion of private R&D expenditures, suggesting that knowledge spillovers might play an important role (Acs and Audretsch, 1990). The idea that these knowledge spillovers could be largely localized due to the importance of tacit knowledge shifted the unit of analysis from firms to regions.

Jaffe (1989) was the first to empirically analyse the presence of localized knowledge spillovers from university research within a regional knowledge production function approach. This was done using a cross-sectional estimation of the relationship between private and university R&D as knowledge inputs and patents as knowledge outputs at the level of U.S. states. After controlling for state differences in private R&D expenditures, higher university R&D expenditures were found to be related to higher levels of innovation input. This result was interpreted as an indication of the presence of localized knowledge spillovers from university research. After this seminal contribution, the knowledge production function approach has been applied in a wide range of studies at a finer spatial scale (Anselin et al., 1997), using indicators other than patents such as new product announcements (Acs et al., 1992), and by distinguishing the role of knowledge spillovers between industries (Audretsch and Feldman, 1996). Whereas these studies focused on the USA, later studies tried to find evidence for the existence of localized knowledge spillovers in European countries (see for example Fischer and Varga, 2003 for Austria; Del Barrio-Castro and Garcia-Quevedo, 2005 for Spain and Fritsch and Slavtchev, 2007 for Germany).

To deal with possible misspecification due to spatial autocorrelation or unobserved regional heterogeneity, techniques from spatial econometrics (see Anselin, 1998) are increasingly being applied. Earlier studies (Jaffe, 1989) applying the knowledge production framework typically focused on the presence of knowledge spillovers within a region. With the incorporation of spatial-econometric techniques, more attention has also been given to the analysis of R&D spillovers from other regions (Anselin et al., 1997 and Varga, 2000). The

9 An alternative approach is introduced by Florax and Folmer (1992), who analyse the geographical dimension of knowledge spillovers by estimating the impact of university research on the investment in equipment in the manufacturing sector using a multi-regional investment model.

estimation of the spatial range of these spillovers is typically done by including the R&D in other regions weighted by distance, often in the form of a distance decay function or introducing different distance bands (see for example Botazzi and Peri, 2003 and Bode, 2004). Despite a wide range of studies on the geographical dimension of knowledge spillovers, no clear consensus has been reached on the spatial range of these spillovers. This might be related to the heterogeneity of the empirical approaches regarding to spatial scales, selected industries, and time dimensions (see Döring and Schnellenbach, 2006 and the appendix of Fritsch and Slavtchev, 2007 for recent overviews of empirical studies on localized knowledge spillovers). Nonetheless, there seems to be a prevalent consensus that knowledge spillovers are largely localized and that they form an important force for the spatial concentration of industries and regional differences in economic growth. Most studies also emphasize the presence of localized knowledge spillovers from university research, suggesting that the presence of academic research organisations might play an important role for the spatial concentration of knowledge intensive industries. The presence of geographically localized knowledge spillovers is explained within these studies from the presence of distance-related costs of tacit knowledge exchange.

The knowledge production function literature provides indirect evidence for the existence of localized knowledge spillovers and focuses on possible sources. Another line of research explicitly focuses on the geographical dimension of knowledge spillovers and the diffusion of knowledge. An important study was pioneered by Jaffe et al. (1993), who analysed the geographical dimension of knowledge spillovers by researching spatial patterns of patent citations. Reacting to Krugman's statement that research on knowledge spillovers is hardly possible because 'they leave no paper trail by which they can be measured and tracked' (Krugman, 1991, p. 53), Jaffe argued that 'knowledge flows do sometimes leave a paper trail' (Jaffe et al., 1993, p. 578) in the form of patent citations. Next to a detailed description of the patented invention and details on the inventor and applicant, patent applications also include references to other patents and, in some cases, scientific publications. The main goal of these references is to indicate which elements in the patented invention are new and which elements have already been patented. According to Jaffe et al. (1993), these references indicate that cited technological knowledge in patents was somehow useful in the development of knowledge in the citing patent. Consequently, patent citations can be seen as an indicator of spillovers that can be measured and tracked.[10] The geographical dimension of knowledge spillovers has been explored by analysing spatial patterns of patent citations in the US. Controlling for technology and time effects, citations to a specific US patent were shown to be more likely to come from the US and also from the same state and same metropolitan area as the original patent. To control for the effect of existing spatial patterns of patenting in different technologies, which could strongly affect this result, control samples of patents within the same technology that were not cited but came from the same region (either a state or metropolitan area) were used. The probability

10 In a later study, Jaffe et al. (1998) analysed this assumption and concluded that patent citations are a valid although 'somewhat noisy' measure of knowledge spillovers. There is a vivid debate on the validity of patent citations as indicators for knowledge spillovers and conclusions following from this type of empirical studies. See, for example, Alcácer and Gittelman (2006), Criscuolo and Verspagen (2008) and the discussion in the American Economic Review between Thompson and Fox-Kean (2005a, b) and Henderson et al. (2005). Given the increasing number of studies using patent data for studies on knowledge spillovers, it seems that it is currently a widely accepted indicator for knowledge spillovers. This is however also related to the lack of alternative data.

that a patent within a specific technology cites another patent in the same technology from the same region was compared with to the probability of two patents within the same technology coming from that region in general. If the former is significantly higher than the latter, a disproportional portion of citations is localized. Combined with the finding that the probability of citation decreases with geographical distance, Jaffe et al. (1993) interpreted this as empirical evidence that knowledge spillovers are localized. Several other studies have applied a similar approach or, at least, similar data, and came to a similar conclusion (see for example Almeida and Kogut, 1997; Maurseth and Verspagen, 2002 and Jaffe and Trajtenberg, 2002; Verspagen and Schoenmakers, 2004). Again, the geographical dimension of knowledge spillovers is related to the tacit dimension of knowledge.

2.3.4 Economic geography

The role of tacit knowledge is also emphasized in the broad literature in geography that focuses on specific regional circumstances influencing knowledge diffusion. Although it is difficult, if not impossible, to define this field, Breschi and Lissoni (2001a, p.255) describe it as 'the vast and heterogeneous literature dealing with regional agglomerations from a non-mainstream economic viewpoint'. Within this field, insights into the sources for agglomeration advantages are found in sociology, institutional economics, and cultural studies. This line of literature has been referred to as territorial innovation systems (Morgan, 2004), new industrial geography (Martin and Sunley, 1996), or economic geography (Giuliani, 2007). The latter term is used in this study. Although most scholars in this field would oppose the idea of localized knowledge spillovers as used in geography of innovation literature, there is a striking similarity in the importance attached to the notion of tacit knowledge as the underlying reason for the role of geographical proximity. The focus in economic geography is on the role of specific local conditions that ease the exchange of tacit knowledge, whereas the geography of innovation literature focuses on distance-related costs of tacit knowledge exchange. These local conditions can be grouped under the heading of relational assets (Yeung, 2005), untraded interdependencies (Storper, 1995), or institutional thickness (Amin and Thrift, 1995). These assets are not tradable or easily substituted due to their origins in social relationships between organisations located in the regions. The presence of a dense network of these relationships in specific regions result from the existence of specific local institutions and cultures which are assumed to promote mutual trust, and possibly lead to some form of a community consisting of firms, research institutes, and governmental organisations. Knowledge is assumed to diffuse relatively quickly between different organisations located in this type of regions through formal and informal relationships. These relationships foster mutual trust and understanding and, consequently, the exchange of tacit knowledge, which leads to knowledge spillovers. Together, these networks of reciprocal relationships for knowledge exchange constitute the learning environment for local firms through which valuable innovation-related resources, such as new knowledge, new ideas, and information on technological improvements, are accessed (Uzzi, 1996). As a result, these relational assets or untraded interdependencies form an important factor for the competitiveness of firms and the potential for regional economic growth.

Empirical studies are typically based on case studies of a limited number of regions such as Silicon Valley, Emilia-Romagna, and Tuscany, where these relational assets are assumed to form an important factor for economic growth. The goal of these studies is often to detect and describe the specific local conditions that foster the exchange of tacit knowledge between agents in the region. Although potentially rich in explanatory power (Saxenian, 1994 serves as a prime example), the attention to the uniqueness of individual regions also seems to come at the cost of conceptual ambiguity (see also Overman, 2004). This is best illustrated by the wide range of different theoretical concepts, such as industrial districts (see Harrison, 1992 and Markusen, 1996) or learning regions (Morgan, 1997), which all seem to be used in very different ways in empirical studies. Nonetheless, an important contribution of this field is the notion that in addition to distance-related costs, the presence of trust and mutual understanding are also important factors for localized knowledge spillovers. Recognising that this line of literature does not contradict the basic ideas of the geography of innovation literature is important. Both are based on the idea that knowledge spillovers and exchange are largely localized and that this is an important element for regional economic growth.

2.4 The underlying mechanisms of localized knowledge spillovers

The previous sections showed that the concept of localized knowledge spillovers has generated a large strand of literature within the field of regional economics and economic geography. Although fundamentally different, their common contribution is the development of the insight that geography matters for knowledge spillovers. Both lines of literature refer to tacit knowledge to explain the presence of localized knowledge spillovers. Over the years, this explanation has been increasingly considered to be too simplistic. As a result, some of the underlying assumptions and conclusions in both lines of research have been increasingly subject to criticism. The most important critique is related to the indirect nature of the empirical evidence for the presence of knowledge spillovers due to lack of knowledge of the underlying mechanisms. To understand the geographical dimension of knowledge spillovers, understanding the role of geographical proximity in these mechanisms is necessary. These critiques have led to new research that builds upon the insights of the geography of innovation and economic geography.[11] The underlying mechanisms of localized knowledge spillovers are being increasingly explored and the insight on how knowledge actually diffuses across space is growing, but is by no means complete. Another critique, disscussed in the following section, is based on the lack of a clear definition of the concept of knowledge spillovers.

2.4.1 Pure and pecuniary externalities

In an attempt to define the various notions of externalities, Scitovsky (1952) distinguishes between internal and external economies of scale. Economies of scale exist when average costs for firms decrease as the amount of output produced increases. Internal economies of scale refer to the decrease of the average cost per unit output that results from an increase of the total output produced by the firm itself. External economies of scale refer to the situation in which a decrease of the average cost per unit output is related to an increase in the output of one or more industries in total. Scitovsky (1952) distinguishes between two types of external economies of scale. The first consists of 'pecuniary externalities' and

11 Additionally, there is need for a better understanding of the relative importance of localized knowledge spillovers and other sources of agglomeration within the broader research area of agglomeration economies.

refers to externalities that occur through market mechanisms. Within the agglomeration economies literature, these are often related to two types of agglomeration economies distinguished by Marshall (1920): pooled labour market advantages and the presence of specialised suppliers. The second consists of 'pure' externalities and refers to externalities assumed to occur through non-market interactions. Manski (2000) argues that many of the interactions leading to knowledge externalities in R&D and human capital formation occur in non-market environments where mutual understanding and trust are important elements. Similarly, the Marshallian notion of knowledge externalities is often implicitly related to Scitovsky's notion of pure externalities.

Several authors, especially Breschi and Lissoni (2001a, b), have argued that knowledge production functions studies at the aggregate level of regions or cities are often too eager to interpret empirical outcomes as evidence of 'pure' knowledge spillovers when other types of externalities might be of at least equal importance. In this context, knowledge spillovers are defined as pure technological externalities occurring through non-market interactions. Breschi and Lissoni (2001a, b) argue that by assuming that all knowledge spillovers are pure externalities, the distinction between pecuniary and pure externalities becomes blurred. Knowledge spillovers may indeed occur through localized, informal face-to-face contacts which rather closely reflect the notion of pure externalities, but can also occur in a market transaction, e.g. from hiring specialised R&D services, which resembles pecuniary externalities. Breschi and Lissoni (2001a, b) criticise empirical studies that conclude on the presence of 'pure' knowledge spillovers through non-market interactions where it might also concern pecuniary knowledge spillovers. Although this critique seems justified, they neglect that the problem of identification of pure and pecuniary externalities is not unique to the notion of knowledge spillovers. The implicit assumption that the other two Marshallian forces of agglomeration are distinct pecuniary externalities, which can be clearly separated from both pecuniary and pure knowledge spillovers, is also questionable. Combes and Duranton (2006), for example, find that pure knowledge spillovers seem to occur within the labour market as a byproduct and argue that is very hard to consider the labour market and knowledge spillovers as two distinct agglomeration forces. The distinction between pure and pecuniary externalities cannot be as easily applied to the three Marshallian forces of agglomeration as is often assumed.

Moreover, despite the claim by several authors that the distinction between pure and pecuniary externalities is crucial, consensus on the exact definition of both does not seem to exist. Following Scitovsky (1952), whose definition seems to be the same as Breschi and Lissoni's (2001a), pure knowledge spillovers are defined as knowledge transmission through non-market mechanisms. In contrast, Huber (2007) defines pure knowledge spillovers as unintentional knowledge transmission without financial compensation, implying that intentional knowledge transmission without financial compensation is not considered as pure knowledge spillovers. In Scitovky (1952) and Breschi and Lissoni's (2001a,b) conception, this would be defined as a pure knowledge spillover. Caniels and Romijn (2003) define knowledge spillovers as knowledge transmission, intentional or unintentional, that occurs when the actual value of the knowledge is more than the compensation given. Following this definition, pure knowledge spillovers can also involve market transactions. The distinction between pecuniary and pure knowledge spillovers is already conceptually difficult, but becomes even harder with empirical research. For example, assume the following definition of pure knowledge spillovers: pure knowledge spillovers occur if the economic agent that generates the knowledge is not compensated in any way for the knowledge that spills over. Despite the conceptual clarity of this definition and ignoring the issue of data availability, it is still almost impossible to apply in empirical analysis of knowledge transmission due to the difficulties in determining whether an economic agent is compensated. First, there is a temporal problem. Knowledge transmitted without direct compensation might be considered as a pure spillover at the moment of transmission, but this might be only one moment in a continuous relationship between two agents that share knowledge on the basis of reciprocity. What seems to be a pure spillover at one moment in time might turn out to be a pecuniary knowledge spillover over a longer time-period because some form of payment or compensation may eventually be involved. Second, there is a multi-level problem because it is unclear what the correct unit of analysis is to determine whether some form of compensation takes place. The issue of whether the transmission of knowledge can be considered a pure knowledge spillover if the firm that indirectly paid for the knowledge generation is not compensated, but the employee through which it spilled over is, is open to debate. Despite being a heavily debated theoretical issue, the distinction between pure and pecuniary externalities seems conceptually and analytically impossible to solve.

Notwithstanding their critical view on the definition of knowledge spillovers, Breschi and Lissoni (2001b) agree with the idea that knowledge flows, either through market or non-market interactions, can act as a very strong agglomerating force. However, a major contribution of their criticism is that research in the field of knowledge spillovers increasingly refrains from automatically placing all types of knowledge flows under the heading of pure knowledge spillovers. Rather, in this study, as in many others, the notion of knowledge spillovers refers to both pecuniary and pure knowledge spillovers, acknowledging that the relative importance of both can hardly be determined. Following Von Hippel (1994), the notion that knowledge transmission costs are related to attributes of both the agents and the knowledge involved, the concept of localized knowledge spillovers then reflects the idea that knowledge flows less costly between economic agents located nearby than between economic agents located at longer geographical distances. In the geography of innovation literature, this is explained by the presence of distance-related costs of tacit knowledge exchange stemming from the need for face-to-face interaction. The economic geography literature adds the notion that localized conditions can facilitate trust, thereby enhancing knowledge exchange.

2.4.2 Mechanisms of knowledge spillovers

Within both the economic geography and geography of innovation literature, knowledge spillovers are implicitly conceptualised as contributing to a regional pool of knowledge. Firms located in regions with an agglomeration of innovative activities are assumed to benefit by simply being co-located. Therefore, the aggregate sum of knowledge spillovers is assumed to be a local public good, freely accessible for firms in the region and inaccessible for firms located elsewhere. This theoretical proposition has been criticised (see for example Breschi and Malerba, 2001; Malmberg and Maskell, 2002) for the contradiction between the assumption of knowledge spillovers as a local public good and the need for face-to-face contacts as the reason for the localization of these spillovers. The notion of face-to-face contacts as an important mechanism of knowledge transmission implies that knowledge spillovers are not accessible to every organisation located in the same region, but that the accessibility depends on the intensity of participating in these knowledge transmission mechanisms. However, due to modeling at the aggregate level of regions, analysis of the underlying mechanisms of knowledge spillovers is typically beyond the scope of knowledge production function studies. Several authors in this empirical tradition acknowledge that 'the mechanisms transmitting knowledge spillovers remain relatively unexplored and unknown' (Audretsch and Feldman, 2004). In recent years, an increasing number of authors are exploring the underlying mechanisms of knowledge spillovers using data on micro-economic linkages between economic agents. Three mechanisms of localized knowledge spillovers can be distinguished: labour mobility, entrepreneurship and spin-off dynamics, and inter-organisational knowledge relationships (Boschma and Frenken, 2006). If knowledge spillovers occur through these mechanisms, it is the role of geographical proximity for each that determines the geographical dimension of knowledge spillovers. This section discusses why these mechanisms are considered to be carriers for knowledge spillovers, what the role of geographical proximity is for each, and how empirical studies have analysed them.

The first mechanism of knowledge spillovers that can be distinguished is labour mobility. The presence of a thick labour market with highly skilled employees has been considered an important agglomerative force since Marshall, as discussed in the second section. A thick labour market improves matching between employees and workers (Helsley and Strange, 1990), making it easier for firms to find new employees and similarly, workers find a job matching their skills and wants more easily. Moreover, Arrow (1962a) argued 'that the mobility of personnel among firms provides an important way of spreading information' (p. 615) and consequently mobility can be an important mechanism of knowledge spillovers. This has been emphasized by a large line of authors since Arrow (see for example Audretsch and Stephan, 1996; Fallick et al., 2006). The main argument for considering labour mobility as a mechanism for knowledge spillovers is the nature of how knowledge is built within organisations. Employees accumulate specific knowledge and skills while working in an organisation through education, learning by doing, and learning by interacting. This knowledge is largely embodied in individuals and is based on experience with particular production processes or firm specific knowledge in fields like marketing or management. This type of knowledge generally can not be fully appropriated by the organisations because it has a large tacit dimension. The mobility of these individuals between different employers is therefore considered to be an important mechanism for knowledge spillovers. Whether these knowledge spillovers consist of pure or pecuniary externalities (or both) remains unclear. Among the few who discussed this issue at length is Moen (2005), who empirically analyses the presence of knowledge spillovers through the mobility of technical personnel within a human capital framework. The main conclusion is that at least a part of knowledge spillovers is internalized in the labour market and is paid for by employees. R&D staff personnel in the Norwegian machinery and industry sector seem to pay for the knowledge they accumulate on their job by accepting a lower wage in the beginning of their career and earning a return on these 'investments' through higher wages in a later stage of their career. However, it is unclear whether these workers pay for the full value of the knowledge they accumulate in R&D intensive firms. Consequently, conclusive statements about the role of pecuniary and pure spillovers are not made, mostly because of the empirical difficulties in distinguishing pure from pecuniary spillovers (see Moen, 2005 p. 108 on this). Note that the presence of knowledge spillovers through labour mobility might also generate negative effects in the form of labour poaching. Labour poaching might lead to an increase in wages for key workers (in order to keep them), or to a decrease in the investments in training of the workforce by firms. However, it is typically argued that at the aggregate level, labour pooling benefits exceed labour poaching costs (Duranton and Combes, 2006; Fallick et al., 2006).

Labour mobility is largely a regional phenomenon and consequently, subsequent knowledge spillovers associated with it as well.[12] Labour mobility is localized for several reasons. First, changing jobs over longer distances involves higher costs for an individual than changing jobs within the same region. Job mobility over longer distances will most likely also involve moving to another region of residence, thus involving relocation costs. These costs also involve the interruption of social relationships with friends and relatives, which are considered by some as the most important reason for the localized dimension of job mobility (Power and Lundmark, 2004). Fischer et al. (1998) and Gordon and Molho's (1995) findings that individuals with a longer duration of stay within a region show a lower propensity to move to another region seem to confirm the importance of social relationships. The second reason relates to the likelihood that information on job opportunities come from the social networks of individuals, as shown in the classic study by Granovetter (1973). Because these social networks are largely localized, the chance that an individual knows about a specific job opportunity is higher if this job is at an organisation located in the same region. Different studies have shown that labour mobility is even more strongly localized within regions with a spatial concentration of a specific industry (Power and Lundmark, 2004; Erikson and Lindgren, 2008). Several studies have empirically analysed the role of labour mobility as a mechanism for localized knowledge spillovers. The overall conclusion seems to be that the mobility of highly skilled R&D personnel and scientists are important mechanisms of knowledge spillovers. Almeida and Kogut (1999) analysed the patterns of labour mobility of individual holders of 'major' patents in clusters of the semiconductor industry and relate this to patterns of knowledge flows measured by patent citations. They find that citation patterns, as indicators of knowledge spillovers, are strongly related to patterns of labour mobility. Almeida and Kogut's results suggest that that the ability of firms to build on specific knowledge is related to the career paths of innovative individuals. Their results further suggest that labour mobility is indeed an important mechanism for knowledge spillovers. Zucker et al. (1998b) and Zucker and Darby (2001) find that mobility of 'star scientists', including their participation in start-up firms, are strongly related to the innovative performance and location of US biotechnology firms. They also conclude that labour mobility forms an important mechanism for knowledge spillovers.

The second mechanism of knowledge spillovers is entrepreneurship. Within the broad field of studies on entrepreneurship, two main research directions are of interest: the knowledge spillover theory of entrepreneurship and the role of spin-offs as mechanisms of knowledge spillovers. Entrepreneurship is often considered to result from an individual's capability to recognise and exploit opportunities for profitable production of goods or

12 This is based on the assumption that on average, the effect of labour mobility of an individual in terms of knowledge spillovers is independent of the spatial scale where it occurs. The validity of this assumption has recently been questioned (see for example Boschma et al., 2008)

services (Shane and Venkataraman, 2000). Whereas considerable research in this field is devoted to the explanation of why individuals differ in their ability to discover, value, and exploit opportunities, the origin of entrepreneurship opportunities is most interesting in the context of knowledge spillovers. The knowledge spillover theory of the firm (see Acs et al., 2005) is based on the idea that knowledge spillovers are an important source of these opportunities and that entrepreneurship is the mechanism through which knowledge spillovers contribute to economic growth. Newly generated knowledge is considered to be an important source of entrepreneurial opportunities. Knowledge generation results from deliberate investments of firms (and other organisations such as universities). The expected economic value of this knowledge, as valued by the generating organisation, determines the probability of further investments in the development and commercialization of this knowledge. Similar to the ability to recognise and exploit entrepreneurial opportunities, the ability to assess the economic value of new knowledge differs between organisations and individuals. The economic value attached to new knowledge by the generating firm might be lower than the expected cost to develop it into a new product or service. However, other economic agents might attach a higher value to the new knowledge, which can initiate an attempt to appropriate this value by starting a firm with the goal of exploiting this knowledge. To the extent that these new firms did not invest in the initial generation of this knowledge, entrepreneurship is considered to be a mechanism of knowledge spillovers. Based on the notion that knowledge spillovers are largely localized, several empirical studies have associated regional differences in start-up rates to knowledge related indicators (e.g. Armington and Acs, 2002; Audretsch and Lehman, 2005). It is typically found that geographical proximity to knowledge sources is an important factor in explaining regional differences in entrepreneurship rates. Within this framework, the way in which knowledge spills over from the investing agent to the agent that starts a business is not specified. Some of the critiques against the geography of innovation literature also apply here. It remains unclear what the mechanisms of knowledge spillovers are.

Another line of research has paid special attention to the role of spin-offs, typically defined as a business startup by former employees. The reasons why spin-offs can be considered as a mechanism for knowledge spillovers resembles that of labour mobility. Spin-off dynamics can be considered as a special case of labour mobility. An employee (or a group of employees) is assumed to start a spin-off if there is a gap between the expected return of a potential innovation by the employee and the reward from the employer for the employee that developed it. This gap may be the result of agency problems (such as asymmetric information of the potential value) or organisational difficulties (innovations that create new sub-markets at the expense of the existing market).[13] If this gap is large enough relative to the costs (and associated risks), a spin-off might be started. A spin-off is considered to form a mechanism for knowledge spillovers since it involves the exploitation of knowledge and experience accumulated from working with previous employers where no (full) compensation is assumed to occur. The most important difference with the knowledge spillover theory of entrepreneurship is the fact that how economic agents (the former employee(s) that start the firm) appropriate knowledge from the investing agent (the parental organisation) is explicitly specified. Within the research on spin-offs, much attention is recently focused on the role of the specific knowledge inherited from the parent

13 For an overview of theoretical views on spin-offs, see Klepper (2001).

in survival rates and growth patterns of spin-offs (Agarwal et al., 2004; Klepper and Sleeper, 2005; Klepper, 2007; Boschma and Wenting, 2007 and Wenting, 2008).

Empirical studies on the location of spin-offs show that spin-offs tend to locate close to the parent organisations, leading to a strong localized character of the associated knowledge spillovers. The reasons for the tendency to locate close to parent organisations are similar to the case of labour mobility. Most founders make their location decision on the basis of personal reasoning (Fornahl and Graf, 2003) which generally follows similar patterns to those observed with individuals changing jobs. This implies that spin-offs might locate near the parent organisation for reasons other than being in the geographical proximity of the parent organisation (see also Dahl and Sorenson, 2007 on this). Establishing a spin-off in another region might be beneficial if there are specific advantages in that region, but relocation usually involves larger costs because the entrepreneur also needs to relocates his household. In addition to these costs, Stuart and Sorenson (2003) argue that the entrepreneur's social relationships are crucial for the mobilization of necessary resources, such as tacit knowledge, financial capital (Sorenson and Stuart, 2001), and skilled employees (Sorenson and Audia, 2000). Because these relationships are largely localized and might be disrupted by moving over longer distances, entrepreneurs tend to start in the same regions in which they previously lived and worked.

Klepper (2007) analysed spin-off patterns of the US car industry and showed that the tendency of spin-offs to locate near parents has been an important agglomerative force for the spatial concentration of the American car industry in Detroit. Before the shakeout process between 1910 and 1920, the US car industry was not as concentrated as it later became and the region of Detroit did not stand out as the center of car manufacturing. However, four of the most successful car manufactures were located in Detroit.[14] Because better performing firms are likely to generate more and also more successful spin-offs, the spin-off firms of the Detroit firms performed, on average, better than inexperienced starters or spin-offs from other firms during the shake-out process. And because spin-offs tend to locate near parent organisations, the main reason for the concentration in Detroit was the better quality of spin-offs rather than the presence of agglomeration economies for existing firms, according to Klepper (2007). A similar study by Buenstorf and Klepper (2005) has been performed for the US tire industry, which is concentrated in the Akron region, and their conclusions are similar. As Klepper (2007) argues, these results should not be directly interpreted as an alternative explanation for the presence of spatial concentrations next to agglomeration economies (p. 629). It is suggested that not all firms benefit equally from the presence of agglomeration economies and that spin-offs from more successful firms might be better in exploiting these advantages. However, Klepper (2007) does suggest that the reason for the specific location of a concentrated industry might be historical accident, rather than due to specific location factors.[15]

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14 According to Klepper (2007), the reason why these four were located in Detroit is related to the influence of Olds Motor Works.

15 Note that this is consistent with Krugman's (1991) idea of a historical accident as a main factor for an initial spatial concentration of an industry. Similar ideas can also be found in Arthur (1994), who introduces a simulation model explaining the spatial concentration of industries based on spin-off dynamics.

The third mechanism of knowledge spillovers involves knowledge flows through formal and informal inter-organisational relationships. Within both the geography of innovation and economic geography literature, this is considered to be the most important mechanism for knowledge spillovers. An important peculiarity of inter-organisational knowledge relationships, relative to other types of spillover mechanisms, is their (possible) repetitive character. Knowledge spillovers between organisations through inter-organisational relationships can occur sequentially and reciprocally over a long time period, whereas knowledge spillovers through labour mobility or entrepreneurship basically occur at one moment in time. Inter-organisational knowledge relationships can take many forms,[16] ranging from more informal contacts on a technological problem between employees from different companies in a bar (referred to as 'cafeteria effects' by Camagni, 1991, as cited by Giuliani, 2007, p.143) to joint research ventures to develop specific new products. Given the focus of this study, most attention is given to inter-organisational relationships as mechanism of knowledge spillovers.

2.4.3 Inter-organisational knowledge relationships as mechanism for knowledge spillovers

An important distinction can be made between informal and formal inter-organisational knowledge relationships. Informal knowledge exchange can be defined as the exchange of knowledge between (individuals from) different organisations without direct financial compensation or a formal agreement (Dahl and Pedersen, 2004). Informal knowledge exchange is a frequently observed phenomenon in R&D processes, product development, and situations in which difficulties arise within production processes. The notion of knowledge or information trading (Von Hippel, 1987; Schrader, 1991; Dahl and Pedersen, 2004) refers to the process of informal knowledge exchange between individuals working for different organisations on the basis of future reciprocity.[17] This implies that individual employees are only willing to exchange knowledge on an informal basis if they expect to receive valuable knowledge in return within a foreseeable time period. The willingness to exchange knowledge is also based on the attractiveness of firms (and their employees) in terms of possessing valuable knowledge. Schrader (1991) argues that informal knowledge exchange is not a substitute for internal knowledge generation but is complementary and necessary to engage in 'knowledge trading'. Despite the possibility of unwanted knowledge spillovers at the level of the firm, informal knowledge relationships based on knowledge trading is generally considered to be beneficial for the individual firms involved. The exchanged knowledge is often related to a specific problem or technological issue that requires a solution (von Hippel, 1987; Schrader, 1991). The internal generation of required

16 This has lead to a wide range of different conceptual terms trying to denote a specific subset of these knowledge relationships, especially more informal local relationships, such as 'buzz' (Bathelt et al., 2004) or 'local broadcasting' (Owen-Smith and Powell, 2004). Although these different notions are conceptually rich, the empirical testing of the assumptions and implications is extremely difficult if not impossible, if only because these concepts in the original articles are defined rather unclearly. For example, knowledge flows denoted as the local buzz (Bathelt et al., 2004) are assumed to be 'more or less automatically received by those who are located within a region' and to occur in 'negotiations with local suppliers, in phone calls during office hours, while talking to neighbours in the garden or when having lunch with other employees and so on' (p. 38).

17 Informal knowledge relationships are considered to form a prime example of a mechanism of pure knowledge spillovers by some (see Dahl and Pedersen, 2004). As discussed in another section, the fact that some form of future non-financial payment does occur implies that this type of knowledge spillovers can be labelled as pecuniary as well.

knowledge might be time-consuming and rather expensive, whereas this knowledge can be acquired externally at a relatively low cost by trading knowledge. Based on the principle of reciprocity, by exchanging knowledge and information at one moment in time, firms are likely to receive needed knowledge in return at another moment in time. The exchange of knowledge on the basis of reciprocity entails relative low transaction costs, but it also risks the possibility of free-rider behavior of other firms because legal means for enforcing the 'obligation' to return information is absent. Consequently, the reputation of an individual firm plays an important role in the decision of other firms to exchange knowledge. The largest risk entails losing knowledge that offers a significant competitive advantage (Von Hippel, 1987). This might be especially the case if it concerns knowledge exchange between competing firms. Firms are less likely to exchange knowledge that forms the basis of a significant competitive advantage because this decreases the rent derived from it. The extent to which knowledge exchange involves knowledge that brings a significant competitive advantage determines its value. It is therefore not surprising that several authors find that informal knowledge exchange mainly involves knowledge that is considered useful, but not of any significance to the maintenance of competitive advantage (Schrader, 1991; Dahl and Pedersen, 2004).

Formal knowledge relationships are based on formal agreements to share knowledge, which can take the form of research alliances, joint ventures, and collaborative R&D. Formal knowledge relationships can have the goal of bringing together specific predefined knowledge, for example, in the form of a joint venture. Formal knowledge relationships can also be based on the joint generation of new knowledge, for example, in the form of collaborative research. In these cases, formal agreement typically has to be reached on issues such as the investment of resources and the appropriation of newly generated knowledge. Because formal knowledge relationships typically involve knowledge with a relatively high value for the organisations involved,[18] the costs of possible opportunistic, free-rider behavior are much higher than in case of informal knowledge exchange. These increased risks are likely to lead to some form of formal agreement. Due to formalized agreements, this type of knowledge spillovers more closely resembles the concept of the pecuniary knowledge spillovers than informal knowledge exchange at the first sight. However several authors argue that is impossible to prevent unintended knowledge spillovers from occurring (e.g. Gomes-Casseras et al., 2006; Hussler and Ronde, 2007). Especially in case of collaborative research, the uncertainty of R&D processes renders it impossible to specify all possible outcomes a-priori in formal agreements. Some even argue that the presence of informal knowledge transfer between individuals from the different organisations involved is necessary for the success of formal knowledge exchange (Mowery et al., 1996; Rosenkopf and Almeida, 2003). Due to the high likelihood that unintended knowledge spillovers occur and the involvement of relatively valuable knowledge in formal knowledge relationships, mutual trust and understanding is considered a crucial factor in the establishment of formal knowledge relationships.

The geographical dimension of knowledge spillovers through inter-organisational relationships depends on the role of geographical proximity in the establishment and maintenance of these relationships. Formal and informal inter-organisational knowledge

18 Hagedoorn and Schakenraad (1990) concluded that over 85% of existing R&D joint ventures, joint R&D agreements, and research pacts are strategically motivated

relationships differ with to the importance and value of the exchanged knowledge, the underlying coordination mechanisms, and the costs involved. Nonetheless, the factors influencing the likelihood of participating in inter-organisational knowledge exchange with a specific organisation are very similar. First, the attractiveness of potential partners depends, understandably, on the value attached to the knowledge possessed by these organisations (Von Hippel, 1987; Poot, 2004).[19] Therefore, a prerequisite for both formal and informal knowledge exchange is information on the knowledge generated and possessed by other organisations, referred to as 'who knows what' by Breschi and Lissoni (2001b). Second, agreement on compensation has to be reached and, as argued above, mutual trust is a prerequisite. In the case of informal knowledge exchange, this is related to the principle of reciprocity. In the case of formal knowledge exchange, this stems from the impossibility of covering all contingencies in an enforceable contract.

Several authors (Breschi and Lissoni, 2003; Sorenson, 2003; Singh, 2005) have argued that social networks are the main determinant of inter-organisational knowledge exchange. Through social networks, information about other organisations is spread and trust between (employees from) different organisations is created. In a sense, information on others' knowledge, mutual trust, and the potential knowledge exchange, is conceptualised as a club good, accessible only to the members of the social network. The subject of social networks has been a research theme in sociology for many decades. Sorenson (2003 pp.515-516) provides an overview of several sociological studies on the geographical dimension of social networks. Social networks consist of relationships between individuals through which knowledge, information, and experiences are shared. To form a relationship, two individuals must meet in time and space (in other words, face-to-face contacts are necessary to establish a relationship). Consequently, social relationships are not formed randomly between people as people interact more frequently with those who live in geographical proximity and with people with similar backgrounds, interests, or affiliations. The latter is sometimes referred to as social proximity. Both enhance the chance of interaction and consequently, the likelihood of forming a social relationship. Social proximity enhances the probability of a social relationship because individuals with a common background and mutual interests are more likely to meet. Geographical proximity enhances the chances of random interaction between individuals without a common background or affiliation, and this interaction may lead to a social relationship (see also Agrawal et al., 2008). If social proximity is assumed to be 'space-less', meaning not influenced by geographical proximity, the relative importance of social versus geographical proximity determines the geographical dimension of social networks. If social proximity is significantly more important than geographical proximity, then social networks and subsequent knowledge spillovers are less likely to be localized and might even occur on a global scale.[20] Similarly, if geographical proximity is more important

19 As argued earlier, this value is also influenced by the possible additional costs needed to use this knowledge. These costs can vary between different pairs of partners (see also Von Hippel, 1990) and are related to the cumulative nature of knowledge. The costs of understanding and using exchanged knowledge are higher if the organisations involved are active in different fields or have greater cognitive distance (Nooteboom, 2004).

20 A good example of how 'space-less' social proximity can form a social network through which knowledge spillovers occur might be found in open source software forums. An example of knowledge spillovers through social networks formed on the basis of pure geographical proximity might be found in the exchange of knowledge between neighbours on the quality and price of goods or services both need.

than social proximity, social networks and subsequent knowledge spillovers are more likely to be localized. However, social proximity is likely to be influenced by geographical proximity because a shared common background might result from similar past affiliations, e.g., going to the same university or being colleagues. As discussed previously, the mobility of most people is not very high, so most former classmates and collegues are likely to live and work in the same geographic area. Consequently, social proximity and geographical proximity often overlap.

If social networks are important determinants of inter-organisational knowledge exchange, the geographical pattern of these social networks determines the geographical dimension of the associated knowledge spillovers. This fact shifts empirical works towards the geographical dimension of social networks and the underlying mechanisms that create social networks. Several empirical studies have analysed the role of social networks as a mechanism for localized knowledge spillovers. Both Breschi and Lissoni (2003, 2006) and Singh (2005) find that social networks, measured by the relationships formed between researchers while working on an invention, can explain a large part of the variation in the spatial patterns of citations as indicators of knowledge spillovers. This is considered empirical evidence that the geographical dimension of knowledge spillovers can be largely explained by the geographical patterns of social networks between inventors. Breschi and Lissoni (2003) conclude that knowledge spillovers are as localized as their underlying social networks. Singh (2005) reaches the same conclusions. Based on a similar empirical approach, he finds that moving inventors maintain their social relationships with former co-inventors and that these social relationships form an important mechanism for knowledge spillovers, regardless of the geographical distance between them. Interestingly enough, he also finds that the geographical span of social networks is larger for groups of inventors working in similar fields than for inventors from different fields that have previously worked together. Agrawal et al. (2006) argues that this might be related to mechanisms which are specific to individual working fields, which in turn makes it easier and less costly to maintain social relationships, such as conferences, publications, and tradeshows. Because researchers from different fields lack such mechanisms, social relationships over longer distances are less likely to be maintained, leading to social networks that are more localized.[21]

Sorenson and Singh (2007) relate the relatively fast diffusion of scientific knowledge (measured by citations to publications) compared to technological knowledge (measured by citations to patents) to the geographical dimension of social networks of scientists and inventors, respectively. Social networks are assumed to be formed by working within the same scientific or technological affiliation. Labour mobility is an important mechanism for the creation of social networks between individuals working for different organisations. Scientists change jobs over relatively long distances and can more easily maintain social relationships over longer distances, for example, by attending international conferences. Consequently, their social networks are geographically more dispersed, which might be an important reason for the more rapid international diffusion of scientific knowledge

21 This might be an interesting explanation for the finding of studies on agglomeration studies that different types of agglomeration economies seem to occur at different spatial scales. According to this line of reasoning, Jacobs or diversity economies should be more important at lower spatial scales, whereas specialization economies can be expected to occur at higher spatial scales.

(Sorenson and Singh 2007). Empirical studies on the geographical dimension of inter-organisational knowledge relationships also suggest that the role of geographical distance differs between types of knowledge relationships. Audretsch and Stephan (1996) analyse different connections between biotechnology firms and university scientists, which are typically considered to be rather localized. They find that the majority of links (70 percent) are non-local. By analysing the characteristics of both scientists and firms and the different connections, they find that the importance of geographical proximity varies with the type of connection. More formalized relationships tend to occur over longer geographical distances than incidental ones, suggesting that the role of geographical proximity differs between informal and formal knowledge exchange.

Dahl and Pedersen (2004) and Giuliani (2007) were among the first[22] to quantitatively analyse the geographical dimension of informal inter-organisational knowledge relationships, using data collected through questionnaires from engineers and firms. Dahl and Pedersen (2004) find that localized informal knowledge relationships form a mechanism for knowledge spillovers. However, the exchanged knowledge is relatively low in value or importance, which is consistent with the findings of Von Hippel (1987) and Schrader (1991). Giuliani (2007) finds that informal knowledge exchange between firms in clusters seems to occur relatively selectively rather than pervasively, as is sometimes implied (see Østergaard 2007 for similar results). These findings are consistent with the notion that social networks serve as carriers for inter-organisational knowledge spillovers. Geographical proximity is not enough to confer benefits from localized knowledge spillovers. Participating in the social networks underlying these spillovers is also necessary. Whereas both Dahl and Pedersen (2004) and Giuliani (2007) limit their analyses to the regional level, Boschma and ter Wal (2007) include non-regional relationships in their analysis. They find that informal inter-organisational knowledge relationships are more likely to occur at the regional level, but only non-regional informal knowledge relationships are found to be beneficial for the innovative performance of firms. Weterings (2006) finds similar results in the software industry in the Netherlands.

A large range of studies have analysed formal knowledge exchange in the form of R&D alliances and collaborative research (see for example Hagedoorn, 2002 for an overview). Most of these studies analyse the effect of formal knowledge relationships on the innovative performance of firms. One of the common findings is that collaboration in R&D and other forms of formal knowledge exchange are an important determinant of the performance of firms, especially in high-tech and science-based industries such as semiconductors and biotechnology (see for example Powell et al., 1996; Cockburn et al., 1998 and Stuart, 2000). Studies that focus on the geographical dimension of formal knowledge exchange are typically interested in the international dimension of collaborative research or alliances (see for example Wagner, 2005), which is often found to be increasing. Research on formal knowledge relationships at lower spatial scales than countries is rare. McKelvey et al. (2003) is among the first to analyse the role of co-location in formal research collaboration in the Swedisch biotechnology and pharmaceutical industries. McKelvey et al. (2003) concludes that formal research collaboration occurs at the regional, national, and international level.

22 This might be somewhat surprising given the emphasis on this type of knowledge spillovers, especially in the economic geography literature. The lack of practically any data on informal inter-organisational relationships seems to be the main cause.

Geographical proximity is not found to be very important for formal research collaboration. McKelvey et al. (2003) relates this to international orientation in these fields, which seems to capture the idea of social proximity – defined here as working in a similar field.

The studies discussed above suggest that social networks are important determinants for both formal and informal inter-organisational knowledge exchange. The geographical dimension of these social networks is related to the role of geographical proximity in the establishment and maintenance of these networks. In the case of formal knowledge exchange, this seems to be less important than in the case of informal knowledge exchange. Consequently, informal knowledge exchange seems to be largely localized, while formal knowledge exchange seems to occur over longer distances. To understand these differences, gaining insight into how geographical proximity influences the establishment and maintenance of social networks underlying formal and informal knowledge exchange is necessary. The following section discusses two lines of research that offer these insights.

2.5 Economics of knowledge diffusion

Building on research from sociology, several economic studies have analysed the mechanisms that influence the diffusion of knowledge among economic agents. From studies authored by Schrader (1991), Audretsch and Stephan (1996), Zucker et al. (1998a) and Breschi and Lissoni (2003), it can be concluded that knowledge spillovers occur mainly from deliberate actions of economic agents rather than involuntarily. Studies on the economics of knowledge diffusion have been focusing on the role of different types of networks and communities of individuals through which knowledge is exchanged. Similar to the literature on localized knowledge spillovers, tacit knowledge plays an important role, though in a different way. The starting point is that tacit knowledge is exchanged by codifying it with a codebook. This codebook can be seen as a language or dictionary necessary for expressing a specific 'piece of knowledge' in such a way that the organisations or individuals involved can understand it. Tacit knowledge is codified according to the rules of a codebook and is exchanged in the form of messages, which remain tacit for economic agents who do not have access to the codebook. The same message, and the knowledge communicated with it, may be tacit and incomprehensible for one individual, but perfectly understandable for those who have access to the codebook. Therefore, understanding of the codebook discriminates between agents that can understand the knowledge being exchanged and those who cannot. Regarding inter-organisational knowledge exchange, this implies that the decision to exchange knowledge depends on the costs and benefits associated with codifying the knowledge (Cowan et al., 2000). The costs of codification depend on the difficulties in establishing the means of codification and a mutually understandable codebook. These costs are relatively low if both organisations have access to a codebook that already exists and belong to the same group of agents that share a codebook. However, these costs are relatively high if there is a need to develop a new codebook, or if one or both of the organisations have to invest in learning a new codebook. If these costs are too high, the knowledge will not be codified and will consequently not be exchanged. These ideas reflect Von Hippel's (1994) observation that the costs of exchanging the same 'piece of knowledge' can vary greatly between different pairs of organisations. Organisations that share a similar codebook can be considered as cognitive communities or networks through which knowledge can be easily exchanged. Inter-organisational knowledge spillovers are assumed to occur within these communities.

The geographical dimension of communities in which knowledge is exchanged is related to the role of geographical proximity in the creation and understanding of the relevant codebook. If this codebook is unarticulated and is based on common experience and history, enduring and frequent face-to-face contacts might be crucial for understanding this codebook. As a result, the community and the associated knowledge spillovers might become rather localized. Lissoni (2001) shows, for example, that within the Breschia mechanical cluster, knowledge flows occur within localized communities centered on engineers. Personal ties, based on trust and reputation, are crucial for participating in these communities and consequently being allowed to access the codebook. Frequent face-to-face contacts form the basis for necessary trust and reputation, and consequently, most of these communities were found to be rather localized because the costs of establishing personal ties rapidly increase with distance. Scientific and technological research, on the demand, is generally considered to take place in international communities bounded by a displaced, or non-manifest, codebook. This codebook is nonetheless highly developed with specific formulations, codes of conduct, and jargon. New knowledge can be codified and exchanged at a relatively low cost to members of the community regardless of geographical distance.[23] Due to the strongly developed codebook, the exchanged knowledge is tacit and incomprehensible for all individuals outside the community. The costs of understanding and learning the codebook are rather high, but independent of the geographical distance between existing members of the community. Formal knowledge exchange, such as collaborative research, often concerns scientific or technological knowledge. Given the wide geographical range of the communities of knowledge exchange and the high costs to enter, formal knowledge exchange is more likely to occur over longer distances (see Hussler and Ronde, 2007). To summarize, the economics of knowledge diffusion theory argues that knowledge exchange occurs through the codification of tacit knowledge within communities consisting of a limited number of agents who have access to the codebook. The geographical dimension of these communities and exchanged knowledge is determined by the characteristics of this codebook and the size of distance-related costs of understanding.

2.6 Proximity

Related to the notion of social proximity, several authors have tried to develop more insight into the role of geographical proximity by distinguishing between different forms of proximity which might play a role in inter-organisational knowledge relationships (see for example Boschma, 2005; Torre and Rallet, 2005 and Knoben and Oerlemans, 2006). The starting point is the idea that some form of social relationship involving trust and mutual understanding is necessary for the exchange of knowledge between economic agents. As already noted in the literature on social networks, the formation of these relationships can

23 This is because these messages typically consist of scientific papers and articles, which can be distributed for very low cost using ICT techniques. Relevant messages also include presentations and a question or remark in discussion for which face-to-face contacts remain important as exemplified by the importance of international scientific conferences and workshops.

be influenced by both social and geographical proximity. This implies that geographical proximity is neither necessary nor sufficient for inter-organisational knowledge spillovers to occur (Boschma, 2005).

The role of social and other forms of proximity in relation to geographical proximity for inter-organisational collaboration has recently captured much attention in different fields.[24] Given the focus of this study, only proximity literature in the field of regional economics and regional science will be discussed. Geographical proximity has traditionally been regarded crucial for inter-organisational knowledge exchange due to the need for face-to-face contacts and the creation of trust-based social relationships (Gertler, 2003). Breschi and Lissoni (2003) concluded in empirical studies that geographical proximity often functions as a proxy for localized social networks. Rallet and Torre (1999) were among the first to argue that the importance of frequent face-to-face contacts does not automatically imply a need for physical co-location of organisations. Temporary geographical proximity in the form of business trips, meetings, or conferences might be sufficient to establish social relationships that can be maintained over longer distances. They introduced the notion of organisational proximity to refer to 'the kind of proximity created by membership of the same organisation or professional community' (p. 375) without being physically co-located. A prime example can be found in scientific communities. Oerlemans and Meeus (2005) referred to organisational proximity as actors belonging to the same space of relationships. The resemblence with the concept of cognitive communities in the literature on the economics of knowledge diffusion is clear. Within innovation and management studies, the notion of technological proximity, which refers to the overlap in technological knowledge of organisations, is frequently used. The concept of technological proximity is closely related to the notion of absorptive capacity (Cohen and Levinthal 1990).

The distinction between different forms of proximity can be useful for a better understanding of circumstances when geographical proximity play an important role for inter-organisational knowledge exchange. Several authors (Boschma, 2005; Torre and Rallet, 2005) argue that the role of geographical proximity is related to the relative importance or presence of other forms of proximity, which may serve as substitutes or complements to geographical proximity. Boschma (2005) introduces four notions of proximity in addition to geographical proximity: cognitive, organisational, social, and institutional proximity.

Cognitive proximity is related to the notion of technological proximity and refers to the overlap in knowledge base between organisations. A certain level of cognitive proximity is considered to be a prerequisite for inter-organisational knowledge exchange (Boschma, 2005 p. 71). Different studies in the field of organisation and management sciences argue that the relationship between cognitive proximity and knowledge exchange has the form of an inverse U-shape (see Nooteboom et al. 2007). A certain level of cognitive distance is necessary to exchange knowledge that is new to the organisations. However, too much cognitive distance precludes mutual understanding. The other forms of proximity are assumed to play an important role in lowering the costs of knowledge exchange and overcoming coordination problems related to the uncertainty regarding inter-organisational knowledge exchange.

24 For an overview of how proximity is used in fields like geography, management sciences, and innovation, see Knoben and Oerlemans (2006).

Organisational proximity refers to the extent to which relationships are shared in an organizational arrangement under common hierarchical control, either within or between organizations. Organisational proximity, such as in case of two branches of the same multinational company, eases the exchange of knowledge.

Social proximity is related to relationships between agents at the micro-level based on friendship, kinship, or mutual experiences. Social proximity is assumed to ease knowledge exchange because it increases mutual trust and consequently lowers the costs of knowledge exchange. If, for example, employees or managers are members of the same business club, the exchange of knowledge between these organisations is likely to be made easier.

Institutional proximity has two dimensions. It refers to similarities in underlying formal and informal institutions that are related to being located in the same country or region such as laws, norms, and values. It also refers to similarities in the incentive structure of economic agents. Institutional differences regarding the incentive structure are sometimes considered to hamper knowledge exchange between industry and academics (see Dasgupta and David, 1994). Boschma (2005) argues that geographical proximity most likely indirectly strengthens other forms of proximity. If proximity is lacking in one or more dimensions, geographical proximity can play an important role by strengthening another form of proximity necessary to facilitate inter-organisational knowledge exchange. Given a specific type of knowledge relationship, such as research collaboration, the proximity thesis implies that other forms of proximity need to be present for knowledge exchange over longer distances. To understand when geographical proximity plays a role, isolating the effect of other forms of proximity in empirical studies is necessary. Until now, only a few studies have actually tried to empirically disentangle different types of proximities in understanding the role of geographical proximity for knowledge flows.

Empirical studies related to this idea can be found in some knowledge production function studies that have the goal of testing the relative importance of geographical proximity and technological proximity for knowledge spillovers between regions. Technological proximity is generally defined as the level of similarity in technological or industrial structures. It is hypothesized that knowledge spills over more easily between regions that have similar technological or industrial structures than between regions with different structures. This is related to Hägerstrand's (1953) distinction between contagious and hierarchical knowledge diffusion. Localized knowledge spillovers resemble contagious knowledge diffusion, whereas hierarchical knowledge diffusion is based on the hypothesis that new knowledge diffuses between larger cities before it trickles down to more peripheral regions. Given a specific industry or technology, regions that are considered to be technologically proximate are relatively specialised in these industries and can therefore be considered to be the most important regions for these industries. If technological proximity is more important than geographical proximity, it seems that hierarchical diffusion is more important than contagious diffusion. If not, the opposite seems to be the case. Studies using this approach tend to conclude that both geographical and technological proximity matter for knowledge spillovers and that a combination of geographical proximity and technological proximity has an additional effect (Autant-Bernard, 2001; Greunz, 2003). Oerlemans and Meeus (2005) try to analyse the impacts of different forms of proximity to assess the effect of supplier-buyer relationships on the innovative performance of firms in the Netherlands.

Their outcomes suggest that organisational and geographical proximity are complementary rather then supplementary regarding the impact of these relationships on innovation. Agrawal et al. (2008) assess the role of geographical proximity and social proximity, defined as co-ethnicity, in the probability of knowledge flows between individual inventors. Agrawal found that both types of proximities enhance the probability of a knowledge flow and that they act, in terms of interaction, as substitutes rather than complements. Taken together, the outcomes of the few empirical studies that have been performed in this area are far from conclusive. However, they show that the use of the proximity framework seems to be an interesting direction for research on the role of geographical proximity for knowledge spillovers.

2.7 Concluding remarks

The goal of this chapter was to provide the background for this study by giving an overview of the literature in the field of regional economics and economic geography. With the rise of the new endogenous growth theory, the interest in the geographical dimension of knowledge spillovers has also grown. Although sometimes different in their underlying assumptions, different theoretical contributions have emphasized the localized dimension of knowledge spillovers and its effect on the agglomeration of industries and regional economic growth. Empirical studies tend to find indirect evidence that knowledge spillovers are largely localized. However, the conclusions on the size and geographical scale of these spillovers are far from consistent. To understand why that is the case, research on localized knowledge spillovers is increasingly focusing on the underlying mechanisms. New theoretical ideas on the role of geographical proximity for knowledge spillovers have shifted the focus of empirical research to the analysis of the geographical dimension of different mechanisms of knowledge spillovers. Research on this topic is only recently emerging and it is not surprising that many unanswered research questions still exist. By analysing the geographical dimension of research collaboration and the importance of research collaboration as a mechanism for knowledge spillovers, this study will answer some of these questions.

Chapter 3
Science-based industries

The focus of this study is on science-based industries. Empirical studies (see e.g. Paci and Usai, 2000) reveal that these industries show a strong tendency to concentrate around universities and other academic research organisations. This suggests that knowledge spillovers from research by these organisations might form an important agglomerative force. This chapter describes the distinct features of science-based industries and the role of university research for processes of innovation in these industries, and explains the choice of the indicators for innovation and collaborative research in this study. The chapter also provides an exploratory analysis of the geographical dimension of innovation in science-based industries in the Netherlands.

3.1 Sectoral differences in innovation

Innovation processes differ greatly between industries in the underlying sources of knowledge and knowledge base, the means of appropriation, and the actors involved. A very crude distinction can be made between high-tech, R&D-intensive industries and low-tech industries and this distinction is often used in international comparative studies from the OECD, EU, and other international organisations. This distinction is considered too broad for studies with an interest in specific industries due to the large differences in innovation processes between high-tech industries (Malerba, 2004). Pavitt (1984) introduced a taxonomy based on differences in the sources of innovation and the mechanisms of appropriation. This taxonomy is still considered to be extremely useful for understanding sectoral differences in technological innovation. Four types of sectors are distinguished.

1 Supplier dominated industries are characterised by a low level of innovation based on internal knowledge resources. Most firms are relatively small and have little to no in-house R&D or engineering capabilities. Most innovations are embodied in new materials or equipment stemming from supplying companies. New technologies are applied on the basis of learning-by-doing and learning-by-using. Consequently, the main mechanism for appropriating innovation lies in the mastering of professional skills necessary for the application of new equipment. In some industries, a specific aesthetic design or a unique marketing approach can also be a mechanism of appropriation.[25] Pavit (1984) refers to traditional sectors of manufacturing (e.g. textiles or shoes), agriculture, construction, and many commercial and financial services as industries with supplier-dominated innovation processes.

25 More recently, the term creative industries or cultural industries have often been used to refer to industries where aesthetic design or marketing are important means of appropriating innovations.

2 Scale intensive industries are industries with large (latent) economies of scale where technological innovation is assumed to result from the incentive to exploit them. As a result, the competiveness of firms depends mainly on 'the capacity to design, build and operate large-scale continuous processes, or (the capacity to) design and integrate large-scale assembly systems in order to produce a final product' (Pavitt, 1984 p. 359). Innovation stems from internal production engineering departments and from suppliers of equipment for the production and assemblage process. Secrecy regarding production processes and patents in case of specialised machinery form the most important appropriation mechanisms. Industries producing standardized materials, e.g. steel or durable consumer goods such as automobiles, are typically seen as scale-intensive industries.

3 Specialised suppliers form the third category and refer to industries producing specific equipment or parts that are inputs for firms in other industries. Innovation is mainly incremental, based on the customisation and improvement of specific products. Internal knowledge, stemming from engineering experience and close interaction with the costumer are the most important sources of knowledge. Appropriation of innovation mainly results from the unique and cumulative nature of specific innovations due to the customisation of products. Specialised suppliers industries are an important source of innovation for firms in scale-intensive and supplier dominated industries. Industries in mechanical engineering and instruments, e.g. machine tools producers, fall under the category of specialised suppliers.

4 Science-based industries are characterised by a high intensity of product and process innovation based on technological developments and scientific discoveries. The development and introduction of new products stemming from an increase in technological opportunities is the most important factor for competition. Internal R&D, R&D of other firms in similar industries, and academic research are the most important knowledge sources. The introduction of new products is typically based on new scientific insights. Consequently, collaboration with universities and other academic research organisations is a central element of innovation processes of firms in these industries. Innovation is appropriated using patenting and secrecy, but also by steep learning curves, which can form important barriers to entry. Electronics, the chemical and pharmaceutical industry, and more recently, the biotechnology and nanotechnology industries are the most important examples of science-based industries.

Marsili (2001) builds on Pavitt's (1984) classification and introduces five technological regimes to distinguish between industries on the basis of the characteristics of innovation processes. Her definition of a science-based regime largely resembles Pavitt's notion of science-based industries. An interesting addition is made with the distinction between science-based industries with a knowledge base in life sciences (e.g. pharmaceuticals and biotechnology) and science-based industries with a knowledge base in physical sciences (e.g. electronics and optics). In this study, this distinction within science-based industries is used in the empirical chapters as well.

3.2 Measuring innovation, knowledge and research collaboration in science-based industries

Research on knowledge and innovation has always relied on partial indicators. The intangible character of knowledge makes it difficult to directly measure it in an encompassing way. Over time, empirical studies have used a wide range of indicators to measure knowledge and innovation. The choice between different indicators is far from trivial (see Kleinknecht et al., 2002). The usefulness of specific indicators differs greatly across industries and is related to industry-specific characteristics of the innovation process, as described by Pavitt (1984). Within science-based industries, innovation processes are strongly related to scientific research, formal R&D, and technological inventions. This has the advantage that innovation related processes often leave a tangible output in the form of scientific publications or patents. Furthermore, the research efforts of firms and research organisations can be relatively well measured by the size of R&D expenditures or the number of individuals engaged in R&D activities. Empirical studies on innovation and knowledge spillovers have made extensive use of patents, scientific publications, and R&D as indicators. This study also uses these indicators. Due to the importance of scientific research, the rise of new science-based industries often coincides with the development of new technologies based on a scientific breakthrough. Consequently, the delineation of industries and technologies is not always possible, as in case of biotechnology (see OECD 2005), which is considered to be a distinct industry by some and a technology influencing several industries by others. Industrial classifications are typically based on the characteristics of the goods and services produced by firms, whereas technological classifications are mainly based on characteristics of the knowledge base and the fields of innovation. Therefore, the expressions of science-based industries and science-based technologies are often used interchangeably. The empirical analyses in this study are based on the technology fields that constitute the areas of innovation, R&D, and research collaboration of the science-based industries.

3.2.1 Patents as an indicator of innovation

In this study, patents are used as an indicator of innovation. Patents have a number of advantages in this regard, making them one of the most used indicators for innovation in empirical studies. Patents have been carefully checked on their novelty ensuring that each patent covers a new technological invention. Patents contain detailed information about the content and technological field of the invention, the year of application, the names and addresses of the researchers (inventors) and organisations involved (applicants) and the underlying knowledge (citations). As a result, patents are the only indicator for innovation with a geographical, temporal, and technological/sectoral dimension. Furthermore, patents are legal documents, which ensures that the level of error in the data is very low. Finally, the increasing availability of patent databases makes it relatively easy and less costly to use for researchers. Nonetheless, there are some disadvantages to the use of patent data (see Griliches, 1990 for an in-depth overview of the advantages and disadvantages of the use of patent data). Most importantly, not all innovations are patented. There are several reasons for this. First, the application for a patent costs time and money, which might be considered too high a cost. Moreover, other forms of appropriating new knowledge, such as secrecy, might be considered more effective than applying for a patent. Finally, some innovations can simply not be patented. This is especially the case for non-technological innovations such as new marketing methods. Thus, the propensity to patent differs greatly between technologies, industries, and countries making it difficult to use patent data to compare industries or technologies (see also Kleinknecht et al., 2002 on the advantages and disadvantages of different innovation indicators). Another disadvantage is that not all patents can be considered as innovations. Several authors point to the increasing use of patents as a mean of blocking competitors from specific technological knowledge (see Cohen et al., 2003). A recent study (Gambardella et al., 2008) based on questionnaires from European inventors showed that more than 75 percent of patents are valued above 100,000. This suggests that the large majority of patents have at least a significant monetary value. Within science-based industries, patents are an important mean of appropriating new knowledge and a large portion of innovations are patented. Based on the assumption that, within a specific technology, there is no regional bias in the share of patents that are not innovations and the share of innovations that are not patented, patents can function as an indicator of regional innovation. The validity of this assumption is tested by Acs et al. (2002) who compared the results of knowledge production function estimations with patents as dependent variable to knowledge production function estimations with innovation counts as the dependent variable. Due to the high level of similarities in the estimation results, it was concluded that patents constitute an appropriate indicator for regional innovation, at least at the level of U.S. metropolitan areas.

3.2.2 Co-publications as indicator of research collaboration

Innovation in science-based industries is strongly related to the development of scientific research in relevant scientific fields. Compared to other industries, basic scientific research constitutes a considerable portion of R&D of science-based industries. Given that scientific research is sometimes considered as being a public good, this might be somewhat surprising. Rosenberg (1990) reviews several reasons why firms in science-based industries invest in basic research. First, an important incentive for basic scientific research is the first-mover advantage. Because results from scientific research are closely interwoven with opportunities for innovation, the benefits associated with being the first to have specific new scientific insights are generally assumed to be larger than the costs of doing research and the risks of unwanted spillovers. The second argument builds on the concept of absorptive capacity (Cohen and Levinthal, 1990). Absorptive capacity refers to the ability of firms to understand, value, and exploit external knowledge. Because new scientific and technological knowledge are the most important sources of innovation opportunity, investments in the development of absorptive capacity in the form of scientific research is crucial. The third reason is not only an explanation for why firms perform scientific research, but also for why they publish their results. This might seem counterintuitive given the goal of private firms to extract rents from possessing specific knowledge, but by performing scientific research and publishing results, firms can actively participate in the scientific research community, which can be considered one of the main vehicles for new knowledge diffusion. Publishing, in the words of Rosenberg (1990), can be regarded as 'a ticket of admission to an information network' (p.170) because it makes firms, or individual researchers working for these firms, active members of specific research communities. The relationship to the insights of the economics of knowledge diffusion economics literature discussed in chapter two is clear. In addition to the advantages of accessing valuable knowledge, linkages to the scientific community also enhance the visibility of firms in their working field. This can, in turn, be very beneficial for recruiting high-quality researchers (Zucker et al., 1998a).

Table 3.1 - Relative importance of different mechanisms of university-industry knowledge exchange

Rank	Interaction type	Relevance Index* (100-0)
1	Collaborative research	74
2	Informal contact	71
3	Education of personnel	60
	Doctoral theses	60
	Contract research	56
	Conferences	56
	Consultancy	52
4	Seminars for industry	39
	Scientists exchange	39
	Publications	35
5	Committees	31

* The relevance index is based on a metric conversion of the valuation of different mechanisms on a four-step scale ranging from very important till not important by university professors and researchers in the industry.
(Source:Meyer-Krahmer and Schmoch 1998).

The importance of being an active member of a research community is related to the inability of individual firms to keep pace with rapid developments in scientific fields like molecular biology. This has led not only to the active participation of firms in scientific communities, but also to a general increase in the importance of inter-organisational collaboration for innovative activities. Within life sciences, small, dedicated biotechnology firms, pharmaceutical and chemical multinationals, hospitals, and venture capitalists all play pivotal roles in the innovation process (Powell et al., 1996; Cockburn and Henderson, 1998 and Cooke, 2005, 2006). Similar trends can be found in other science-based industries, like semiconductors, where inter-organisational R&D alliances have become a structural feature in innovation processes (Stuart, 2000). Consequently, inter-organisational networks are increasingly regarded as the 'locus of innovation'(Powel et al., 1996). Because universities are the most important source of scientific knowledge and are characterised by an incentive system towards the diffusion of this knowledge, university-industry collaboration is considered to be the most important type of inter-organisational knowledge relationships.

Due to the growing importance of science-based industries,[26] increasing attention has been given to the role of universities in innovation processes (see Etzkowitz and Leydesdorff, 1997, 2000). The interaction between universities and firms occur via a wide range of mechanisms from collaborative research to informal knowledge exchange. The relative importance of different university-industry relationships differs across industries (Cohen et al., 2000). Collaborative research is considered to be especially important in science-based

26 The (growing) role of science-based industries in economic growth is also emphasized in newer variants of new endogenous growth theories focusing on the importance of science-based, general purpose technologies such as ICT or biotechnology (see Bresnahan and Trajtenberg, 1995; Helpman, 1998) and a large and diverse literature claiming the rise of the knowledge-based economy (Abramowitz and David, 1996; Foray and Lundvall, 1996; OECD, 1996)

industries due to the direct relationship between scientific research and innovation. This is confirmed by empirical studies analysing the relative importance of different channels of knowledge exchange for firms in science-based industries, such as Meyer-Krahmer and Schmoch's (1998) study on Germany. Table 3.1 shows their findings with different mechanisms of knowledge exchange ranked from the most to the least relevant.

Given that organisations involved in science-based innovation processes are active in publishing, co-publications are used as an indicator of research collaboration. Several of the advantages and disadvantages of patents also apply here. Scientific publications contain valuable information on the names and addresses of the researcher and their affiliations, the year of publishing, and the content of the research. The peer review process also guarantees a minimum level of quality and originality. Data on publications is available across different science fields and countries, and over longer time periods. However, not all research ends up in a scientific publication and the propensity to publish varies greatly among disciplines. Regarding collaborative research, the occurrence of multiple authors and/or multiple organisations on a scientific publication can be used as indicator for collaboration in the research leading to this publication. Because individuals and their affiliations are generally only mentioned on a publication after a substantial contribution, publications with multiple authors and multiple organisations are considered to be good indicators for collaborative research (for an extensive overview of these arguments, see Katz and Martin, 1997 and Glänzel and Schubert, 2004). Whereas (almost) all co-publications might be considered to represent some form of collaboration, not all collaboration in research ends up in a co-publication and thus, not all research collaboration is measured by the use of co-publications. Laudel (2001) showed that this is most often the case for collaborative research between individual researchers within the same organisation. Research collaboration with other organisations, on the other hand, generally leads to a joint publication (Laudel 2001). Therefore, publications with multiple organisations can be considered as valuable indicators of collaborative research

3.2.3 Selection of science-based technologies and science fields

The selection of technologies is based on a classification of patent fields (2 and 3 digit IPC fields) into thirty technological coherent groups. This classification has been developed by the Fraunhofer-Institut für System- und Innovationsforschung in Karlsruhe and the Observatoire des Sciences et des Techniques (OST) in Paris and is widely used in empirical studies of science and technology. The selection of science-based technologies from these 30 technologies is based on the comparison of the relative strength of the interaction with scientific knowledge in each technology field by Verbeek et al. (2002). Following Narin and Noma (1985) and Meyer-Krahmer and Schmoch (1997), the relative scientific intensity of each technology is analysed by comparing the relative importance of citations on patents to scientific publications. Citations on patents refer to prior knowledge upon which patented knowledge is built. The majority of these patent citations refer to other patents, but a significant number of citations refer to scientific publications and indicate that the patented knowledge builds partly on scientific knowledge in these publications. Science-based technologies are consequently defined as technology fields where patents have a relatively large share of citations to scientific publications. Based on this analysis, the following eight technology fields have been selected.

- agriculture and food chemistry;
- analysis, measurement and control technology;
- biotechnology;
- information technology;
- optics;
- organic fine chemistry;
- semiconductors
- telecommunications.

Patent data was retrieved from the EPO patent bulletins available from 1979 until 2004. However, after 2001, the total number of patents drops sharply due to the time lag between the application for a patent and its announcement.

The journals in which the cited scientific articles are published can be classified into scientific sub-fields. The classification of journals into scientific fields is done by the Institute for Scientific Information (ISI), owned by Thompson Scientific, which also publishes the Web of Science databases. Based on the classification of the scientific publications to which patents refer in different technology classes, it is possible to link scientific sub-fields to different technology classes. Based on the analysis of Verbeek et al. (2002), the relevant scientific sub-fields for each of the eight selected science-based technologies are selected and shown in table 3.3. As can be seen in table 3.3, some technologies are more similar in terms of their knowledge base and some scientific fields are relevant for more technologies. Based on the comparison of relevant scientific fields for each technology, a distinction can be made between life sciences and physical sciences (following Marsili, 2001).

Research collaboration has been analysed on the basis of publications with multiple organisations in the journals belonging to relevant fields for a specific technology. The source for this data was the Web of Science database. Web of Science contains information on publications in all major journals in the world starting in 1988. It covers three databases. First, it includes the Science Citation Index (SCI), which includes natural science journals. Second, it includes the Social Science Citation Index (SSCI), which includes social science journals. Finally, it includes the Arts and Humanities Citation Index (A&JCI), which includes journals belonging to the arts and humanities. Based on the lists of journals for each relevant field, all publications relevant to the eight selected technologies with at least one address in the Netherlands have been retrieved for 1988-2004.

3.2.4 R&D expenditures

Estimation of the knowledge production function in chapter six is based on technology specific R&D expenditures of firms and universities. This section describes the source and characteristics of this data. Data on total R&D expenditures at the combined regional and technological/sectoral level are not available. As an alternative, data on R&D wage expenditures by private firms have been used from SenterNovem from 1996 until 2003. Senternovem is an agency of the Ministery of Economic Affairs tasked to administer, monitor, and analyse subsidies to projects related to innovation and research. From the different subsidies available, the 'WBSO' the Dutch abbreviation for 'law on the stimulation of research and development', subsidy is the largest. This subsidy consists

Table 3.2 - R&D Expenditures per Hoop Area in 2003

Hoop Area	Hoop Subarea	R&D expenditures (million euro's)
Total		2356
Agriculture	Agricultural Sciences	134
Natural Sciences	Mathematics & Computer Science, Physics & Astronomy, Chemistry, Pharmacology, Biology, Geology	456
Technology Sciences	Technological Mathematics & Computer Science, Civil Engineering, Building Engineering, Mechanical Engineering, Electronics, Chemical Engineering, Applied & Technological Physics, Other technological sciences	482
Health	Medical science, Dental Surgery, Veterinary Science, Other medical sciences	653
Economics	Economics, Business & Management	129
Law	Law	119
Social Sciences	Psychology, Pedagogy, Social & Cultural Sciences, Political sciences, Geography, Other Social Sciences, Sports	225
Languages & Cultural Studies	Theology, Philosophy, Western Languages, History and, Art History, Other Languages	157
Others		2

Source: own elaboration of the National Statistical Office and VSNU (2007)

of a tax deduction of wage costs of R&D projects. There are no restrictions regarding the industry or technology of a project. Most requests for this tax deduction of R&D wages are granted, which creates a very strong incentive for firms to apply. During evaluation of this policy measure, around 80 percent of industrial firms with ten or more employees that performed R&D in 2001 participated in the WBSO (Ministry of Economic Affairs, 2007). Therefore, these data can be used as an indicator for R&D expenditures of firms because a large portion of R&D projects consist of wages.[27] The total sum of R&D wages from the WBSO will be somewhat lower than the actual sum of R&D wages because some firms that perform R&D did not apply and because there is a maximum limit of tax deductions for each firm. Each project that has been granted is classified to a technology according to the British Standards Institutes (BSI), which can be linked to the OST-Fraunhofer technology classification (see table 3.3). Based on the address of the project applicant, expenditures for R&D wages of each project can be associated to a region. By aggregating each project, regional R&D wage data per technology is available, which is used as an indicator of R&D expenditures.

Data on R&D expenditures of universities are based on the combination of data from the national statistical office and the VSNU (the Federation of Dutch Universities). The former provides data on the total R&D expenditures for different research areas and the latter provides data on the number of researchers per university and research area. Based on the

27 Although this policy measure is primarily aiming at firms, universities and other research institutes can also benefit from it if they are collaborating with a firm. Only firms however were selected.

Table 3.3 - Concordance between technologies, scientific fields and R&D classifications

Technology	Patents (IPC codes)	Science fields for co-publications (ISI fields)	Private R&D (BSI technology fields)	University R&D (HOOP areas)
Agriculture & food chemistry	A01H, A21D, A23B-D, A23F, A23G, A23J-L, C12C, C12F-H, C12J, C13D, C13F, C13J, C13K	Biochemistry & Molecular Biology; Microbiology; Genetics & Heredity; Food Science & Technology; Agriculture Dairy & Animal Science; Nutrition & Dietetics	H agriculture; I food processing; VI-VJ agrichemical technology	Agricultural Sciences; Natural Sciences; Health
Analysis, measurement and control technology	G01B-D, G01F-H, G01J-N, G01P, G01R, G01S, G01V, G01W, G04, G05B, G05D, G07, G08B, G08G, G09B-D, G12	Biochemistry & Molecular Biology; Applied Physics; Instruments & Instrumentation; Electrical & Electronical Engineering; Immunology; Analytical Chemistry	B measurement and testing	X
Biotechnology	C07G, C12M, C12N, C12P-S	Biochemistry & Molecular Biology; Microbiology; Genetics & Heredity; Immunology; Virology; Biophysics; Biotechnology & Applied Microbiology	V chemical technology; DV steroids & DNA	Agricultural Sciences; Natural Sciences; Health
Information technology	G06, G11C, G10L	Electrical & Electronical Engineering; Computer Applications; Computer Cybernetics; Telecommunications; Acoustics	L communications; M computer technology	Natural Sciences; Technology sciences
Optics	G02, G03B-D, G03F-H, H01S	Optics; Electrical & Electronical Engineering; Applied Physics; Polymer Science	B measurement & testing; L communications	Natural Sciences; Technology sciences

Table 3.3 *- continued*

Technology	Patents (IPC codes)	Science fields for co-publications (ISI fields)	Private R&D (BSI technology fields)	University R&D (HOOP areas)
Organic fine chemistry	C07C, C07D, C07F, C07H, C07J, C07K	Biochemistry & Molecular Biology; Organic Chemistry; Pharmacology & Pharmacy; Immunology; Genetics & Heredity; Microbiology	D chemistry (except DV)	Agricultural Sciences; Natural Sciences; Health
Semiconductors	H01L	Electrical & Electronical Engineering; Physics Condensed Matters; Crystallography; Applied Physics; Nuclear Science and Technology; Material Science	K electrotechnology	Natural Sciences; Technology sciences
Telecommunications	G08C, H01P, H01Q, H03B-D, H03H, H03K-M, H04B, H04H, H04J-L, H04N1, H04N7, H04N11, H04Q	Electrical & Electronical Engineering; Telecommunications; Optics; Applied Physics; Computer Applications; Computer Cybernetics	L communications	Natural Sciences; Technology sciences
Source	EPO – FhG-OST classification	ISI/Web of Science	Senternovem/ Ministry of economic affairs	VSNU and CBS (national statistical office)

assumption that the average R&D expenditure per researcher in a specific area is the same across universities, the R&D expenditure per university is estimated. University research is classified according to HOOP (Hoger Onderwijs en Onderzoek Plan – Higher Education and Research Plan) areas, defined by the Ministry of Education and Science. Table 3.2 shows the different HOOP areas, sub-areas, and the R&D expenditure per area in 2003 to provide an indication for relative size. These HOOP areas can be linked to different technologies as well but are relatively broad and can only be linked to physical science-based technologies or life science-based technologies.

Based on the description of the HOOP areas by the VSNU natural sciences, agricultural sciences and health are assumed to be the most important areas for life science-based technologies and natural sciences and technology sciences have been linked to physical science-based technologies. In the case of analysis, control, and measurement technology, it is difficult to select specific HOOP areas because parts of all mentioned areas seem to contribute to some extent.

Table 3.3 shows the overall concordance table between the OST-Fraunhofer technology fields, the ISI scientific sub fields, the BSI fields for private R&D, and the HOOP areas for university R&D.

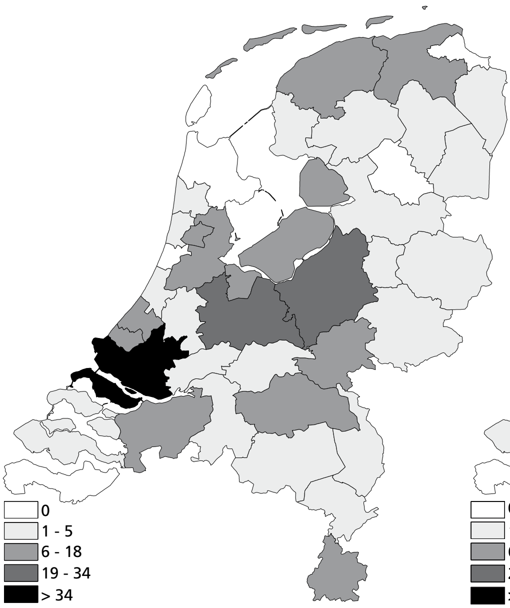
3.3 Geographical patterns of innovation in science-based industries[28]

This section provides an exploratory view of the geographical dimension of innovation in science-based industries in the Netherlands by analysing spatial patterns of patenting. This is done at the level of NUTS3 regions. There are 40 NUTS3 regions in the Netherlands and they consist of the 'Corop regions'. The delineation is based on labour market regions defined by commuting patterns. Therefore, the NUTS 3 regions, at least in the Netherlands, can be considered functional regions consisting of daily urban systems. [29] The geographical location of the inventor has been used to assign each patent to a region. The location of the inventor is preferred over the location of the applicant to avoid 'the headquarters problem'. This refers to large companies that have several subsidiaries where the headquarters fills out patent applications even if the knowledge or innovation is developed by subsidiaries in other regions. Because the main focus of this section is on the spatial patterns of new knowledge and innovation, the use of the location of inventors is more appropriate. In case of multiple inventors located in different regions, a proportion of the patent is assigned to each region. This implies that if three inventors on a patent are located in three different regions, the patent is counted for one-third in each region. The spatial patterns of innovation from 1996 to 2001 of the eight selected technologies are shown in figures 3.1 through 3.8. Altogether, these figures show that there is an uneven geographical distribution of innovation in these technologies with a relatively high spatial concentration in some regions.

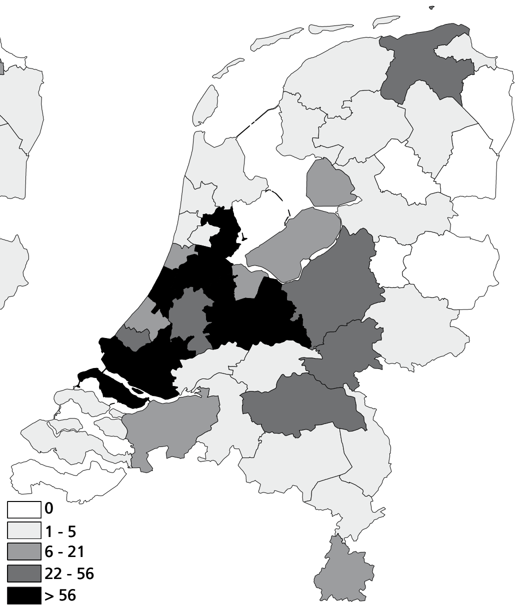
Tables 3.4 and 3.5 show the top five regions in terms of the share of total patents for life science-based technologies and physical science-based technologies, respectively. In the case of life sciences, patent activity is concentrated in regions where related public research institutes are concentrated with large specialised firms. The region of the Veluwe is home to an important cluster in life sciences with the University of Wageningen, related research institutes, and many life sciences and food industry firms. The region of Rijnmond (the city of Rotterdam and its surroundings) is home to several life sciences firms and a large Unilever research lab. As a result, this region has the highest share of agriculture and food chemistry patenting. Utrecht, Leiden, and Amsterdam are three other regions where biotechnology patenting is concentrated. In the case of organic fine chemistry, the presence of a large chemical industry (DSM) leads to a high concentration of patents in the region

28 This section is to a large extent based on Ponds and Van Oort (2008).

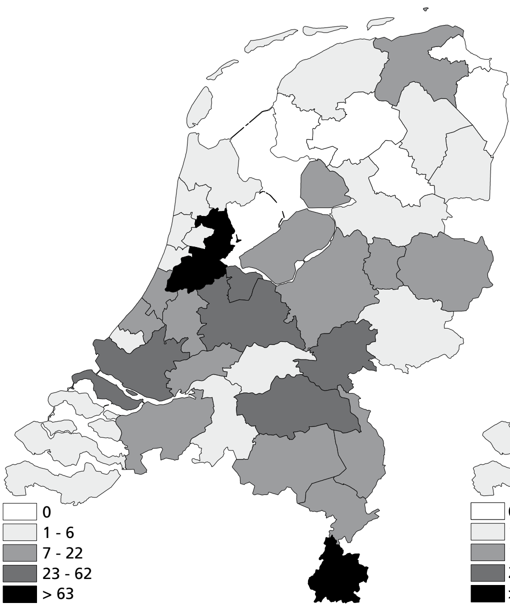
29 A recent study by Cörvers et al. (2008) confirmed the validity of the use of Corop or NUTS3 regions as functional regions. The important exception seems to be the region of Greater-Amsterdam, which attracts employees from a relatively large number of regions, most notably the region of Flevoland, home to the city of Almere, which is planned as the suburb of Amsterdam.



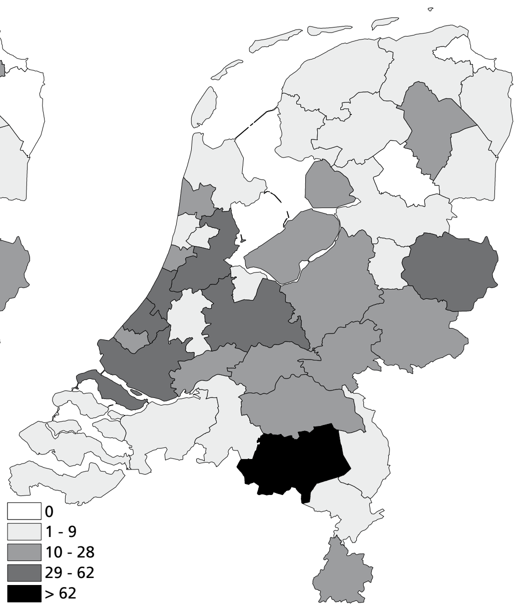
3.1 **-** Agriculture and food chemistry



3.2 **-** Biotechnology

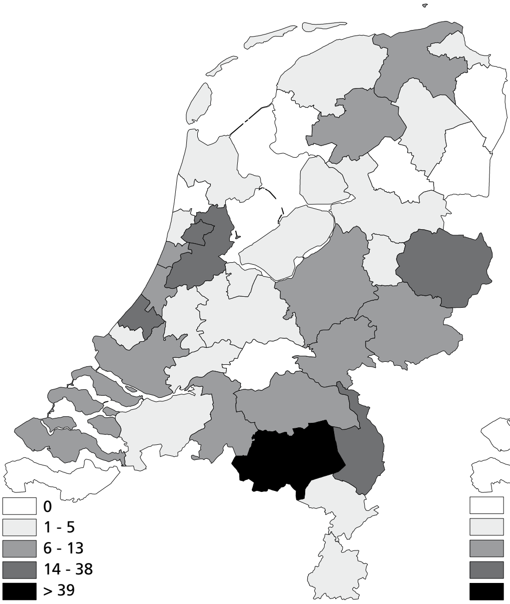


3.3 **-** Organic fine chemistry

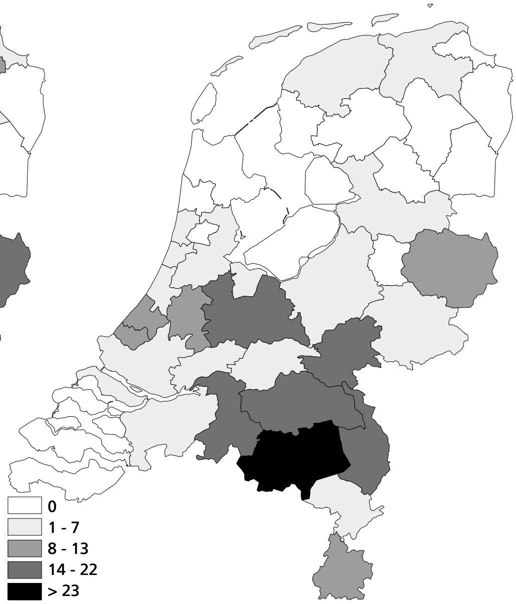


3.4 **-** Analysis, measurement and control technology

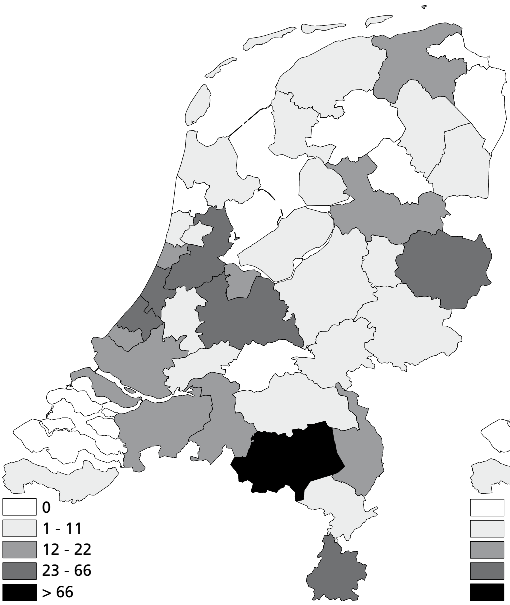
Figure 3.1-3.4 - Spatial patterns of innovation – number of patents between 1996-2001



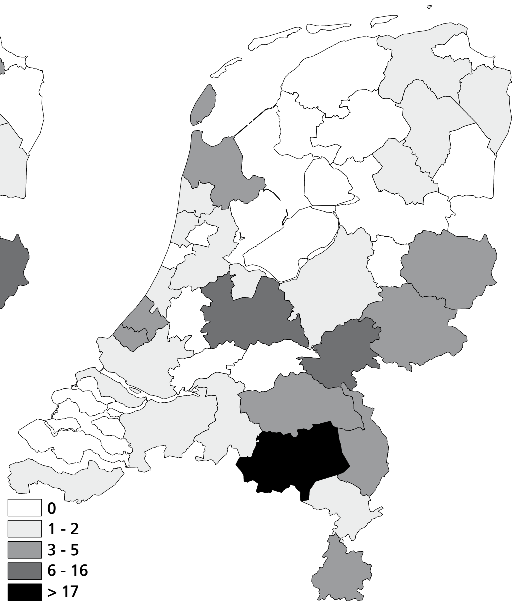
***3.5* -** Information technology



***3.6* -** Optics



***3.7* -** Telecommunications



***3.8* -** Semiconductors

Figure 3.5-3.8 - Spatial patterns of innovation – number of patents between 1996-2001

Table 3.4 - Share of top five regions in life science-based technologies

Agriculture & foodchemistry		**Biotechnology**		**Organic fine chemistry**		**Analysis, measurement & control technology**	
Region	**Share in patenting**	**Region**	**Share in patenting**	**Region**	**Share in patenting**	**Region**	**Share in patenting**
Agglomeration Rijnmond	35.4%	Utrecht	15.2%	South-Limburg	20.8%	Southeast-North-Brabant	42.7%
Veluwe	9.1%	Agglomeration Leiden	12.7%	Agglomeration Amsterdam	13.0%	Agglomeration Amsterdam	6.6%
Utrecht	7.1%	Agglomeration Amsterdam	10.5%	Northeast-North-Brabant	10.2%	Utrecht	6.0%
Northeast-North-Brabant	4.8%	Agglomeration Rijnmond	9.8%	Utrecht	8.3%	Agglomeration Rijnmond	4.5%
Delft and Westland	4.6%	Veluwe	8.6%	Agglomeration Rijnmond	6.0%	Agglomeration The Hague	3.7%
Total	61.0%	Total	56.9%	Total	58.3%	Total	63.6%

of South-Limburg. Innovative activity in science-based technologies seems to concentrate in regions containing a university and other public research institutes that specialise in research in a related scientific field.

The presence of Philips in the region of Eindhoven causes a very strong concentration of innovative activity in physical science-based technologies (table 3.5). Philips has by far the highest R&D expenditures in this research field in the Netherlands (CPB 2002), and also has the largest number of patents.

In some technologies (such as telecommunications and semiconductors), Philips accounts for half of the total number of patents from 1996 to 2001. Consequently, the Southeast North-Brabant region has an extremely high share of physical science-based patents ranging from nearly 70 percent for optics to almost 84 percent for semiconductors. To assess the impact of Philips on overall spatial concentration patterns in patenting in physical sciences, the shares of the top-five patenting regions with all patents from Philips removed from the data have been calculated.

The shares of the top five regions in the total number of patents excluding Philips for physical science-based technologies are shown in brackets in table 3.5. The Southeast North-Brabant region still has the highest share of the patenting activity, but the differences between this region and the other regions are much smaller, especially in information technology and telecommunications. In the cases of optics and semiconductors, a clear, but smaller, gap remains between the Eindhoven and other regions. Taken together, this implies that the Eindhoven region can be considered as the region with the strongest concentration of innovation in physical science-based industries, even after controlling for the effect of Philips. The top five regions with the highest shares account for more than 50 percent of all patents in the eight technologies studied, suggesting a considerable spatial concentration in these regions. Furthermore, considerable variation in the level of spatial concentration

Table 3.5 - Share of top five regions in physical science-based technologies (shares excluding Philips between brackets)

Information technology		Optics		Semiconductors		Telecommunications	
Region	**Share in patenting**	**Region**	**Share in patenting**	**Region**	**Share in patenting**	**Region**	**Share in patenting**
Southeast-North-Brabant	79.2% (17.0%)	Southeast-North-Brabant	68.2% (44.4%)	Southeast-North-Brabant	83.9% (36.4%)	Southeast-North-Brabant	75.8% (15.1%)
Groot-Amsterdam	3.1% (11.6%)	North-Limburg	4.0% (7.2%)	Utrecht	3.5% (13.5%)	Utrecht	3.2% (11.4%)
Twente	2.5% (9.0%)	Middle-North-Brabant	3.3% (5.9%)	Arnhem/ Nijmegen	3.1% (12.8%)	Twente	3.1% (10.9%)
Agglomeration The Hague	2.0% (8.2%)	Utrecht	2.9% (5.0%)	Twente	1.0% (4.3%)	Agglomeration The Hague	2.9% (10.2%)
North-Limburg	1.3% (5.4%)	Northeast-North-Brabant	2.9% (4.9%)*	Agglomeration The Hague	1.0% (1.9%)	South-Limburg	2.2% (7.9%)
Total	88.1% (51.2%)	Total	81.4% (67.5%)	Total	92.5% (71.0%)	Total	87.2% (55.4%)

* The region of Arnhem/Nijmegen enters the top five at the cost of Northeast- North-Brabant here.

exists across technologies given the differences in the sum of the top-five shares between the technologies.

A wide range of indicators has been developed for assessing the level of spatial concentration. These indicators all measure the extent of over- or under-representation of a specific activity across a group of spatial units.[30] In this analysis, the indicator for the level of spatial concentration is based on the relatively simple Hoover concentration coefficient.[31] This indicator has the advantage of comparability across industries or technologies and the ability to control for the overall concentration of economic or innovative activity. It is based on the difference in the spatial distribution between the variable of interest (patents in a certain technology) and a reference variable (such as population or total economic activity):

$$C = \frac{1}{2}\sum_{i=1}^{n}\left|\frac{x_i^g}{x^g} - \frac{y_i}{y}\right| \tag{3.1}$$

Where g refers to a technology and i to a specific region, x_i^g is the number of patents in region i in technology g and x^g reflects the total number of patents in technology g across all regions. y_i stands for the value of the reference variable in region i and y stands for the sum of the value of reference variables across all regions.[32] Therefore, this indicator is

30 Similarly, indicators for specialisation measure the over- or under-representation of a region in a group of activities.

31 For an overview of various indicators, see Combes and Overman (2004).

32 If no reference variables are taken into account then $\frac{y_i}{y}$ is simply $\frac{1}{n}$ where n stands for the total number of regions. This is referred to as the absolute index of spatial concentration.

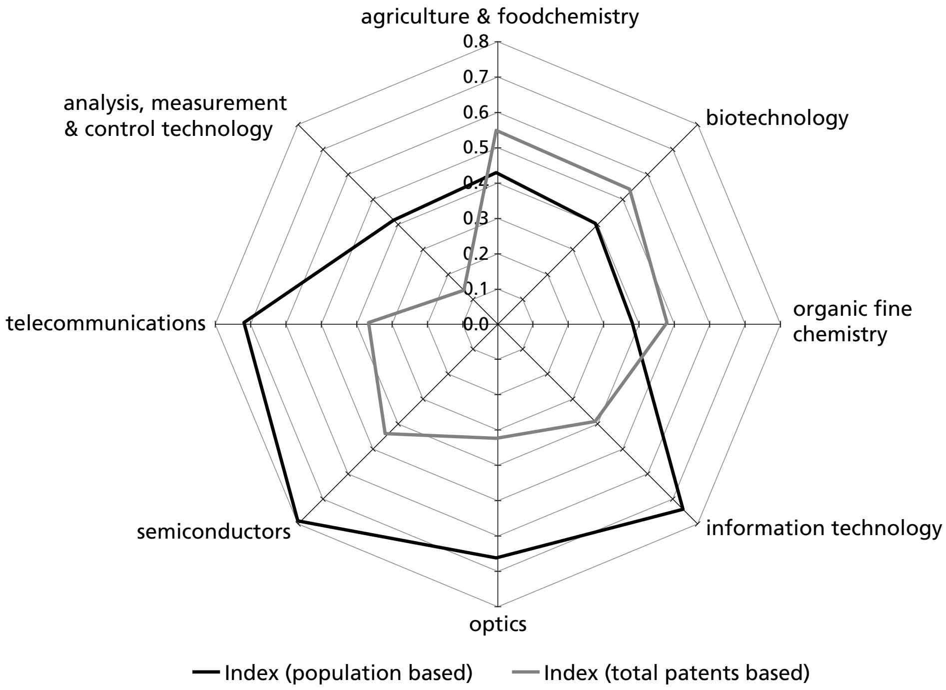


Figure 3.9 - Index of relative concetration per technology

actually a measure of dispersion, indicating the degree to which the spatial distribution of a variable differs from the spatial distribution of another variable. A relatively large deviance of the actual spatial distribution from the expected spatial distribution of patents (the spatial distribution of the reference variable) indicates a high level of spatial concentration. To see whether the spatial distribution of innovation is different from what can be expected from regional differences in size, population can, for example, be used as reference variable. The value of this indicator lies between zero (patents are equally distributed as the reference variable) and one (concentration of all patents in one region).

Figure 3.9 shows the relative spatial concentration for all science-based technologies. Two different relative indices have been calculated. The first uses population as a reference variable, thereby defining the level of spatial concentration as the deviation from the relative size of the regions. The values for each technology are shown by the black line. The second uses the total patent activity of all technologies from 1996 to 2001 as the reference variable.[33] This implies that the level of spatial concentration of innovation in a specific science-based technology is defined by the deviance from the general spatial distribution of technological innovation. These values are shown by the grey line. Figure 3.9 indicates that innovation in science-based technologies tends to be rather concentrated in space – either related to population or innovation in general. Innovation in physical science-based technologies is most strongly concentrated when related to regional size, whereas innovation in life science-based technologies is most strongly concentrated when related to

33 Based on EPO patent data.

the overall geographical pattern of technological innovation. This implies that innovation in physical science-based technologies takes place outside the major urban areas, in middle-sized regions. In contrast, innovation in life science-based technologies takes place in relatively more specialised regions – defined by the deviation from the overall pattern of technological innovation.

3.4 Concluding remarks

This chapter discussed the specific characteristics of science-based industries. Based on these characteristics, the choice of co-publications, R&D expenditures, and patents as indicators of research collaboration, investment in knowledge, and innovation, respectively, is justified. Innovation in science-based technologies shows a clear tendency of spatial concentration compared to both the spatial distribution of the population and the spatial distribution of the overall level of patenting. The important role of inter-organisational knowledge exchange for innovation in science-based industries suggests that localized knowledge spillovers through this mechanism are an important agglomerative force explaining this tendency. Empirical studies of science-based industries (see e.g. Cooke, 2001; Gertler and Levitte, 2005) nonetheless tend to conclude that national and international dimensions seem to be at least equally important for knowledge spillovers, even though localized knowledge spillovers are indeed important. Science-based industries are therefore an extremely interesting case regarding the research aim of this study.

Chapter 4

The limits to internationalisation of scientific research collaboration [34]

4.1 Introduction

Collaboration in research is a growing phenomenon. In the last years, this phenomenon has been studied extensively by various authors (see for example Katz and Martin, 1997 and Wagner-Doebler, 2001). Collaboration in research is associated with an enhancement of the quality of the research (Narin et al., 1991 and Frenken et al., 2005). Collaborative research is also assumed to lead to a faster diffusion of scientific knowledge (Breschi and Lissoni, 2003 and Singh, 2005). As a result, policymakers in different countries and at the international level are increasingly stimulating research collaboration. For example, the European Commission aims to create a European Research Area (ERA) by stimulating research collaboration between different member states. National policymakers on the other hand are generally focusing on the stimulation of academic-industry collaboration within their country with goal to improve the interaction between science and technology and, hereby, to stimulate innovation. It has been argued that research collaboration between academic and non-academic organisations has been growing over time (Gibbons et al., 1994), leading towards an increasing intertwining of academic organisations, firms and governmental organisations in research activities (Etzkowitz and Leydesdorff, 2000). At the same time, research collaboration at the international level has been growing as well (Glänzel, 2001; Zitt and Bassecoulard, 2004). As a result there is no reason to assume that the potential benefits of the increased academic-industry interaction remain within regional or national borders. The rise of international research collaboration renders the occurrence of international knowledge spillovers from public research more likely to occur. This could be the case when a university collaborates and exchanges knowledge with a foreign firm, which in turn reaps the economic benefits of this knowledge.

The possible tension between policies stimulating collaboration between academic and industry and policies promoting internationalisation of research collaboration can be considered as a tension between 'technology-nationalism' and 'techno-globalism' (Ostry and Nelson, 1995; Archibugi and Michie, 1997). The former refers to the idea that national technology policies should try, amongst other things, to maximize the benefits of international collaboration by focusing on specific science and technology areas where national firms might develop international competitiveness. Several Asian countries have been seen as countries adopting such a policy (Niosi and Bellon, 1994), which has been not unsuccessful (see for example Chung, 2002; Sung and Carlsson, 2003). Policy responses to the internationalisation of science and technology based on a 'techno-nationalism' view are generally driven by concerns on reciprocity in international collaboration and prevention of a too high level of international knowledge spillovers from domestic research (Edler and

34 This chapter is accepted and forthcoming in a slightly different version as Ponds, R. (2008) The limits to internationalisation of scientific research collaboration. The Journal of Technology Transfer.

Boekholt, 2001). The techno-globalism view sees the internationalisation of science and technology as a 'natural' trend where countries are increasingly integrated into international research networks, which is in the end beneficial for all countries. According to Edler (2008), that the growth of internationalisation in public and private R&D is best considered as a positive-sum game for the countries involved.

Due to the ongoing internationalisation of science and technology more and more firms will be able to appropriate knowledge stemming from academic research in other countries. As a result, a continuation of national science and technology policies focusing primarily on the strengthening of the knowledge base of national industries can ultimately result in conflicts of interest between nations in the area of science and technology. Mowery (1998) argues that the increasing importance of intellectual property rights issues and the characteristics of technology policies on negotiations on international trade are prime examples of this. This might result in increasing overlap between foreign policy and some fields of science and technology policy in the future (Wagner, 2001).

Given the potential conflict between national policies and the increasing international research collaboration, it seems somewhat surprising that little is known about the levels of internationalisation for different types of collaboration, or about the 'balance of trade' of countries in the number of collaborations between domestic academic organisations with foreign firms and between domestic firms with foreign academic organisations. This chapter tries to contribute to the scientific and policy debate on the case of international research collaboration by focusing on these two issues. It is shown that the level of international research collaboration in eight leading science-based technologies in the Netherlands is indeed impressive. Around three out of four collaborations take place at the international level, showing the globalised nature of science. However, no evidence has been found that during the 17-year period of investigation the level of internationalisation has grown more rapidly than the level of collaboration at the national level. This suggests that the globalization of research has come to an end. It is also found that the national embeddedness of research is mainly related to collaboration between academic and non-academic organisations. The national dimension seems to be important in order to overcome potential problems due to differences in incentives, and norms and values by providing some common institutions. Finally, it is shown that the number of international collaborations between Dutch academic organisations and foreign firms and between Dutch firms and foreign academic organisations have become more balanced over time and no longer shows a persistent asymmetry.

This chapter continues as follows. In the second and third part, the rationales for the growth of (international) research collaboration in general and the growing importance of research collaboration between academic and non-academic organisations are discussed. The data and methodology used will be described in the fourth section. The fifth section presents the outcomes of the regression models on the effect of time and different types of collaboration on the probability of international collaborations to occur. In section six, the changing balances in international collaboration between academic organisations and industry are analysed. Session seven concludes and discusses the policy implications.

4.2 Research collaboration

Research collaboration is an increasing phenomenon during the last decades and has drawn the attention of various authors (see for an overview Katz and Martin, 1997). Despite this growing interest in collaboration in research and inter-organisational partnerships, Hagedoorn et al. (2000) conclude that there is no uniform definition of the phenomenon. Taking into account that any attempt towards a formal definition will be subject of debate, they argue that it is necessary to have a clear idea on what is meant by research collaboration and research partnership in studies on this subject. Here, research collaboration is defined in the way proposed by Hagedoorn et al. (2000, p. 58): a collaborative arrangement between organisations to pool resources for a common R&D goal. This chapter is focusing on scientific research collaboration, which implies that the goal of this collaboration is based on the development of new scientific knowledge that might or might not be used for the development of new products or services.

Several studies have shown that collaboration is growing over time in different fields (Wagner-Doebler, 2001) and in different countries (Glänzel, 2001). Different reasons for the growth of collaboration in research can be distinguished. First, the costs of conducting scientific research (e.g. the building of large laboratory facilities such as CERN – Centre Européen de Recherche Nucléaire) have been rising sharply which brings along a need for the pooling of resources from different organisations. As a result, researchers from these organisations collaborate more intensively as well (Katz and Martin, 1997). The second reason is the growth of the number of scientific fields and subfields, which results in an increasing specialisation within these fields (Stichweh, 1996). This division of labour leads consequently to a greater propensity to collaborate. This is even further enhanced by the growth of interdisciplinary fields such as biotechnology. Third and related to this, the increase in the use of complex instrumentation has lead to the growth of specialised experts in the use of these instruments (Katz and Martin, 1997). All these developments lead to an increase in the division of labour between individual researchers and individual organisations, which is accompanied by a higher propensity to collaborate.

Several of the factors enhancing collaboration in general are enhancing international collaboration as well, such as the creation of international research facilities. Next to this, international research collaboration is enhanced by the rapid fall of transport costs. This makes it easier to collaborate with distant partners and to visit international conferences to meet new potential collaborators. This is further stimulated by the increasing importance of English as the 'lingua franca' of most scientific fields. Also, the rise of the internet and the improvement of other communication technologies is considered as an important enabling factor making it more easy to collaborate. Nonetheless Laudel (2001) argues, based on qualitative research on collaborating scientists that face-to-face contacts and geographical proximity remain at the beginning of nearly all research collaborations. This does not have to imply that collaborating researchers have to be located nearby each other; temporarily geographical proximity (Rallet and Torre, 1999), for example at international conferences, can be sufficient. Another potential reason for the increase in international research collaboration is given by Wagner et al. (2001) who suggest that over time the number of countries worldwide that provide public support for scientific research has grown, leading to a larger number of potential collaborators worldwide. Finally, international organisations such as the EU are becoming an increasingly important source of funds and this is often accompanied with specific conditions for collaboration. Especially in the EU framework programmes funding depends on collaboration between organisations from different member states (Caloghirou et al., 2001).

The above-mentioned factors contributing to research collaboration at both the national and the international level are partly overlapping and, even more important, mutually reinforcing. Several factors that are internal to science, such as the increasing specialisation, lead to a greater propensity to collaborate. The propensity for international collaboration is further enhanced by factors external to science, such as the rise of ICT, the rapid decrease of transport costs and the growing importance of English. Given these developments, one would expect international collaboration to increase more rapidly than national collaboration.

4.3 Collaboration between academic and non-academic organisations

A second and partly related trend in scientific knowledge production has been the rise collaboration between academic and non-academic organisations. According to several authors (Gibbons et al., 1994; Etzkowitz and Leydesdorff, 2000), science and technology are increasingly organized in collaborative relations between academic organisations, firms and governmental organisations. Over time the boundaries of these types of organisations have become blurred and their activities are increasingly overlapping. This is often illustrated by concepts as academic capitalism and entrepreneurial universities (Slaughter and Leslie, 1997; Etzkowitz et al., 2000). The interaction between academic organisations, firms and governmental organisations has been subject of empirical analysis of several authors trying to measure academic-industry-government relations. Although methodologies differ widely, ranging from patents citations analysis (Narin et al., 1997; Meyer, 2000), scientific publications from firms (Godin, 1995) and questionnaires on academic patentees (Meyer et al., 2003), the common conclusion seems that there is an increase of cross-institutional interaction and collaboration. The growing importance of non-academic organisations in science may be commonly agreed upon, the fact that this leads to a 'new mode of scientific production' or a change into a Triple-Helix model is less undisputed. Some authors argue that scientific research has always been based on interaction between universities, firms and governments and, that in that sense 'nothing new is going on' (Weingart, 1997; Godin and Gingras, 2000). Possibly, over time the form and intensity of this interaction may have changed and this is reflected in the rise of cross-institutional research collaboration.

An important reason for the rise of these cross-institutional collaborations is the growth of science-based industries (Pavitt, 1984), like biotechnology and ICT. Innovation in science-based industries is strongly related with, and often based on the outcomes of scientific research. Firms in these industries are actively involved in scientific research and collaborate intensively with academic research organisations. Governmental research organisations are also actively involved in these fields, which is especially apparent in case of the life sciences. Within these industries new technologies are complex and often based on the fusion of existing technologies and new scientific subfields. Organisations are generally unable to keep up with the increasing complexity and the rapid development within these technologies and scientific fields. As a result different types of organisations are increasingly collaborating (Hagedoorn, 2002) and some authors argue that inter-organisational networks are becoming the 'locus of innovation' in biotechnology and other science-based industries (Powell et al., 1996; Stuart, 2000).

The management of these academic-industry-government collaborations, however, is inherently difficult due to fundamental differences in the underlying incentives, norms and values (Dasgupta and David, 1994). Researchers working in academic organisations have an incentive to maximize the diffusion of their knowledge by publishing the outcomes of their research. The incentive structure also stimulates to do research on subjects that are most likely to enhance the scientific discourse. Firms, by contrast, produce knowledge to maximise the rents that can be derived from the right to use this knowledge. As a result, firms have an incentive to minimize knowledge diffusion (at least before it is possible to appropriate it) and to do research on subjects where it is most likely to be successfully applicable in new products and goods. Governmental research organisations have an incentive to produce knowledge that is in the interest of the government and its policy goals.

The differences in incentive structures can give rise to conflicts regarding the direction of the research as well as the diffusion strategy. Since it is impossible to formalize all contingencies of joint research projects in a contract, trust, common norms and values, and mutual understanding are also important for successful collaboration. This explains why research collaboration is especially difficult in case of international collaboration and between different types of organisations. Organisations located in the same country share norms and values, a common legal framework and (often) a language, and also have access to national funding schemes. As a result, successful research collaboration between organisations with different institutional backgrounds is expected to occur more often within national borders than across national borders. Academic collaboration, by contrast, is expected to be less restrained by national borders due to the common incentive structure and the 'universal' norms of science. Therefore the main hypothesis here is that academic collaboration has a higher propensity to take place at the international level than collaborations between academic and non-academic organisations.

4.4 Data and methodology[35]

Research collaboration can take place in different ways and through different channels. Consequently, research collaboration can be analysed by several indicators (Levy et al., 2008). Among the most commonly used indicators of scientific research collaboration are co-publications. The notion of a growing importance of collaboration is generally based on the comparison of the number of co-authored scientific publications and the number of single authored papers. A co-publication in this context can be seen as the tangible result of a successful collaboration. The general assumption is that researchers from the

35 If the reader has read chapter three, he or she might consider skipping to the third section of this paragraph.

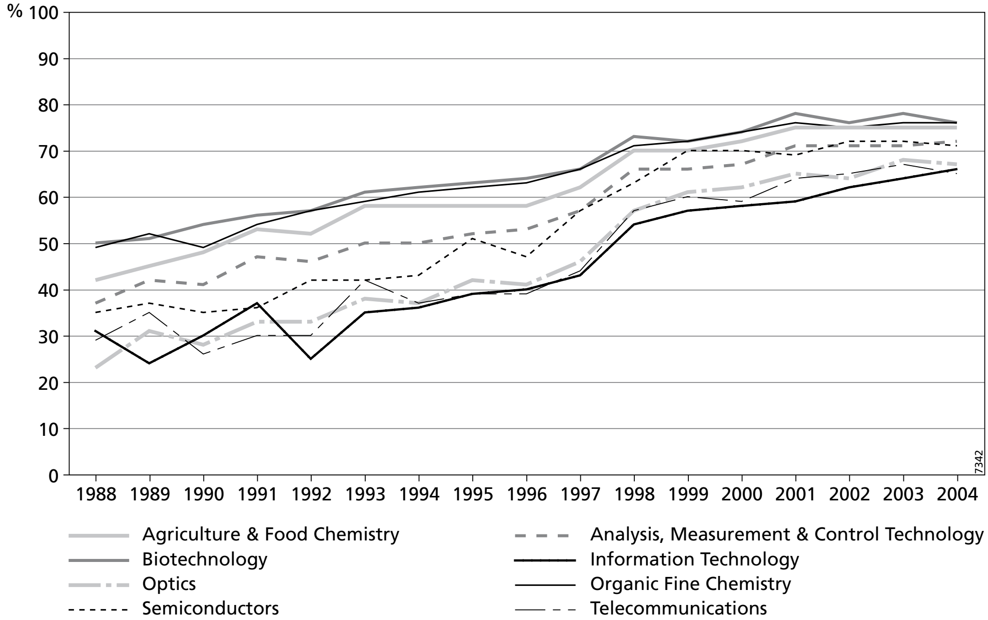


Figure 4.1 - The share of co-publications in the total number of publications

organisations listed on the publication have in some way pooled resources, for example by working together or exchanging knowledge (Cockburn and Henderson, 1998). Some disadvantages of using co-publications exist, however, including the fact that not all forms of collaboration are reflected by co-publications and that not all co-publications are alike in terms of the intensity of collaboration between the organisations and authors mentioned (see Katz and Martin, 1997 for a broader discussion). Nonetheless co-authorship is generally considered to be a valid and useful indicator (Lundberg et al., 2006), especially due to its comparability across time and across countries.

In this chapter the main interest lies in the analysis of research collaboration in scientific disciplines that are closely connected to science-based technologies. The selection of specific technologies was based on a study of Van Looy et al. (2003). They analysed the citations from patents to scientific articles in different technological classes.[36] The science-intensity of a technology was estimated by comparing the average share of citations on patents to scientific articles in the total number of citations for each technology. In the second stage the relevant scientific fields for each science-based technology were detected by analysing the journals in which these scientific articles were published. Based on the classification of sub-disciplines provided by Web of Science, the relevant scientific subfields for each technology can be defined. Using this methodology, eight science-based technologies are selected.[37] The following technologies were selected: (1) Agriculture & food chemistry, (2) Biotechnology, (3) Organic fine chemistry, (4) Analysis, measurement & control technology, (5) Optics, (6) Information technology, (7) Semiconductors and (8) Telecommunications. As can be seen in table 3.3, there is some overlap between the science bases of various

36 Based on the so-called OST-INPI/FhG-ISI technology classification

37 The relevant scientific subfields for each technology are shown in table 3.3.

Table 4.1 - Share of international and national collaborations

	National	International
Agriculture & food chemistry	28%	72%
Analysis, measurement and control technology	23%	77%
Biotechnology	30%	70%
Information technology	30%	70%
Optics	23%	77%
Organic fine chemistry	33%	67%
Semiconductors	19%	81%
Telecommunication technology	23%	77%

technologies. In the following, a distinction is made between life science-based technologies (1, 2 and 3) and physical science-based technologies (5, 6, 7 and 8). Analysis, control and measurement technology (4) is a technology with a more mixed science base.

Research collaboration can be defined at the level of individual researchers or organisations and, by aggregating using address information, at the level of cities, regions or countries as well (Katz and Martin, 1997; Ponds et al., 2007). In the database format of Web of Science it is not possible to link individual researchers to organisations and as a result the addresses of the organisations cannot be used to identify the location of individual researchers. This has as a consequence that a single-authored paper with two or more affiliations is counted as research collaboration whereas a multi-authored paper with one affiliation is not. Figure 4.1 shows the share of co-publications in the total number of publications per year.

From figure 4.1 it can be concluded, that the share of co-publications is clearly rising for each technology. This tendency reflects a higher propensity to collaborate in research as suggested by several other authors (such as Katz and Martin, 1997; Frenken, 2002).

In order to derive collaboration patterns from co-publications involving more than two organisations the 'full counting' method was used. This means that every co-occurrence of two organisations on a co-publication has been counted as one collaboration. Based on the addresses of the organisations on co-publications the spatial scale – national or international – of each collaboration was determined. Table 4.1 shows the share of national and international collaboration in the total number of collaborations. The static comparison in the figure shows that the share of international collaboration is significantly higher[38] than the share of national collaboration in all technologies, ranging from 81 percent till 67 percent. From table 4.1 it can be concluded that the level of internationalisation in scientific research collaboration in the Netherlands is rather high.

In order to see whether there is a trend towards internationalisation, figure 4.2 shows the share of international collaborations in the total number of collaborations over time for each technology. In figure 4.2, it can be seen that the share of international collaboration in the total number of collaborations remains fairly stable in all technologies. Given the growth of

38 Tested by t-tests on differences in shares

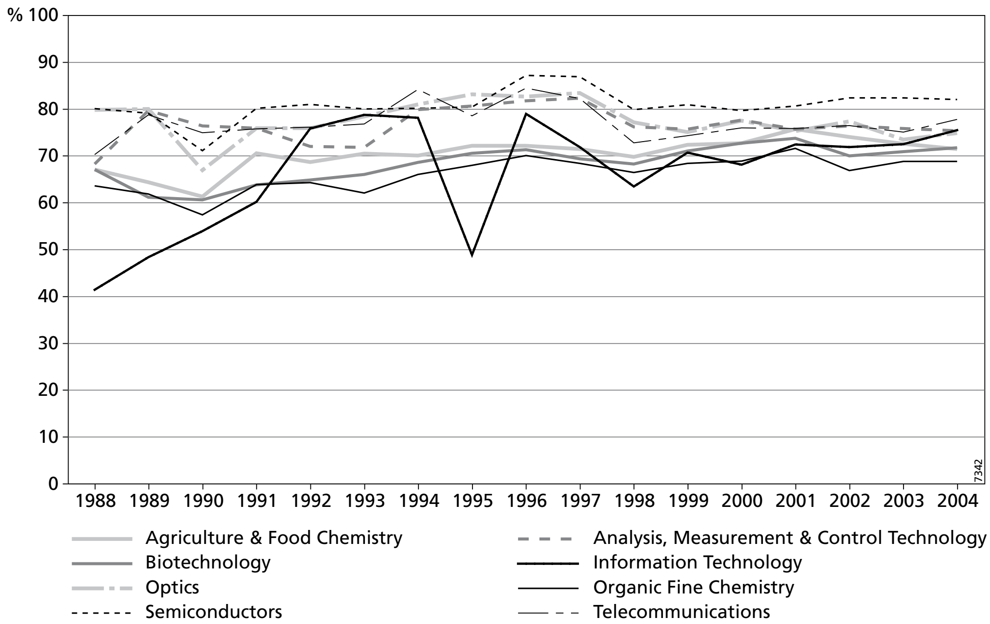


Figure 4.2 - The share of international collaboration over the years

research collaboration in general (figure 4.1), this implies that the number of both national and international collaborations is rising at more or less the same pace.[39]

Three types of organisations are distinguished; academic organisations, firms and governmental/non-profit organisations. Universities and national academic research organisations such as the Max Planck institutes in Germany have been labeled as academic organisations'. In the Netherlands the largest national academic research organisations are NWO (Netherlands Organisation for Scientific Research), KNAW (the Royal Netherlands Academy of Arts and Sciences) and academic hospitals. Research organisations such as TNO in the Netherlands or the National Institutes of Health in the USA and non-profit organisations are labeled governmental organisations. Based on a primary classification of organisations into these three categories an algorithm was designed to assign each organisation to one category. A test on a subset of collaborations revealed that up to 99 percent of the organisations was assigned correctly. The remaining collaborations have been classified manually. Six types of collaborations can be distinguished. These have been abbreviated as 'acad' 'gov', 'com', (collaboration between respectively two academic organisations, two governmental organisations and two firms), 'acad-com' 'acad-gov' and 'com-gov' (collaboration between different type of organisations). Table 4.2 shows the relative importance of each type of collaboration in the total number of collaborations.

In table 4.2 it can be seen that, not surprisingly, academic collaboration accounts in all technologies for the largest share of collaborations (about 50 percent). Collaborations

39 Note that in case of information technology there seems to be a rather strange sudden drop of the share of international collaboration in 1995. This is likely to result from the relative low number of total collaborations in information technology, which make sudden shocks more likely to occur.

Table 4.2 - The relative importance of various forms of collaborations

	acad	com	gov	acad-com	acad-gov	com-gov	Number of collaborations
Agriculture & food chemistry	50.8%	0.6%	7.3%	5.7%	33.4%	2.1%	56606
Analysis, measurement and control technology	56.6%	2.4%	3.2%	11.2%	23.8%	2.9%	35292
Biotechnology	49.3%	0.5%	7.7%	5.7%	34.8%	2.0%	65286
Information technology	47.0%	6.9%	2.5%	20.2%	18.7%	4.7%	6932
Optics	49.6%	5.7%	2.1%	21.3%	17.3%	4.1%	12687
Organic fine chemistry	47.7%	0.7%	8.4%	6.6%	34.3%	2.3%	68076
Semiconductors	57.8%	3.0%	2.5%	14.9%	18.8%	3.0%	14830
Telecommunication technology	50.2%	6.1%	2.0%	19.9%	17.6%	4.4%	10920

between academic organisations and governmental organisation and between academic organisations and firms are also frequent, whereas the shares of other collaboration categories are rather small. This does not mean that these organisations do not collaborate in research, but these collaborations are less likely to end up in co-publications as mentioned earlier. The focus in this chapter lies therefore primary on the possible differences between academic collaboration and collaboration between academic and non-academic organisations.

The aforementioned hypothesis holds that different types of collaboration have different probabilities to take place at the international level. As a result the variable of interest in this analysis is binary; it can take only two values, national (value '0') or international (value '1'). The effect of the type of collaboration on the probability that this collaboration is international can be analysed by the use of probit (or logit[40]) models (Long and Freese, 2003).

These models are based on a function, which takes strictly values between zero and one, and is given by:

$$P(y=1 \mid x) = G(\beta_0 + \beta_1 x_1 + ...\beta_k x_k) = G(\beta_0 + x\beta) \qquad (4.1)$$

The function G is an underlying latent variable model with y* as the latent variable:

$$y^* = \beta_0 + x\beta + \varepsilon, \; y = 1[y^* > 0] \qquad (4.2)$$

The coefficients in a probit model reflect the effect of a one-unit change in variable on y^* and are therefore not very easy to interpret, given the interest in the effect on y. It is more useful to analyse the marginal effect of a variable, which indicates the effect on y and therefore on the change in the probability of the collaboration to be international or national. The marginal effect can be calculated in two ways, depending on the type variable.

40 The difference between probit and logit models lies in the underlying specification of function G. In logit models G is a logistic function and in probit models G is a standard normal cumulative distribution function (Wooldridge, 2003).

Table 4.3 Results of the probit regression on the probability of international collaboration – life science-based technologies

	Agriculture & Food Chemistry		**Biotechnology**		**Organic Fine Chemistry**		**Analysis, Measurement & Control technoloy**	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Year-trend	0,004*** (0,000)	0,005*** (0,000)	0,005*** (0,000)	0,005*** (0,000)	-0,001 (0,001)	-0,000 (0,000)	0,005*** (0,000)	0,005*** (0,000)
Dummy com		-0,005 (0,025)		-0,017*** (0,022)		-0,092*** (0,017)		-0,019 (0,028)
Dummy gov		-0,136*** (0,008)		-0,164*** (0,007)		-0,127*** (0,015)		-0,117*** (0,008)
Dummy acadcom		-0,143*** (0,009)		-0,094*** (0,008)		-0,195*** (0,009)		-0,098*** (0,009)
Dummy acadgov		-0,094*** (0,004)		-0,116*** (0,004)		-0,095*** (0,006)		-0,096*** (0,004)
Dummy govcom		-0,091 (0,015)		0,010 (0,012)		-0,033*** (0,015)		-0,009 (0,013)
Loglike-lihood	-33744	-33365	-39949	-42372	-19083	-18703	-39949	-39590
LR statistic (df)	80,1***	837,9***	155,1***	1249,4***	1,8	762,5***	155,1***	873,5***
McFadden R2	0,001	0,012	0,002	0,015	0,000	0,020	0,002	0,019
N	56606	56606	65286	65286	68076	68076	35292	35292

Marginal effects are reported, standard errors in parentheses. ***indicates significance at 0.01 level, **indicates significance at 0.05 level, *indicates significance at 0.1 level

If x is a continuous variable, its marginal effect is obtained by the partial derivative at a specific value of x, often the average. If x is as binary (dummy) variable, the marginal effect is simply calculated by deducting the values for G with and without x, holding the other variables constant.

4.5 What type of collaboration is more likely to be international?

For each technology two different models are estimated. The first one includes a time trend variable in order to analyse if the probability of a collaboration taking place at the international level has been rising over time as previous studies on research collaboration repeatedly suggested. The second model includes the time trend variable and dummy variables for each form of collaboration. Academic collaboration is the reference dummy since the main interest lies in possible differences between academic collaborations and collaborations involving academic and non-academic organisations. Following our main hypothesis, the expectation is that the dummy variables for collaborations involving a non-academic organisation and an academic organisation (acad-com and acad-gov) are negative and significant, since these types of collaboration have a smaller probability to take place at the international level.

Table 4.4 - Results of the probit regression on the probability of international collaboration – physical science-based technologies

	Information technology		**Optics**		**Semiconductors**		**Telecommunications**	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Year-trend	0,007*** (0,001)	0,008*** (0,001)	-0,003*** (0,001)	-0,004*** (0,001)	0,002** (0,000)	0,000 (0,000)	-0,002* (0,001)	-0,002** (0,001)
Dummy com		0,064*** (0,021)		-0,117*** (0,019)		-0,114*** (0,023)		-0,057*** (0,019)
Dummy gov		-0,051 (0,038)		-0,164*** (0,031)		-0,088*** (0,025)		-0,118*** (0,034)
Dummy acadcom		-0,129*** (0,016)		-0,235*** (0,011)		-0,227*** (0,012)		-0,213*** (0,012)
Dummy acadgov		-0,063*** (0,016)		-0,085*** (0,012)		-0,065*** (0,009)		-0,051*** (0,012)
Dummy govcom		0,020 (0,029)		-0,096*** (0,022)		-0,103*** (0,023)		-0,024 (0,022)
Loglike-lihood	-4214	-4161	-6862	-6604	-7165	-6916	-5909	-5731
LR statistic (df)	30,9***	138,4***	11,6***	526,6***	6,8***	505,5***	3,2*	359,1***
McFadden R2	0,004	0,015	0,001	0,038	0,000	0,035	0,000	0,030
N	6932	6932	12687	12687	14830	14830	10920	10920

Marginal effects are reported, standard errors in parentheses. ***indicates significance at 0.01 level, **indicates significance at 0.05 level, *indicates significance at 0.1 level

Table 4.3 and 4.4 show the results for each technology. The life science-based technologies are shown in table 4.3 together with the analysis, measurement and control technology and the physical science-based technologies are shown in table 4.4. In the tables only the marginal effects are shown. The results of the models 1 suggest that the level of internationalisation in research collaboration is increasing over time only in some technologies. In five out of eight technologies the time trend variable has a positive effect on the probability of a collaboration being international.

Table 4.3 shows that within life sciences, agriculture & food chemistry and biotechnology have a positive and significant time-trend as does analysis, measurement and control technology, indicating a trend towards a growing level of internationalisation. From table 4.4 it can be concluded that this also holds for semiconductors and information technology, but not for the other two physical science-based technologies. Within table 4.4, optics and telecommunications even show a significant negative effect of the time trend on the probability of an international collaboration, suggesting a decreasing level of internationalisation. And, in models 2, the time trend variable is no longer significant in case of the semiconductors (table 4.4) as well. Together, the results suggest that there might be a trend towards internationalisation in research collaboration, but this trend is not so evident as often assumed and apparently different across technologies and scientific fields.

The results in models 2 include the dummy variables for different types of collaborations. The general conclusion seems to be that academic collaboration is indeed more likely to occur at the international level than other forms of collaborations in all technologies. A comparison of the marginal effects shows that 31 out of 40 are negative and significant whereas only one is positive and significant (collaboration between companies in case of information technology in table 4.4). Collaboration between academic and non-academic organisations is thus more likely to take place at the national level confirming the hypothesis formulated. This suggests that national research systems indeed facilitate interaction between academic and non-academic organisations, while academic collaborations are less dependent on such a system.

In sum, two important conclusions can be drawn from these results. First, the level of internationalisation in research collaboration is clearly high, but no convincing evidence for an increasing internationalisation trend can be found. Given the rise of collaboration in general, as shown in figure 4.1, the conclusion holds that that the rise of collaboration in general is much more pronounced as a trend than internationalisation of research collaboration (cf. Frenken, 2002). Second, the national level remains important, especially for collaboration between academic and non-academic organisations. This suggests that co-location in the same country might provide advantages in overcoming problems of collaboration between academic and non-academic organisations due to differences in incentive structures, norms and values. This might limit the effectiveness of policies stimulating international academic-industry collaboration as long as national systems do not converge institutionally.

4.6 The 'balance of trade' in international academic-industry collaboration

Despite the importance of the national level for collaboration between academic and non-academic organisations, the phenomenon of international academic-industry collaboration should not be neglected in discussions about the role of national science policies. According to some (Edler and Boekholt, 2001; Edler, 2008), most national governments are still – despite some 'strategic rhetoric' – mostly concerned with reciprocity in international collaboration and the danger of international knowledge spillovers from public research. It is therefore interesting to gain insight in the balance between national academic organisations collaborating with foreign firms on the one hand and foreign academic organisations collaborating with national firms on the other. Although far from a complete picture of international knowledge spillovers, the analysis of the development of this 'balance of trade' can give some indication of asymmetries in gains from international academic-industry collaboration, and the possible change in this over time.

This analysis has been done by computing the standardized proportion of the absolute number of Dutch academic organisations working with foreign companies and the absolute number of Dutch firms working with foreign academic organisations. The development of this standardized proportion is then plotted in graphs. The proportion is calculated by the following formula:

$$P = \left[\frac{x_{ij}}{x_{ji}} - 1\right] / \left[\frac{x_{ij}}{x_{ji}} + 1\right] \qquad (4.3)$$

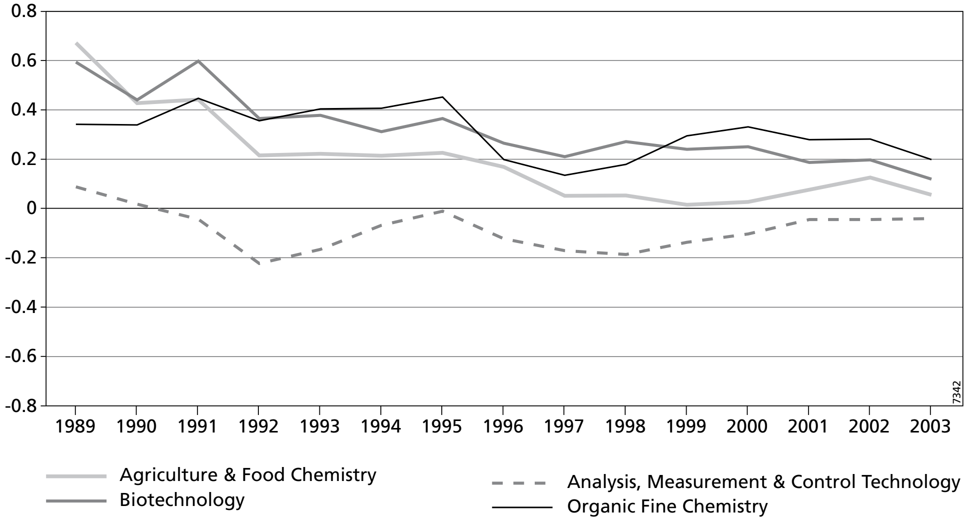


Figure 4.3 Change of standardized proportion of international academic-industry collaboration over time (life science-based technologies) – three year moving average

where P is the proportion between Dutch academic organisations working with foreign firms and foreign academic organisations working with Dutch firms. X_{ij} is the absolute number of collaborations between Dutch universities working with foreign firms and X_{ji} is the absolute number of collaborations between foreign universities working with Dutch firms. The value of P lies between -1 and 1 and has value zero if X_{ij} and X_{ji} have exactly the same value, which reflects a 'perfect balance'. If P is positive (negative) it indicates that foreign firms collaborate more (less) with Dutch academic organisations than vice versa. Figure 4.3 and 4.4 show the changes of the standardized proportion P over time for respectively the life science-based technologies (including analysis, measurement & control technology) and the physical science-based technologies.

Figure 4.4 shows that in life science-based technologies the value of P is positive, indicating that Dutch academic organisations collaborate more with foreign firms than vice-versa. In the mid-nineties the value of P has declined till nearly zero and it remains fluctuating around zero till 2004. It can be concluded that within life sciences, international academic-industry collaborations have become more balanced over time. This implies a decrease of the size of what maybe can be seen as international knowledge spillovers from public research. Contrary to the life science-based technologies, the value of P is negative till the mid-nineties for the physical sciences (with the exception of information technology) after which it is slowly increasing till its value is around zero as shown in figure 4.4. Thus, in both the life science- and the physical science-based technologies the value of P has become more stable over time and got closer to zero.[41] 'Techno-nationalist' fears that foreign firms profit disproportionally more from Dutch academic research than Dutch firms profit from foreign academic research, seem unfounded.

41 The fluctuations in the beginning of the period may be partly due to the smaller amount of observations in these years as compared to the more recent period.

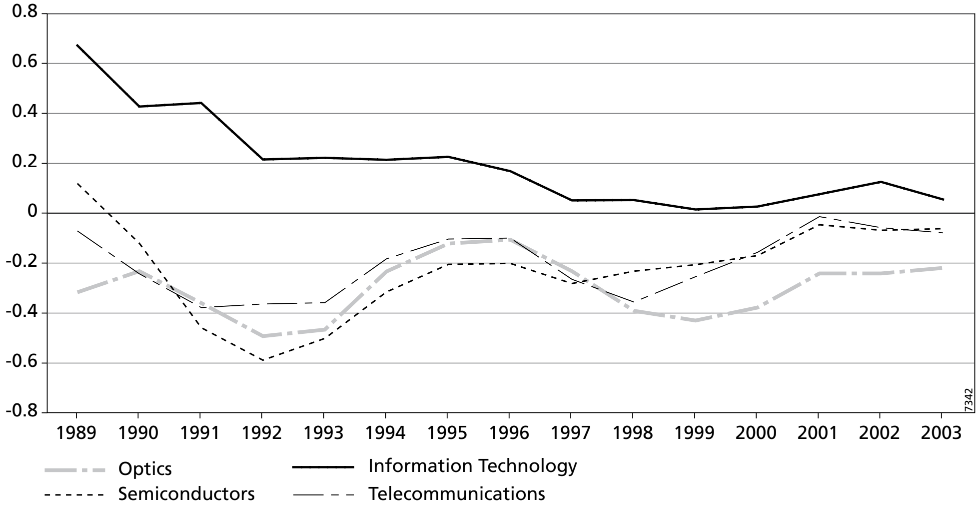


Figure 4.4 - Change of standardized proportion of international academic-industry collaboration over time (life science-based technologies) – three year moving average

A general conclusion is that international academic-industry collaboration has become more balanced over time, although small differences between life sciences and physical sciences remain. Given this dynamic trend towards symmetry, unbalanced patterns and consequently a high level of possible international knowledge spillovers from domestically funded public research, might be a temporarily phenomenon. This imbalance might be necessary to enter the international system of science and technology in a specific field (Archibugi and Iammarino, 1999). This could have been the case in life sciences in the Netherlands where international academic-industry collaboration was dominated by Dutch academic organisations and foreign firms in the beginning of the period of analysis. Through these collaborations valuable learning effects on the valorization of scientific knowledge in these fields might have taken place, which could have resulted in the more balanced pattern hereafter. At this moment not much is known about the mechanisms of these learning and observation effects and how this affect the science and technology dynamics in a country. Future research on this topic might reveal valuable insights for the ongoing discussion on national science and technology policy and internationalisation.

4.7 Conclusions and discussion

This chapter analysed the internationalisation of research collaboration for eight science-based technologies in the Netherlands from 1988 till 2004. The growth of international research collaboration has increased the interest of scholars and policymakers in this phenomenon. The main goals of this chapter were to analyse the development of internationalisation over time, to detect possible differences in the level of internationalisation between different types of collaborations and to gain some insights in the balance of international academic-industry collaboration. Co-publications involving two or more organisations have been used as an indicator for research collaboration.

International research collaboration is clearly an important phenomenon; the majority of all collaborations involving a Dutch organisation are international. Yet, contrary to the conclusions of some other authors, no compelling evidence has been found for an increasing trend of internationalisation of research collaboration. Some technologies exhibit a small steadily increase in international collaboration while that share remains constant or is even decreasing in case of others. It is thus important to distinguish between the growth in international research collaboration in absolute numbers, and the growth in the level of internationalisation of research collaboration. The rise of international research collaboration in absolute numbers goes hand in hand with a rise of research collaboration at the national level, leaving the share of international research collaboration more or less constant. This means that the rise of international research collaboration in absolute numbers reflects an increasing tendency of collaboration in general, and regardless of the spatial level, rather then an increase of the level of internationalisation.

The outcomes of this chapter have important policy implications at two spatial levels. The importance of the national scale for collaboration between academic and non-academic organisations points to the continuing importance of national institutions for systems of innovation (Carlsson, 2006). Research collaboration between organisations with different institutional backgrounds and incentive structures seems to be eased by being located in the same country. Potential problems resulting from these differences might be (partly) overcome due to a common legal framework, the use of the same language and similar norms and values. Furthermore, the high level of national academic-industry collaboration could also reflect effects of national science and technology policies. In case of the Netherlands this can be related to the launch of national 'leading technology institutes' in 1996. These institutes were set up as public-private partnerships for fundamental research collaboration between academic organisations and firms in designated fields such as ICT and food related biotechnology.

The outcomes of this chapter are also interesting from an international policy point of view. For example, the EU stimulates international research collaboration in general and university-industry collaboration in particular by means of the framework programmes. Based on the continuing importance of national borders, there might be several barriers that can limit success of the stimulation of international research consortia consisting of firms, governmental and academic organisations from different countries, some of them being cultural defined whereas others might be more related to regulation issues (Frenken et al., 2007).

Nevertheless, international collaboration between academic organisations and firms is frequently occurring as well. International academic-industry collaboration can be seen as a mechanism of international knowledge spillovers. Policy makers might be concerned with the occurrence of asymmetric benefits of these types of collaborations when foreign firms appropriate knowledge being produced within national publicly funded research programmes. In case of the Netherlands these asymmetries (both positive and negative) were found in the earlier stages of the period under investigation. Over time patterns of international academic-industry collaboration have become more balanced suggesting that the occurrence of asymmetrical benefits is a temporarily phenomenon, possibly reflecting a dynamic necessary in order to enter the international field (as suggested by Archibugi and Iammarino, 1999). Therefore, the mere possibility that the outcomes of public funded R&D are being appropriated by foreign firms does not seem to legitimate policy measures preventing these types of collaboration to occur. Moreover the chance of success of such measures is rather low as shown by Mowery (1998), who argues that the (sporadic) efforts of US policymakers to restrict foreign participation in publicly funded R&D programs turned out to be infeasible. Mowery (1998) also warns that such policy measures impair the fundamental open nature of the science system. According to Archibugie and Michie (1997) this form of techno-nationalism versus techno-globalism dilemma is best encountered by the abandoning of tax measures that financially stimulate R&D by firms. They and others (such as Edler, 2008) conclude that governments should try to avoid tax competition and focus on the support of a national science and technology infrastructure in order to make a country attractive for science and technology activities for both private and public organisations. Nonetheless managing the tensions between national science and technology policies and international interdependencies remain a major policy challenge.

Chapter 5

The geographical and institutional proximity of research collaboration [42]

5.1 Introduction

For many years now, the relationship between scientific research, technological innovation and regional economic development has been an important theme in innovation studies and economic geography. Relevant literature indicates that, particularly in science-based industries, the interaction between research institutes and firms is a crucial factor in innovation processes. A number of scholars have focused on the role of geography in these interaction processes and have found evidence for localised knowledge spillovers from universities and other academic organisations (see amongst others; Jaffe, 1989; Varga, 1998; Anselin et al., 2000; Acs, 2002). It is often assumed that geographical proximity renders collaboration more likely, because the tacit character of knowledge requires face-to-face interaction. Recently however, this line of reasoning has been questioned by several authors (Malmberg and Maskell, 2002; Torre and Rallet, 2005; Boschma 2005). They suggest that geographical proximity can only have an indirect role, and is neither a prerequisite nor sufficient for successful collaboration. Geographical proximity supposedly plays a more 'subtle and indirect role' (Howells, 2002 p.874) in positively influencing collaboration and knowledge exchange. Little is known about the role of geographical proximity in scientific collaboration and how this affects the nature and probability of collaboration. Since collaboration in scientific knowledge production has become a central policy issue (Canton et al., 2005), it is surprising that only few researchers have tried to understand the geography of these research collaborations. An important part of research collaboration, especially within applied sciences, takes place between different universities, companies and governmental institutes (Etzkowitz and Leydesdorff, 2000). In this context, it has been argued that the regional scale is highly relevant where the differences in institutional contexts are to be overcome (Cooke et al., 1997). In other words, geographical proximity can compensate the lack of institutional proximity. The hypothesis that research collaboration involving different kinds of organisations (companies, universities, governmental research institutes) is more geographically localised than collaboration between similar organisations is tested. To this end, data on collaboration patterns in eight science-based technologies at different spatial scales for the period 1988-2004 are analysed.

The following section first elaborates on the relation between proximity and knowledge exchange (section 5.2). In third section the central hypothesis – focusing on spatial characteristics of collaboration in scientific knowledge production between various organisations – is embedded in the empirical literature on the subject of science and

42 This chapter is published in a slightly different version as Ponds, R., F. van Oort and K. Frenken (2007) The geographical and institutional proximity of research collaboration. Papers in Regional Science 86: 423-444.

proximity. Section four focuses on data and measurement issues. It explains how the importance of geographical proximity for collaboration in science is measured taking into account institutional proximity by differentiating by the background of the organisation. Section five describes the spatial structure of scientific collaboration in the Netherlands on several spatial scales. In sections six and seven the hypothesis that research collaboration between academic organisations and non-academic organisations (companies or governmental organisations) is more regionalized than collaboration between academic organisations is tested. A censored tobit regression is applied in order to test whether or not certain types of collaborations are indeed occurring at different distances (section six). A further test for the influence of geographical proximity on the intensity of different forms of collaboration within the Netherlands is performed using a gravity model (section seven). Section eight concludes.

5.2 Geographical proximity and knowledge exchange

Consensus has grown among economists and economic geographers that knowledge production and knowledge spillovers are, to a great extent, geographically localised (Jaffe, 1989; Audretsch and Feldman, 1996; Feldman, 1999; Van Oort, 2004). To test for knowledge spillovers, most scholars apply a knowledge production function approach in order to explain the regional production of patents or innovations as a result of public and private R&D inputs and a local spillover index. In more than one case, and at different spatial levels, scholars have been able to indicate that such spillovers turn out to be statistically significant, that is, they exert a significant and positive effect on knowledge output as measured by patents or innovations. In particular, the money spent on university research in a region is said to be very beneficial for innovation in that region (Jaffe, 1989). Knowledge spillovers from universities and other academic research institutions seem to be spatially bounded, as shown by Jaffe et al. (1993), who found that the large majority of citations for U.S. patents stem from the same state as the one from which the cited patent originated, even when corrected for differences in regional sector distributions.

Geographical proximity is frequently claimed to be beneficial for successful collaboration and knowledge exchange. This is most often explained by the importance of face-to-face contacts for the exchange of tacit knowledge. In many studies this localised interaction is however, only implicitly assumed rather than examined in an explicit manner. A number of authors have theoretically questioned the importance of geographical proximity in itself for collaboration and knowledge exchange (see for example Breschi and Lissoni, 2001a,b; Howells, 2002; Gertler, 2003; Torre and Rallet, 2005 and Boschma, 2005). The main argument is that 'simple co-location is neither a prerequisite nor a sufficient condition' (Boschma, 2005 p.71) for collaboration. Other forms of proximity may well be at least as important for collaboration and knowledge exchange. For example, different branches of a multinational are considered to be organisationally close and can easily exchange knowledge regardless of the geographical distance between them. Scientists can also easily collaborate over long distances due to the common language and incentive structure (publishing). Geographical proximity however, can be very important in a more indirect way by overcoming possible difficulties due to differences in institutional or organisational backgrounds such as in academic-industrial or academic-governmental collaboration.

In these types of collaboration, problems typically arise from conflicts of interest or from differences based on a lack of institutional proximity. For successful collaboration mutual trust is necessary in order to overcome these problems. Geographical proximity can positively influence the building of mutual trust due to frequent interaction and face-to-face contacts. According to Boschma (2005), geographical proximity can compensate for the lack of institutional proximity. And, reversely, institutional proximity facilitates interaction over long geographical distances.

5.3 Science and proximity

Scientific research collaboration is a growing phenomenon and the proportion of co-publications in the total number of scientific publications has also been steadily increasing (Wagner-Doebler, 2001). Several reasons can be distinguished for the growing importance of collaboration which can be seen as the outcome of an increasing division of labour between researchers (Katz and Martin, 1997) First of all, there seems to be an increase in the number of scientific fields and subfields, many of them being interdisciplinary fields such as biotechnology. As a result, research increasingly depends on the combination of the knowledge and skills of researchers from different subfields. Secondly, the costs of research facilities are increasing rapidly, especially in sciences such as physics or life sciences. Resources are consequently more and more pooled at the regional, national and sometimes international level which forces researchers from different research organisations to collaborate more intensively. Thirdly, and related, is the increasing need for specialisation in those fields where the instrumentation is becoming more and more complex (Gordon, 1980). Fourthly, funding in different countries and at the EU level is becoming more and more dependent on the level and intensity of collaboration, as illustrated by the aim of the EU framework programs to create a 'European research area'.

While internationalisation has received a lot of scholarly attention, this being facilitated by Internet and cheap air travel, only a few scholars have focused on the role of geographical proximity in scientific knowledge production. There are at least two reasons why geography is still important for research collaboration. First of all, collaboration across greater distances remains more costly than collaboration at closer range, despite improved transportation possibilities and the rise of ICT. Some scholars found that geographical proximity is indeed important and does have a positive effect on the intensity and frequency of scientific collaboration (Katz, 1994; Liang and Zhu, 2002). Secondly, collaboration between academic and non-academic organisations, which is a frequently occurring phenomenon in science-based technologies (Pavitt, 1984; DeSolla Price, 1984), is assumed to be more localised in space. The increasing importance of non-academic organisations in science is sometimes referred to as the Triple-Helix (Etzkowitz and Leydesdorff, 2000).

To understand the impact of geographical proximity for research collaboration in science-based technologies, the differences between science and technology should be taken into account in more detail. Scientific research is fundamentally different from industrial innovation (Dasgupta and David, 1994). Gittelman and Kogut (2003 p.367) state it like this; '...the logic of scientific discovery does not adhere to the same logic that governs the development of new technologies'. Scientific research and the research for industrial innovation are conducted within different socio-economic structures (Dasgupta and David, 1994). The major difference lays in the goal of the research and as a consequence the underlying incentive structure (Dasgupta and David, 1994; Frenken and Van Oort, 2004). The main goal in science, and of scientific publishing, is to add new knowledge to the existing 'stock of knowledge' and to diffuse this new knowledge as widely as possible, whereas industrial research and innovation is concerned with '…adding to the streams of rents that may be derived from possession of (rights to use) private knowledge' (Dasgupta and David, 1994 p 498). As a result the incentive structures regarding knowledge production in academics and in industry are conflicting: in academics actors want to maximise the diffusion of their knowledge, while actors in industry want to minimize such diffusion.

When universities and companies collaborate in research, the differences in incentive structure and institutional backgrounds give rise to complex arrangements. The complexity of these collaborations renders it generally impossible to encode all contingencies in a contract and consequently, these collaborations has to rely, at least partially, on less formal institutions thereby reducing the risk of opportunism. One may therefore argue that, in the case of collaboration between academic and non-academic organisations (such as university-industry relations), geographical proximity may be supportive in establishing successful partnerships between organisations with structurally different institutional backgrounds. Geographical proximity may help to overcome these problems, because of a common interest in exchanging labour, accessing local funds and mutual trust induced by informal contacts and interaction. By contrast, when organisations with the same institutional background collaborate in research, that is when institutional proximity is high as in the case of two universities, successful interaction is less dependent on geographical proximity as collaboration takes place within a common framework of incentives and constraints. Thus, the main hypothesis underlying this chapter thus holds that research collaborations between organisations with different institutional backgrounds occur more often over short geographical distances than research collaborations between organisations with the same institutional background.

In the following sections, the spatial characteristics of collaboration in scientific knowledge production between various organisations will be analysed. The main goal is to find out what the spatial patterns of different forms of collaboration in scientific knowledge production are. The importance of geographical proximity for collaboration in science is measured, taking into account institutional proximity by distinguishing between the institutional backgrounds of different organisations. Organisations with the same incentive structures are defined as being institutionally close. Cognitive distance is controlled for by focusing exclusively on collaborations within scientific disciplines. Thus, from now on it is assumed that cognitive distance is small.

5.4 Data: co-publications as an indicator for research collaboration[43]

Co-publications are used as an indicator for collaboration in scientific research. Scientific publications are the most common form of output in scientific research, which implies that collaboration in scientific research will often be reflected in a co-publication.[44] The data stem from Web of Science, a product offered by the Institute of Scientific Information. Web of Science contains information on publications in all major journals in the world for 1988 onwards. It covers three databases: the Science Citation Index (SCI) including natural science journals, the Social Science Citation Index (SSCI) including social science journals, and the Arts and Humanities Citation Index (A&JCI) including journals belonging to the arts and humanities. Using Web of Science, one can construct data on a specific discipline in a relatively straightforward way. Once a list of journals that is representative for the scientific discipline in question is obtained, publications belonging to a discipline can be simply retrieved by using the set of journals as a query. The publications for those disciplines are analysed that contributed the most to technological innovation in science-based technologies. The selection of the technologies and the relevant scientific disciplines was based on the analysis of citations from patents to scientific articles by Van Looy et al. (2003). They estimated the science intensity of a technology by comparing the proportion of citations to scientific articles for different technological coherent patent classes. Based on the ISI grouping of journals into sub-disciplines, the relevant scientific fields for each science-based technology were estimated. For a further description of this method of linking science to technology see Van Looy et al. (2003). Based on their analysis the following technologies are selected: agriculture & food chemistry, biotechnology, organic fine chemistry, analysis, measurement & control technology, optics, information technology, semiconductors and telecommunication. Some technologies are more alike in terms of their science base than others and based on a comparison of the relevant scientific subfields it is possible to make a distinction between life science-based technologies and physical science-based technologies.[45]

Collaboration is defined as the co-occurrence of two or more addresses on a publication. Although collaboration in its essence takes place between people, the focus is on organisations. Addresses attached to the publications refer to institutional affiliations and not to single persons per se. Although individual authors can be distinguished in ISI, it is not possible to link these individuals to organisations since this information is not available when the data is downloaded in a database format. This means that a single-author paper with two or more affiliations is also counted as collaboration whereas a multi-

43 If the reader has read chapter three or four, he or she might consider skipping to section 5.5.

44 The question remains as to why firms publish (some of) the results of their research in scientific journals. Rosenberg (1990) views publications by firms as 'a ticket of admission to an information network' (p.170). For a firm to learn from external sources, their employees have to collaborate with external actors and to be active in a network of research institutes, universities and other companies. To become a member of these networks, they have to adhere to the social norm of publishing so as to become part of the scientific community (Cockburn and Henderson, 1998). In particular, when firms collaborate with universities or governmental research institutes, publication is likely. Goddard and Isabelle (2006) indicate, for example, that co-publications are the most frequently occurring outcome of research collaboration between French academic organisations and firms.

45 Table 3.3 shows the relevant science-fields for technological innovation for each of the eight selected technologies.

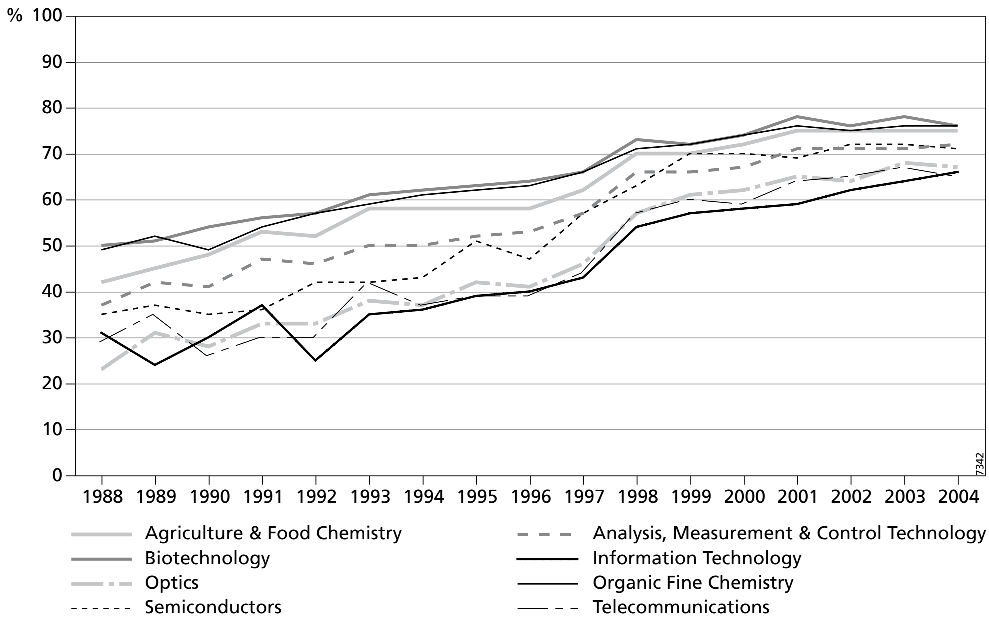


Figure 5.1 - The share of co-publications in the total number of publications

authored paper with one address (i.e. an intra-organisation collaboration) is not regarded as collaboration (see also Katz and Martin, 1997). All publications in the relevant scientific subfields for the period 1988-2004 with at least one address in the Netherlands have been retrieved for each of the eight selected technologies.

Figure 5.1 shows the shares of co-publications in the total number of publications for all technologies in every year between 1988 en 2004. Every co-occurrence of two organisations is counted as collaboration. Thus, no distinction is made between collaborations stemming from co-publications with two organisations or co-publications with more than two organisations involved. A co-publication with *n* organisations has *n(n-1)/2* collaborations. These collaborations are then aggregated and these collaborations are the unit of analysis in this chapter. The number of collaborations is growing over time in all technologies. This is not only because of the growth of the number of co-publications but also because of the growth of the average number of organisations per co-publication.

5.5 Spatial structure of scientific collaboration

The spatial scale of a collaboration was determined by analysing the addresses of the organisations involved. These collaborations were aggregated at the NUTS3 level. This regional classification is based on regional labour markets, which usually consist of a city and its surrounding municipalities. Within the Netherlands there are 40 NUTS3 regions. At the international level a distinction is made between collaboration with EU countries (including Switzerland and Norway), the USA and other countries (labelled international collaborations). Table 5.1 shows the importance of the various spatial scales for collaboration

Table 5.1 - Importance of various spatial scales for collaboration in science per technology

	National	EU	USA	International
Agriculture & food chemistry	28%	42%	16%	13%
Analysis, measurement and control technology	23%	45%	17%	15%
Biotechnology	30%	41%	17%	12%
Information technology	30%	40%	16%	14%
Optics	23%	44%	14%	19%
Organic fine chemistry	33%	40%	16%	11%
Semiconductors	19%	46%	13%	23%
Telecommunication technology	23%	42%	17%	18%

in science for the different technologies. Collaboration in science has a clear international focus. The majority of all collaborations is at the international level. The EU countries are by far the most important partners.

Although the phenomenon of international research collaboration is an interesting one, in the remainder of this chapter the focus lies on collaboration within the Netherlands. Figures 5.2 to 5.9 show the spatial pattern of scientific collaboration in the different technologies within the Netherlands at the NUTS3-level for the period 1988-2004. The thickness of the lines shows the intensity (in terms of the total number of collaborations) of collaboration between two NUTS3 regions and the size of the dot shows the intensity of collaboration within a region. The spatial patterns of collaboration within the different life science-based technologies are very much alike. To a lesser extent, this is also the case for the different physical science-based technologies. The earlier made distinction between two broad sectors of life science-based and physical science-based technologies seems therefore justified.

A comparison of the physical science-based technologies with the life science-based technologies shows that the spatial structures or collaboration are clearly different, suggesting regional specialisation in related scientific subfields. Collaboration within life sciences like biotechnology takes to a large extent place between and within regions in the Western part of the Netherlands like Amsterdam, Leiden and Utrecht, in the economic centre called the Randstad. The spatial structure of collaboration within the different physical science-based technologies shows a somewhat different picture. The importance of the South-East Brabant region (around the city of Eindhoven) is apparent and can be traced back to a concentration of (micro-) electronics companies and related organisations clustered around the Dutch electronics multinational Philips and the Eindhoven University of Technology.

In order to analyse whether collaborations between different kinds of organisations have another spatial configuration than those between the same kind of organisations three different types of organisations are distinguished: academic organisations, companies and governmental/non-profit-making organisations. Academic organisations are those organisations whose primary goal is the advance of science – universities and other academic research organisations alike. Many governmental and non-profit-making organisations are additionally engaged in scientific research, but their main goals are often not the advance of science itself but lie merely in the use of the results of this research for

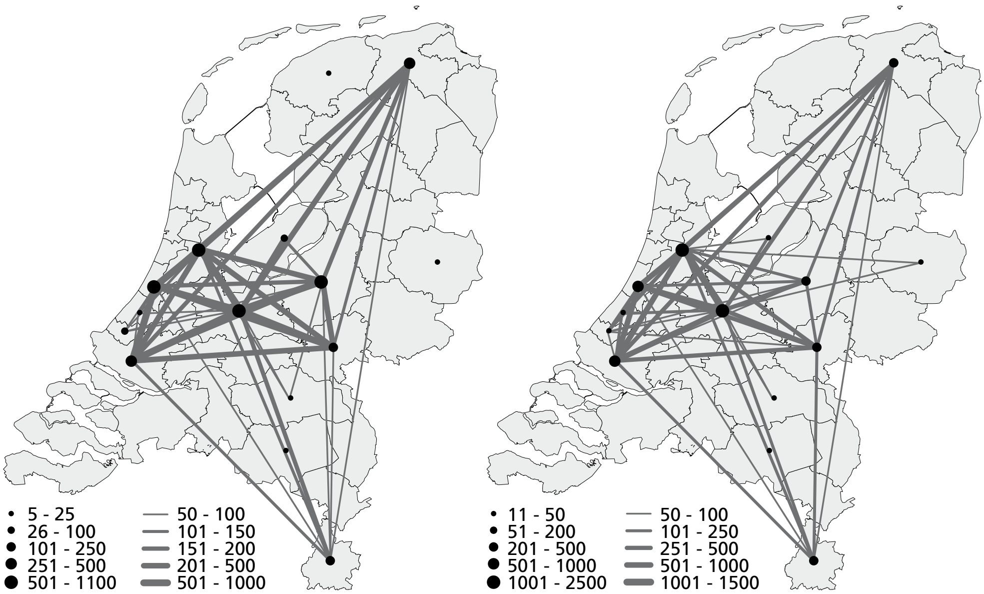


Figure 5.2-5.3 - Spatial patterns of scientific collaboration in agriculture & food chemistry and biotechnology

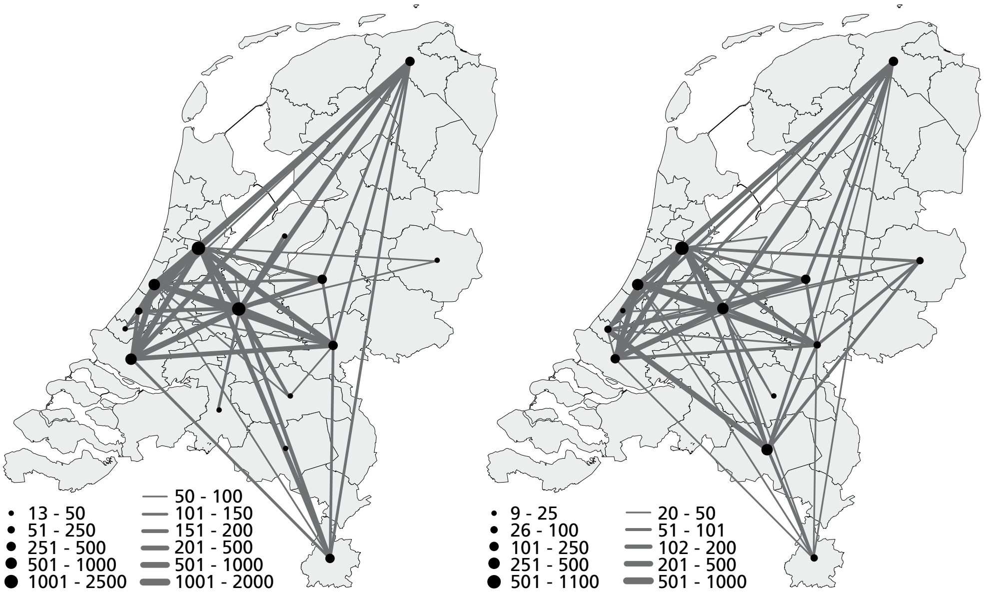


Figure 5.4-5.5 - Spatial patterns of scientific collaboration in organic fine chemistry and analysis, control & measurement technology

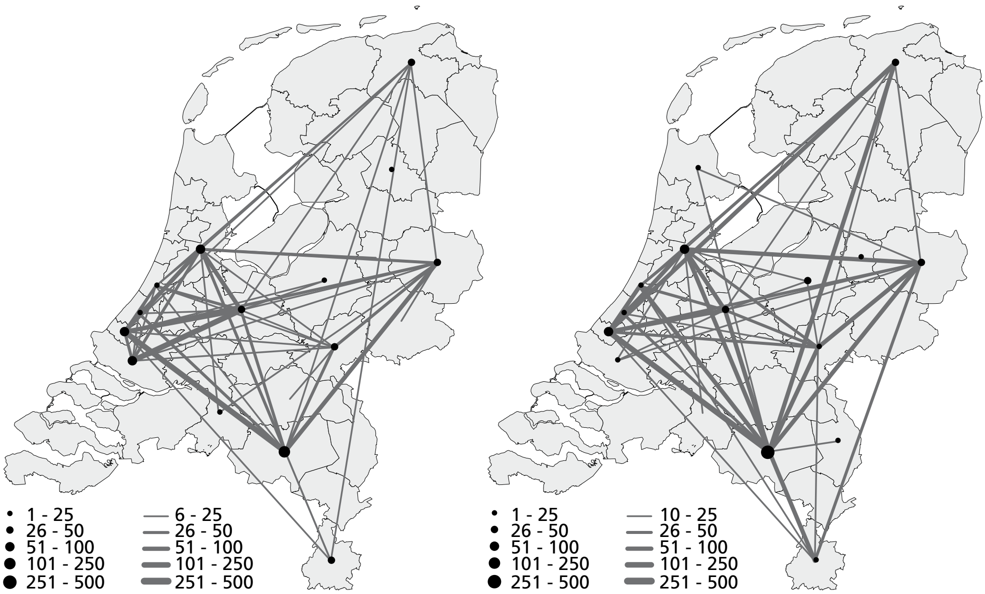


Figure 5.6-5.7 - Spatial patterns of scientific collaboration in information technology and optics

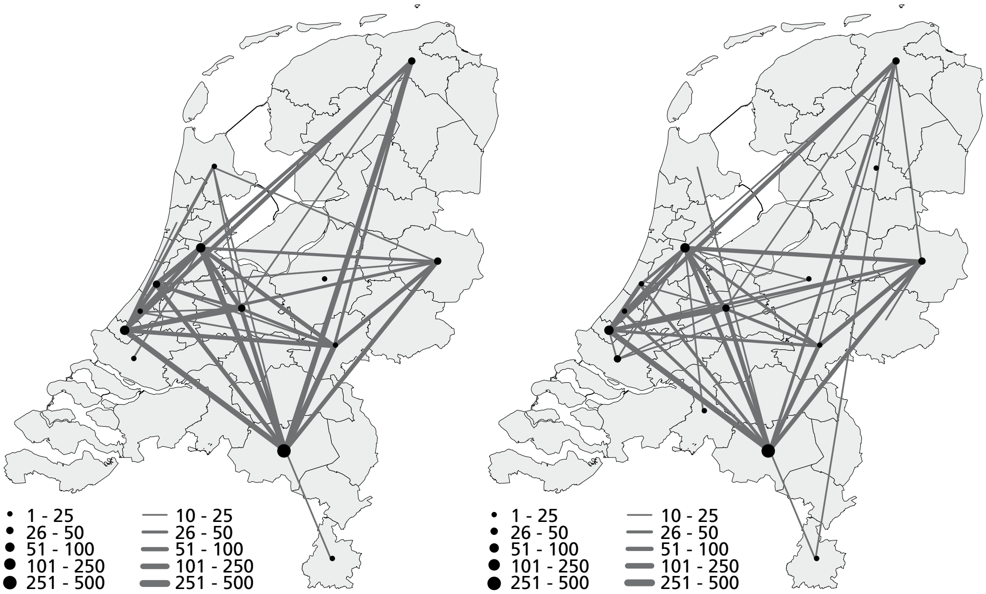


Figure 5.8-5.9 - Spatial patterns of scientific collaboration in semiconductors and telecommunications

Table 5.2 Share of different forms of collaboration per technology

	Acad	Com	Gov	Acad-com	Acad-gov	Com-gov
Agriculture & food chemistry	50.8%	0.6%	7.3%	5.7%	33.4%	2.1%
Analysis, measurement and control technology	56.6%	2.4%	3.2%	11.2%	23.8%	2.9%
Biotechnology	49.3%	0.5%	7.7%	5.7%	34.8%	2.0%
Information technology	47.0%	6.9%	2.5%	20.2%	18.7%	4.7%
Optics	49.6%	5.7%	2.1%	21.3%	17.3%	4.1%
Organic fine chemistry	47.7%	0.7%	8.4%	6.6%	34.3%	2.3%
Semiconductors	57.8%	3.0%	2.5%	14.9%	18.8%	3.0%
Telecommunication technology	50.2%	6.1%	2.0%	19.9%	17.6%	4.4%

society-broad goals. In order to identify the different types of organisations, an algorithm with a list of abbreviations and words to assign each address to one of three types of organisations has been developed. For example organisations with 'univ' in its name were assumed to be a university and therefore an academic organisation. Furthermore, the names of different governmental research institutes such as TNO in the Netherlands and academic organisations such as the academic hospitals were included in the algorithm. This algorithm was then tested and improved several times on a changing subset of 2000 collaborations until more than 99% of the organisations were assigned correctly to one of the three types of organisations.

Table 5.2 shows the share of the various forms of collaboration. Academic organisations are abbreviated as 'acad', companies as 'com' and governmental and non-profit-making organisations as 'gov'. Not surprisingly, collaboration between academic organisations is the most important form of collaboration in science. Collaboration between governmental organisations and academic organisations however, as well as between companies and academic organisations also frequently occurs. The share of collaborations between companies and between companies and governmental organisations is low. This is not because collaboration in fundamental research does not occur. On the contrary, this is a common phenomenon in science-based industries as shown by Powell et al. (1996) for life sciences and Stuart (2000) for physical science-based industries. It is merely that it seldom leads to co-publication.

It should be noted that there are differences between life sciences and physical sciences; collaboration between companies and academic organisations is considerably more important in physical sciences whereas collaboration between academic organisations and governmental organisations seems to be more important within the field of life sciences. The latter can be related to the importance of organisations such as hospitals and governmental health institutes in life sciences research (Owen-Smith et al., 2002). In agricultural research, large governmental research institutes also traditionally play an important role in scientific knowledge production. With this distinction between different forms of collaborations, it is possible to analyse whether the spatial patterns of collaboration between organisations with a different institutional background are different from those between organisations with a similar one.

Table 5.3 - Censored regressions of distance of collaborations in life science-based technologies

	Agriculture & food chemistry		**Biotechnology**		**Organic Fine Chemistry**		**Analysis, Measurement & Control technology**	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Constant	3.791** (0.010)	4.043** (0.011)	3.733** (0.009)	4.026** (0.010)	3.788** (0.009)	4.011** (0.010)	3.814** (0.015)	4.027** (0.015)
Dummy homogenous	0.213** (0.015)	-	0.241** (0.013)	-	0.181** (0.012)		0.166** (0.021)	-
Dummy acad		**Ref.**		**Ref.**		**Ref.**		**Ref.**
Dummy comp		-0.096 (0.101)		-0.072 (0.101)		-0.176** (0.080)		-0.332** (0.064)
Dummy gov		-0.291** (0.026)		-0.276** (0.024)		-0.227** (0.021)		-0.457** (0.053)
Dummy acadcomp		0.038 (0.029)		0.000 (0.027)		0.104** (0.025)		0.040 (0.029)
Dummy acadgov		-0.310** (0.016)		-0.349** (0.014)		-0.283** (0.014)		-0.393** (0.025)
Dummy govcomp		0.019 (0.049)		-0.070 (0.050)		-0.035 (0.048)		0.117* (0.065)
McKelvey and Zavoina's R2	0.13	0.13	0.017		0.009	0.024	0.008	0.043
N	15,949	15,949	19,719	19,719	22,194	22,194	8,160	8,160

Note: Significance levels: ** 0.95, * 0.90. Standard errors in parentheses.

5.6 Geographical proximity and scientific collaboration

To test the hypothesis that research collaboration between academic organisations and non-academic organisations (companies or governmental organisations) is more regionalized than collaboration between academic organisations, two different approaches are used. The first approach analyses whether different forms of collaborations take place over different distances. The second approach analyses the extent to which the possible differences in distances between different forms of collaborations are a result of the spatial distribution the various organisations across the Netherlands, or whether that geographical distance in itself is truly more important for some forms of collaborations.

In order to test the existence of variations in distance between different forms of collaboration the distance is modelled as a function of the type of collaboration. Different types of collaboration are specified by dummy variables. Two different models are estimated for each technology: model 1 distinguishes between homogenous collaborations (between the same type of organisations) and heterogeneous collaborations (between different types of organisations) and model 2 distinguishes between the six different types of collaborations. Using a logarithmic transformation for the dependent variable a tobit or censored model can be applied since distance is censored to the left at zero and to the right since the maximum is bounded by the country area (see also Johnson et al., 2006). The

Table 5.4 - Censored regressions of distance of collaborations in physical science-based technologies

	Information technology		Optics		Semiconductors		Telecommunications	
	Model 1	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**	**Model 1**	**Model 2**
Constant	3.956** (0.043)	4.183** (0.033)	4.076** (0.025)	4.478** (0.031)	4.132** (0.026)	4.352** (0.028)	4.006** (0.028)	4.332** (0.032)
Dummy homogenous	0.147** (0.043)	-	0.235** (0.038)		0.130** (0.038)	-	0.212** (0.041)	
Dummy acad		**Ref.**		**Ref.**		**Ref.**		**Ref.**
Dummy comp		-0.603** (0.098)		-0.819** (0.077)		-0.853** (0.098)		-0.732** (0.088)
Dummy gov		-0.458** (0.142)		-0.639** (0.111)		-0.661** (0.113)		-0.562** (0.132)
Dummy acadcomp		-0.167** (0.052)		-0.208** (0.043)		0.006 (0.044)		-0.214** (0.047)
Dummy acadgov		-0.330** (0.058)		-0.821** (0.053)		-0.532** (0.050)		-0.583** (0.058)
Dummy govcomp		-0.021 (0.122)		-0.329** (0.031)		-0.133 (0.101)		-0.086 (0.107)
McKelvey and Zavoina's R2	0.01	0.031	0.013	0.098	0.004	0.071	0.011	0.057
N	2,070	2,070	2,939	2,939	2,788	2,788	2,530	2,530

Note: Significance levels: ** 0.95, * 0.90. Standard errors in parentheses

distance of collaboration is measured by the travel time[46] between the regions where the organisations collaborating are located. Table 5.3 and 5.4 show the results.

Within table 5.3 the results of the life science-based technologies are presented together with those of the analysis, measurement and control technology. In the table 5.4 the four physical science-based technologies are presented. In the first model the dummy variable takes value one if the collaborations are between the same types of organisations. In all technologies this variable has a significant and positive relation with distance. These outcomes suggest that homogenous collaborations take place over longer distances than heterogeneous collaborations.

In order to analyse possible differences in distance between various types of relations the second model includes dummy variables for the different types of relations. Academic collaboration is the reference dummy and as a result the other variables should be interpreted in comparison with this type of collaboration. The hypothesis is that collaborations between organisations with different institutional background take place over a smaller geographical distance. Thus, the expectation holds that the dummy variables for

46 The average travel time between and within functional regions is based on a study of the OVG 2003 research of Statistics Netherlands (CBS) where the average travel time is estimated by a weighted average of private and public transport time.

academic-industry, academic-governmental and company-governmental collaborations have a significant negative effect.

In the case of academic-industrial collaboration the results differ. In the case of life sciences there are no significant differences between academic collaborations and academic-industrial collaborations in travel time and in the case of organic fine chemistry academic-industrial collaborations have a significantly higher travel time, which is rather unexpected. A possible explanation could be that the national level is the most relevant level for academic-industrial collaboration and the international level for academic collaboration. In the case of the physical sciences, academic-industrial collaborations have a significant lower travel time than academic collaboration in three of the four technologies, which is in line with the hypothesis. No significant differences in travel time can be found between academic and academic-industrial collaboration in the case of semiconductors. Governmental-industry collaborations sometimes have a significantly lower travel time across different technologies but this form of collaboration does not frequently occur.

Taking together, these outcomes suggests that geographical proximity is more important for collaborations with different institutional backgrounds than for collaborations with organisations with the same institutional background. One has however, to be careful when interpreting this as strong evidence for the hypothesis, as geographical proximity seems to be less relevant for academic-industrial collaboration than is often assumed.

5.7 Interregional collaboration: a spatial interaction approach

Alternatively, one can analyse whether geographical proximity between two organisations affects the probability of collaboration. To formally test whether geographical proximity is more important for collaborations of institutionally different actors than for similar ones, a gravity model approach is applied. The gravity-model is a well-known and often used spatial interaction model, which predicts or analyses the interaction between two places (see Maggioni and Umberti, 2007 and Dalgin et al., 2008 for recent applications).

The gravity model is described by the following formula:

$$I_{ij} = K \frac{M^{\alpha_1}{}_i * M^{\alpha_2}{}_j}{d_{ij}^{\beta}} \tag{5.1}$$

In this context I stands for the intensity of collaboration (measured in numbers of collaboration) between regions i and j, M for the total number of collaborations with at least one organisation in region i or j and d for the functional distance (measured in average travel time) between region i and j. K is a constant. Because the interaction I is based on collaboration (which has no direction) between regions, the distinction between the mass M of regions i and j is not applicable and therefore $\alpha_1=\alpha_2$. This formula can be rewritten into the following regression model:

$$Ln(I_{ij}) = K + \alpha Ln(M_i M_j) + \beta Ln(d_{ij}) + \varepsilon \tag{5.2}$$

Table 5.5 - Results of the negative binomial regression models

Life Sciences		*mass*	*travel time*	*constant*	*N*	*number of collaborations*	*Pseudo R2*	*Log likelihood*
Agriculture & foodchemistry	Total	0.857*** (0.018)	-0.008*** (0.001)	-7.647*** (0.186)	1,521	15,949	0.2970	-2,481.06
	Acad	0.937*** (0.030)	-0.003*** (0.001)	-8.363*** (0.328)	324	6,763	0.2840	-713.76
	Acad-com	0.957*** (0.039)	-0.004*** (0.001)	-7.032*** (0.308)	1,024	1,175	0.3260	-833.60
	Acad-gov	0.955*** (0.028)	-0.007*** (0.001)	-8.177*** (0.274)	1,444	6,106	0.3120	-1,681.04
Biotechnology	Total	0.851*** (0.018)	-0.009*** (0.001)	-7.616*** (0.184)	1,521	19,719	0.2924	-2,598.28
	Acad	0.912*** (0.028)	-0.004*** (0.001)	-8.122*** (0.308)	324	8,222	0.2985	-713.90
	Acad-com	0.956*** (0.041)	-0.005*** (0.001)	-6.940*** (0.323)	1,024	1,296	0.3093	-895.36
	Acad-gov	0.942*** (0.027)	-0.006*** (0.001)	-8.258*** (0.268)	1,444	7,931	0.3010	-1,784.66
Organic fine chemistry	Total	0.827*** (0.017)	-0.008*** (0.001)	-7.417*** (0.175)	1,600	22,194	0.2834	-2,989.88
	Acad	0.943*** (0.025)	-0.004*** (0.001)	-8.642*** (0.281)	400	8,720	0.3353	-700.48
	Acad-com	1.017*** (0.043)	-0.005*** (0.001)	-7.663*** (0.334)	1,089	1,591	0.2880	-1,034.85
	Acad-gov	0.975*** (0.028)	-0.006*** (0.001)	-8.769*** (0.281)	1,600	8,908	0.2914	-1,957.25
Physical Sciences		*mass*	*travel time*	*constant*	*N*	*number of collaborations*	*Pseudo R2*	*Log likelihood*
Information-technology	Total	0.927*** (0.034)	-0.006*** (0.001)	-7.047*** (0.289)	1,089	2,070	0.3118	-991.23
	Acad	0.953*** (0.066)	-0.002* (0.001)	-6.838*** (0.516)	289	873	0.2459	-481.66
	Acad-com	0.927*** (0.049)	-0.006*** (0.001)	-5.874*** (0.343)	784	554	0.3721	-434.24
	Acad-gov	0.894*** (0.071)	-0.006*** (0.001)	-5.381*** (0.448)	441	417	0.2416	-494.71
Optics	Total	0.955*** (0.030)	-0.003*** (0.001)	-7.890*** (0.271)	1,024	2,939	0.3219	-1,076.16
	Acad	1.043*** (0.061)	-0.000 (0.001)	-8.124*** (0.501)	225	1,004	0.2557	-447.97
	Acad-com	0.935*** (0.046)	-0.002 (0.001)	-6.831*** (0.335)	900	1,025	0.3254	-667.01
	Acad-gov	0.881*** (0.065)	-0.005*** (0.001)	-5.517*** (0.445)	361	517	0.2895	-411.03

Physical Sciences		*mass*	*travel time*	*constant*	*N*	*number of collaborations*	*Pseudo R2*	*Log likelihood*
Semiconductor technology	Total	0.954*** (0.033)	-0.005*** (0.001)	-7.612*** (0.291)	784	2,788	0.3522	-815.79
	Acad	0.974*** (0.057)	-0.001 (0.001)	-7.477*** (0.475)	196	1,179	0.3096	-377.47
	Acad-com	0.902*** (0.060)	-0.004** (0.020)	-6.113*** (0.398)	529	783	0.2695	-480.78
	Acad-gov	0.882*** (0.077)	-0.005*** (0.001)	-5.487*** (0.504)	324	544	0.2605	-413.58
Telecom-munication technology	Total	0.964*** (0.032)	-0.004*** (0.001)	-7.722*** (0.278)	1,089	2,530	0.3435	-975.47
	Acad	0.989*** (0.060)	-0.002* (0.001)	-7.326*** (0.469)	289	968	0.2668	-488.21
	Acad-com	0.960*** (0.049)	-0.004*** (0.001)	-6.611*** (0.363)	784	830	0.3544	-497.37
	Acad-gov	0.908*** (0.063)	-0.004*** (0.001)	-5.688*** (0.410)	441	428	0.2788	-456.64
Analysis, control & measurement technology	Total	0.911*** (0.022)	-0.005*** (0.001)	-8.107*** (0.224)	1,521	8,160	0.3319	-1,746.27
	Acad	0.914*** (0.043)	-0.002* (0.001)	-7.695*** (0.420)	289	3,650	0.2356	-685.66
	Acad-com	0.932*** (0.039)	-0.006*** (0.001)	-6.736*** (0.301)	1,089	1,452	0.3187	-975.01
	Acad-gov	0.855*** (0.033)	-0.007*** (0.001)	-6.333*** (0.289)	1,156	2,281	0.3396	-958.93

Significance levels: *** 0.99, ** 0.95, * 0.90. Standard errors in parentheses

By transforming the original equation (5.1) a logarithmic transformation of both the dependent and the independent variables is applied, which also adjust for non-normal distribution of the variables. In the case of the independent variable however, this provides only a partial solution to the problem of non-normality. Alternatively, spatial interaction data could also be treated as count data, whereas in this case the intensity of interaction is expressed by the number of collaborations between two regions (Cameron and Travedi, 1998). Due to the characteristics of count data, linear regression models are generally not appropriate since many of the assumptions such as normal distribution are not satisfied (Long, 1997). Most often, a Poisson regression is applied, which is estimated using maximum likelihood techniques. In this case the observed intensity of collaboration between region *i* and *j* has as Poisson distribution with a conditional mean. This conditional mean is a function of the independent variables, which is specified in equation 3:

$$\Pr[I_{ij}] = \frac{\exp(-\mu_{ij})\mu_{ij}^{I_{ij}}}{I_{ij}!}, \text{ where } \mu_{ij} = \exp(K + \alpha Ln(M_i M_j) + \beta Ln(d_{ij})) \quad (5.3)$$

However, the amount of zeros in the dependent variable (indicating that there are many regions without any collaboration between them) is larger than assumed for a Poisson distribution and as a result the conditional variance is larger than the conditional mean. In order to allow for this overdispersion a negative binominal specification is used where an extra parameter is introduced (see also Long, 1997).

Table 5.5 shows the results. Due to the low number of observations of other forms of collaborations only those collaborations with at least one academic organisation are included. Within this table the results for the life sciences are presented first, the results for the physical sciences second and the results for analysis, measurement and control technology last.

The co-efficient of mass in all technologies for all forms of collaborations is both significant and positive, which seems to be a logical outcome. The possible differences in the coefficients of travel time on the intensity of collaboration form an indication for the possible differences in the effect of geographical proximity on collaboration. For the aggregated number of collaborations the co-efficient for travel time has a negative sign and is significant for all technologies. This seems to suggest that distance still matters for collaboration in science, a finding that is line with the findings of Katz (1994) and Liang and Zhu (2002).

Within life sciences, travel time has a significant and negative effect on the intensity of collaboration for all the three distinguished forms of collaboration. The coefficient for travel time is higher for collaboration between academic and governmental organisations than for academic collaboration and collaboration between companies and academics. These differences are however, relatively small. The higher coefficients for collaboration between academic and non-academic organisations suggest that geographical proximity is more important for these forms of collaboration.

In the case of the physical science-based technologies, travel time has no significant effect on the intensity of academic collaboration for semiconductors and optics. Within the field of information technology and telecommunication the coefficient is only significant at a significance level of 90%. Neither in the field of optics does average travel time have a significant effect on the intensity of collaboration between companies and academic organisations, thereby indicating that geographical proximity is not important for university-industry collaborations either. There are no differences between the coefficient of travel time of academic-firm and academic-governmental collaboration in telecom and information technology, indicating that the effect of geographical proximity is more or less the same. The reason for the absence of travel time as a significant contributor to collaboration intensity may lie in the fact that physical science-based technologies are more mature in nature, and companies in sectors that use these technologies have fewer opportunities to catch onto new market niches. Relationships between companies, universities and governmental institutions are then more established, enhancing the institutional proximity based on trust and experience. This renders geographical proximity less important in sectors that apply this technology.

The coefficient of travel time is also significant and almost the same in the case of collaboration between academic and governmental organisations and academic organisations and companies in the analysis, measurement and control technology. Average travel time has as a smaller effect for academic collaboration, indicating that here also, geographical proximity is less relevant for collaboration.[47]

These results suggest that geographical proximity is important for collaboration in research within the Netherlands and the importance varies between the form of collaboration and between life sciences and physical sciences. Within life sciences geographical proximity seems to be more significant for collaboration than within physical sciences and geographical proximity seems to matter more for collaboration between academic and non-academic organisations than for collaboration between academic organisations. These results therefore seem to confirm the main hypothesis that geographical proximity is more relevant for collaboration between organisations with different institutional background than for collaboration between organisations with the same institutional background.

5.8 Conclusions

In this chapter, the spatial characteristics of collaboration in scientific knowledge production in the Netherlands is analysed. Within science-based industries, collaboration between governmental, academic and private organisations in scientific knowledge production is an important and growing phenomenon. Based on theoretical insights from the literature of the geography of innovation it was hypothesized that geographical proximity is more important for collaboration between organisations with different institutional backgrounds. Using co-publications in scientific fields that are relevant for technological innovation as a proxy for collaboration in research, this hypothesis was tested for eight science-based technologies in the life sciences and the physical sciences.

The main finding of this chapter is that geographical proximity is more relevant for collaboration between academic and non-academic organisations than for purely academic collaboration. This suggests that geographical proximity is indeed a way of overcoming the institutional differences between organisations, which is necessary for successful collaboration.

This chapter also shows however, that the importance of geographical proximity does not imply that the regional level is therefore the relevant spatial scale. The national level seems to be more significant for collaboration between companies and academic organisations than the regional level. For collaborations between academic and governmental organisations the regional level seems to be relatively important. These findings suggest that the regional dimension of the innovation system in science-based industries in the Netherlands should not be overemphasized. Geographical proximity plays a significant, yet minor role for collaboration between academic organisations within the Netherlands, which is also evident from the high share of international collaborations. Geographical proximity

47 A residual analysis has been performed for all regressions and it showed that the most northern and most southern regions with a university (Groningen and Maastricht) collaborated over longer distances than predicted by the model. A closer look revealed that this was almost entirely dependent upon the universities that collaborated with other universities in the Netherlands, which again suggests that institutional proximity is more important than geographical proximity here. Results of the residual analysis are available on request.

therefore especially seems to matter for collaboration in case of institutional differences, thereby facilitating successful collaboration. These results fit into the recent proximity debate about the exact role and effect of geographical proximity for collaboration and knowledge exchange between organisations (Boschma, 2005; Torre and Rallet, 2005) and suggest that geographical proximity is more important in an indirect way by overcoming institutional differences than in directly stimulating interaction as it is often assumed.

Chapter 6

Innovation, spillovers, and university-industry collaboration: An extended knowledge production function approach[48]

6.1 Introduction

Regional differences in the rate of innovation are currently an important topic in economic geography and in policy debates on regional development. The possible determinants of regional differences in innovation have been analysed in many studies over the years (see Döring and Schnellenbach, 2006 for an overview). The presence of public research organisations such as universities is generally assumed to have a large impact on regional innovation due to localised knowledge spillovers resulting from their research. Within the literature, various empirical studies have suggested the presence of localised academic knowledge spillovers for the USA (Jaffe, 1989; Anselin et al., 1997; Adams, 2002) and various European countries (Florax, 1992; Autant-Bernard, 2001; Andersson et al., 2004; Fritsch and Slavtchev, 2007). In line with these insights, many countries have implemented regional innovation policies based on the presence of universities and research institutes in a region.

Research on academic knowledge spillovers on the micro-level finds that the different mechanisms through which spillovers occur are indeed localised to a large extent. Besides the importance of local labour markets and spin-off dynamics, many studies have emphasized the role of networking between individuals and between organisations as a mechanism for knowledge spillovers. Informal networking often takes place at the regional level, and as a result, knowledge spillovers are localised to the extent that these networks are (Breschi and Lissoni, 2003, 2006). Formal networks of research collaboration are an important mechanism of knowledge spillovers as well. However, empirical research on the geographical dimension of these networks has suggested that these are not limited to the regional scale. Rather, formal research collaboration occurs largely at the national or even the international scale (McKelvey et al., 2003; Ponds et al., 2007). As a result, knowledge spillovers through research collaboration are expected to occur over long distances. This implies that, especially in industries where formal research collaboration frequently occurs, the structure of collaboration networks needs to be taken into account to fully understand the impact of academic knowledge spillovers.

The goal of this chapter is to analyse the relative importance of both collaboration networks and geographical proximity for academic knowledge spillovers and their effect on regional innovation. A novel approach to measure academic spillovers is proposed with the incorporation of the geographical structure of research collaboration networks between

48 Revised after reviews and resubmitted in a slightly different version as Ponds, R., F.G. van Oort and K. Frenken. Innovation, spillovers, and university-industry collaboration: An extended knowledge production function approach

universities and industries into a regional knowledge production function framework. The focus is on seven science-based industries in the Netherlands, where academic research and university-industry collaboration are especially important. The chapter is structured as follows. In the second section, the existing literature on academic knowledge spillovers and the roles of geographical proximity and collaboration networks is reviewed. In the third section, the data and the extended knowledge production function methodology are discussed. Section four discusses the econometric results, and section five concludes.

6.2 Academic knowledge spillovers and the role of geography and networks

Differences in innovative performance between regions are often explained by agglomeration economies, which are advantages that firms obtain from being located in a region with a geographical concentration of similar firms and knowledge institutes. A key element in the concept of agglomeration economies are localised knowledge spillovers, which reflect the advantages firms can have in accessing knowledge that, intentionally or unintentionally, 'spills over' from other firms and knowledge institutes. The existence of localised knowledge spillovers is generally treated as one of the most important explanations for regional differences in innovation (Jaffe et al., 1993).[49] It is often argued that localised knowledge spillovers give rise to increasing returns, which further induce innovative activities to cluster within specific regions exhibiting these agglomeration economies. The importance of geographical proximity for knowledge spillovers for firms and organisations is also emphasized in concepts like regional innovation systems (Cooke et al., 1997) and learning regions (Morgan, 1997).

The literature on knowledge spillovers pays special attention to the role of academic research institutes and especially universities (for recent examples, see Audretsch et al., 2005; Del-Barrio-Castro and Garcia-Quevedo, 2005; Fritsch and Slavtchev, 2007). Universities are assumed to be important sources of localised knowledge spillovers due to their explicit focus on the generation and diffusion of knowledge. Nonetheless, the importance of academic research for innovation differs strongly across industries (Klevorick et al., 1995; Cohen et al., 2002). The results of academic research are especially important for firms in the so-called science-based industries. The notion of science-based industries was introduced by Pavitt (1984) in his classification of industries based on differences in their sources of innovation and characteristics of the processes of innovation. Science-based industries, such as biotechnology and semiconductors, are characterised by the importance of scientific knowledge for their innovative activities. As a result, firms in these industries invest relatively heavily in R&D and collaborate intensively with academic organisations such as universities. Given the importance of scientific research, it can be assumed that the presence of knowledge spillovers from academic research is especially important for explaining regional differences in innovation in science-based industries.

Academic knowledge spillovers are localised to the extent that the mechanisms underlying such spillovers take place at the regional level. Within the literature, three major

49 There is a large body of literature on the issue of whether a specialized or diversified regional economic structure is more beneficial for the occurrence and magnitude of localized spillovers (see for an overview Rosenthal and Strange, 2004).

mechanisms of knowledge spillovers have been distinguished. First, spin-offs form an important mechanism of commercialisation of academic knowledge. Spin-offs and start-ups tend to locate in proximity to the parent organisation, resulting in a geographical concentration of these firms around universities and research institutes (Zucker et al., 1998a; Klepper. 2007). Second, by moving from one organisation to another, the knowledge embodied in individuals is transferred. Labour mobility can thus be considered another important mechanism of knowledge spillovers (Almeida and Kogut, 1999). Since labour mobility is a regional phenomenon to a considerable extent, knowledge spillovers through labour mobility are often localised as well. Third, informal knowledge exchange is an important mechanism for knowledge spillovers (Breschi and Lissoni, 2003, 2006; Singh, 2005). Informal knowledge exchange often takes place through social networks, which are to a large extent localised as well.

Besides informal social networks, formal networks of research collaboration also form an important mechanism of knowledge spillovers. This is especially the case in science-based industries, where collaborative networks are considered to be crucial for innovation (Powell et al., 1996; Stuart, 2000). Though research collaboration can be considered a simple co-production of knowledge where inputs are transformed into outputs, knowledge spillovers will occur as a by-product of such processes. Moreover, following the line of reasoning of Breschi and Lissoni (2003, 2006), collaborative research can lead to enduring social relationships between researchers over longer distances. As such, research collaboration is likely to lead to future spillovers in the sense that researchers who have collaborated in the past are likely to continue to exchange knowledge informally. This is especially important in science- and engineering-based industries where informal knowledge exchange is commonplace due to the professional norms of communities of engineers and researchers (Von Hippel, 1994; Lissoni, 2001). The importance of this form of knowledge exchange is apparent from the fact that collaboration is increasingly important within processes of knowledge creation in both academia (Wagner-Doebler, 2001) and the private sector (Hagedoorn, 2002). Here, the focus is on university-industry collaboration as a channel for academic knowledge spillovers in science-based industries (Etzkowitz and Leydesdorff, 1997).

Research on the geographical dimension of university-industry collaborations shows that these linkages are not limited to the regional level; rather, they occur mostly on the national or even the international scale (McKelvey et al., 2003; Ponds et al., 2007). These findings are in line with the increasing attention to the non-regional dimension of knowledge flows (Bunnell and Coe, 2001; Faulconbridge, 2006). Geographical proximity itself is neither necessary nor a sufficient condition for inter-organisational knowledge spillovers to occur (Boschma, 2005). In the case of research in science-based industries, collaboration is more likely to be based on the presence of specific knowledge of potential partners than on geographical proximity (Moodysson et al., 2008).

Altogether, this body of literature argues that knowledge flows and knowledge spillovers can occur at different geographical scales. This implies that knowledge spillovers from universities can also occur over longer distances between regions. If this is the case, it is unlikely that the relationship between academic knowledge spillovers and regional innovation is fully captured by taking only the regional dimension of spillovers into account. Rather, if networks of formal research collaboration are an important mechanism of knowledge spillovers, it is necessary to include the structure of these networks when analysing academic knowledge spillovers. The objective of the empirical analysis is to capture and weight this effect of formal collaboration networks between university and industry, as a channel for academic knowledge spillovers, on regional innovation.

6.3 Research design

A large number of empirical studies on knowledge spillovers have been based on the application of a regional knowledge production function as introduced by Jaffe (1989), who analysed the presence of localised academic knowledge spillovers at the level of US states. In a regional knowledge production function framework, regional knowledge inputs (such as R&D expenditures) are expected to contribute to regional innovation output (such as number of patents or new products). Based on Jaffe's seminal contribution, various authors have refined this approach by using a smaller geographical scale (Audretsch and Feldman, 1996) and distinguishing between different industries (Anselin et al., 2000). Whereas in an early stage most of this research was based on US data, more recent studies on European countries have produced similar findings.[50] Whereas the largest part of this research has focussed on the roles of different R&D inputs and the presence of knowledge spillovers for innovative output, several studies have tried to account for region-specific conditions that influence the innovative output as well (see, for example, Rodriguez-Pose and Crescenzi, 2008; Crescenzi et al. 2007). It was found that conditions such as human capital or demographic structure significantly influence the innovative output. This suggests that there is a need to take these regional 'contextual conditions' into account within empirical studies of regional differences in innovation.

We test the importance of geography and networks for knowledge spillovers from academic research using an extended regional knowledge production function framework. The innovative output of a region depends on the size of its own private and university R&D expenditures and the size of such expenditures in other regions to the extent that these inputs are accessible to a region. It is assumed that that external R&D can be accessed through localised mechanisms and through social relationships over longer distances stemming from formal research collaboration. This means that the size of these spillovers depends on the geographical distance to other regions in the case of localised spillovers, and on the intensity of collaboration with universities in other regions in the case of spillovers from research collaboration. Maggioni et al. (2007) explored such an approach, but, in contrast to their study, the two sources of spillovers are included simultaneously as independent variables.[51] Possible regional differences in conditions that might influence innovative output are taken into account in two different ways. Following Rodriguez-Pose and Crescenzi (2008), several variables that measure different aspects of these regional

50 See, for example, Autant-Bernard (2001) for France, Fischer and Varga (2003) for Austria, Del Barrio-Castro and Garcia-Quevedo (2005) for Spain, and Fritsch and Slavtchev (2007) for Germany.

51 Previous studies by Greunz (2003) and Moreno et al. (2005) included technological proximity in the knowledge production function next to spatial proximity. Technological proximity matrices take into account to what extent two regions have similar technological specialisations. Technological proximity is not included because the analyses are carried out at the level of individual technologies.

conditions are included in the first set of models. The second set of models includes regional fixed effects, which control for regional unobserved heterogeneity (see Fritsch, 2001 for a related approach).

6.3.1 Data[52]

We analysed the relative importance of geography and networks for academic knowledge spillovers for seven science-based technologies in the Netherlands at the level of NUTS3 regions. Within the Netherlands, NUTS3 regions are defined as labour market regions or functional regions centered around a central city. Innovation at the regional level was measured by the number of patents applied for by firms at the European Patent Office between 1999 and 2001. Patents are one of the few innovation indicators that have regional, temporal, and technological dimensions, and are therefore often used in empirical studies. Nonetheless, the use of patents as indicators for innovation is not undisputed. Most importantly, not all patents are innovations, and not all innovations are patented (on this topic, see Griliches, 1990). Furthermore, the rate of patenting differs systematically between industries and technologies due to differences in the relative importance of patents as a means of appropriating an invention. The latter problem, however, is 'solved' by the focus on science-based technologies, where patents do form an important appropriating mechanism (Pavitt, 1984).

We classified patents into technologies according to the IPC-technology concordance table developed by FHG-ISI and OST.[53] To select science-based technologies, Verbeek et al. (2002) and Van Looy et al. (2003) are followed, who used the relative number of citations in patents to the scientific literature as a measure of the interaction between science and technology (see also Schmoch, 1997). The higher the share of citations to the scientific literature, the more science-based the technology is considered to be. The technologies with the most intensive interactions with science were agriculture and food chemistry, biotechnology and organic fine chemistry (three life science-based technologies), and optics, information technology, semiconductors and telecommunications (four physical science-based technologies).[54] Patents were assigned to the different NUTS3 areas based on the addresses of the inventors. Patents with multiple inventors were proportionally distributed across different regions.

Figures 6.1 and 6.2 show the geographical patterns of patents in one life science-based technology (biotechnology) and one physical science-based technology (optics). Within biotechnology, some regions exhibit a relatively large number of patents. Besides the larger cities of Amsterdam and Utrecht, these are the regions of Leiden and Veluwe/Wageningen, two regions that host life sciences clusters in the Netherlands, fuelled by the presence of their respective universities. In the case of optics, the relatively high number of patents in the Southern region of Eindhoven is striking. This is caused by the location of the research laboratories of Philips, a large multinational in electronics, and several related firms nearby.

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52 If the reader has read chapter three, he or she might consider skipping to the last part of section 6.3.1.

53 Fraunhofer-Institut für System- und Innovationsforschung in Karlsruhe and L'Observatoire des Sciences et des Techniques in Paris.

54 Table 3.3 shows the relevant scientific fields for each technology.

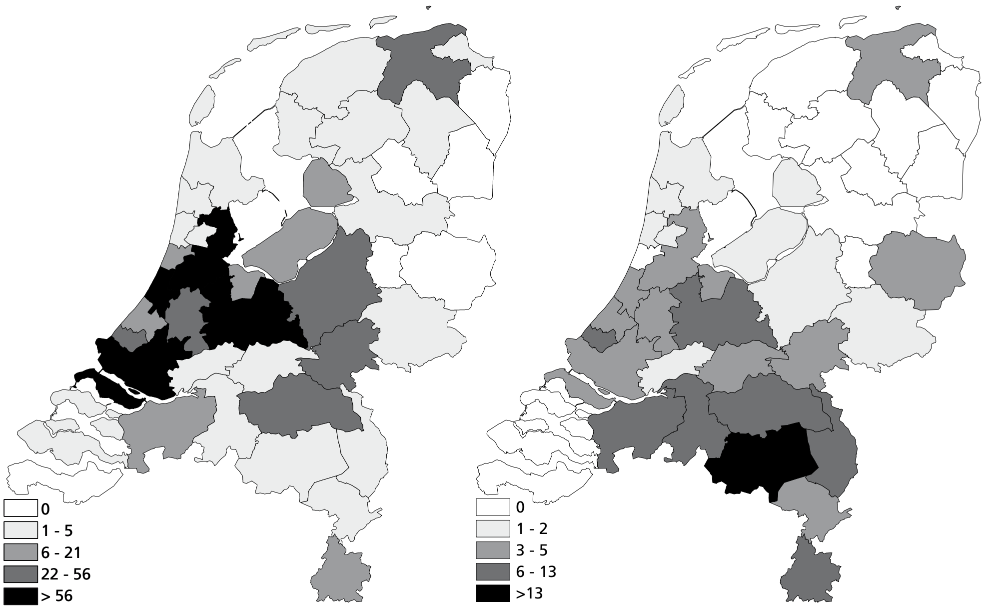

Figure 6.1-6.2 - Number of patents in biotechnology and optics in NUTS3 regions in the Netherlands 1999-2001

Private and university R&D expenditures are used as indicators for knowledge inputs. Regional private R&D expenditures are measured by the sum of the private wages for R&D employees for each technology.[55] University R&D expenditures are only available for broad science fields as defined by the Ministry of Education and Science, which can be linked to either physical sciences or life sciences.[56] Within both types of technologies, university R&D expenditures were assigned to each technology in proportion to its share in the total number of scientific publications in the life sciences or physical sciences. In line with other studies (Fischer and Varga, 2003; Fritsch and Slavtchev, 2007), a time lag of three years between R&D expenditures and patenting is assumed. The R&D variables refer to the years 1996 to 1998.

In the first set of empirical models, three different variables have been included to account for region-specific conditions that might influence the innovative output of regions next to R&D inputs and spillovers. All of these variables are based on the years of 1996 to 1998 as well. First, the size of the workforce educated at a polytechnic or university is included as an indicator for human capital. A higher level of human capital is assumed to increase innovative output. Second, a dummy variable is included, which indicates the presence of a branch of the semi-public contract research organisation TNO in either the physical sciences or life sciences. TNO is a multi-branch organisation with the explicit goal to bridge scientific research and innovation activities in different industries. As such, TNO can be compared with the Fraunhofer Institute in Germany. The presence of a branch of TNO in one of the fields of science-based technologies is expected to increase the absorption

55 Data on technology specific R&D wage sums at the regional level are provided by the Ministry of Economic Affairs and are based on information from the tax deduction scheme for R&D personnel.

56 See table 3.3 for the relevant scientific subfields for each technology.

capacity of spillovers within a region. Based on the analysis of annual reviews and the corporate website, the activities of each TNO branch in the Netherlands were determined and related to one of the science-based technologies. Third, urban density was included to assess the effect of the level of urbanisation economies. A higher concentration of economic activities is associated with more knowledge exchange and more supporting services and consequently with a higher level of innovation at the regional level. Urban density is measured by the number of addresses per square kilometre.

6.3.2 Defining interregional spillovers

We expect academic knowledge spillovers to occur between regions through geographical proximity and/or research collaboration networks. Geographically localised knowledge spillovers from academic research are assumed to take place through various mechanisms, such as labour mobility or spin-offs. The occurrence of such spillovers is assumed to decay over geographical distance. A spatial weight matrix based on a distance decay function is assumed to reflect the geographical structure of these mechanisms.

The spatial weight matrix for spillovers through research collaboration is based on the intensity of collaboration between universities (including academic hospitals) and firms for each pair of regions. Formal collaboration between universities and firms are considered as a direct knowledge flow from academia to industry and consequently as a prime form of academic knowledge spillovers. Co-publications are frequently used as an indicator of research collaboration (see, for example Cockburn and Henderson, 1998; Zucker et al., 1998a; Wagner-Doebler, 2001). The appearance of multiple authors and/or multiple organisations on a scientific publication can be used as an indicator of collaboration in the research leading to the knowledge that is published. Within science-based industries, firms are actively involved in scientific publishing (Rosenberg 1990). Therefore, co-publications with both an academic affiliation and a corporate affiliation can be considered meaningful indicators of university-industry collaboration. Since individuals and their affiliations are generally only mentioned on a publication after a substantial contribution, publications with multiple authors and multiple organisations are considered good indicators of collaborative research (for an extensive overview of these arguments, see Katz and Martin, 1997 and Glänzel and Schubert, 2004). Whereas (almost) all co-publications might be considered to represent some form of collaboration, not all collaboration in research ends up in a co-publication, and consequently, not all research collaboration is measured by co-publications. Laudel (2001) showed that this most often occurs in collaborative research between individual researchers within the same organisation. Research collaboration with other organisations, on the other hand, generally does lead to a joint publication (Laudel, 2001). As such, publications with multiple organisations can be considered valuable indicators of collaborative research. The underlying assumption is that a co-publication reflects formal research collaboration between the organisations involved and that knowledge has been exchanged between these organisations. Next to this, collaborative research is assumed to form an indicator of spillovers through social relationships, resulting from the notion that researchers who have collaborated in the past are likely to continue to exchange knowledge and advice.

All publications between 1993 and 1995 with at least two addresses in the Netherlands were selected from Web of Science in the scientific fields that are relevant for each

Figure 6.3-6.4 - Spatial structure of interregional university-industry research collaboration in biotechnology and optics – 1993-1995

technology. Based on the address information of the organisations on a co-publication, each organisation was assigned to a NUTS3 region. This was done on the basis of full-counting, meaning that each pair of organisations on a co-publication was counted as a collaboration. By aggregating these collaborations, a matrix was constructed with the number of collaborations between each pair of regions as an indicator of the intensity of formal collaboration. Based on the names of the organisations on the publication, universities, firms, and governmental research organisations were distinguished. Collaborations between universities and firms were selected to create the university-industry collaboration weight matrix.

This resulted in an asymmetric weight matrix (without values on the diagonal) for each technology, with directed relationships from regions with universities towards regions with firms collaborating with these universities. From now on, this matrix will be referred to as the network weight matrix. It must be noted, though, that this matrix consists strictly of bilateral relationships and cannot be considered a 'true' network in the sense that indirect relationships are also taken into account. The values of the interregional network weight matrix are based on co-publications from the years 1993 to 1995, whereas the R&D data are from the period of 1996-1998. As such, the network weight matrix is considered an indicator for the presence of social relationships between researchers in the period 1996-1998 based on collaborative research in the period 1993-1995.

As two examples, figures 6.3 and 6.4 show the spatial structure of interregional research collaboration between universities and firms in biotechnology and optics, respectively. In both technologies, university-industry research collaboration takes place between nearby regions and over longer distances. As a result, research collaboration cannot be attached to a specific geographical scale. Rather, figures 6.3 and 6.4 show that it takes place at both the regional and national levels.

In the following, the weighted R&D expenditures in other regions are used as an additional explanatory variable, rather then as a means to deal with spatial autocorrelation. Nonetheless, the use of accessibility variables can eliminate the problem of spatial autocorrelation as well (see Andersson and Karlsson 2007). High accessibility between two regions implies a high level of interaction opportunities and, consequently, a high level of potential spillovers between two regions. Accessibility measures for region i are generally based on the weighted average of variable x in all other regions j, where the weights are based on the size of the possible interaction between regions i and j. The size of the possible interaction is generally based on the geographical distance between regions (see e.g., Andersson and Karlsson. 2007), but can also be based on the structure of economic or functional relationships (see, for example, Boix and Trullen, 2007).

Whereas the spatial weight matrix is clearly exogenous, the network weight matrix might exhibit a problem of potential endogeneity, as the geographical structure of collaboration is likely to be related to geographical patterns of patents. This problem is minimized in this chapter by using time lags; the network weight matrix refers to university-industry collaboration between 1993-1995, the R&D data are from 1996-1998, and patents are from 1999-2001.[57] The time lag is likely to be even larger since co-publications result from collaborative research done long before actual publication. Given the fact that the geographical structure of R&D and innovation is relatively stable over time, the network weight matrix might still suffer from potential endogeneity. This is a common problem with the use of actual data on spatial interaction patterns for the construction of the weight matrix. Yet, the use if this data has the clear advantage that it bears 'a direct relation with the theoretical conceptualisation of the structure of spatial dependence, rather than (.....) an ad hoc description of a spatial pattern' (Anselin 1988, pp. 20-21).

In the context of a regional knowledge production function, Peri (2005) analysed the effect of knowledge flows on innovation output as measured by patents in European regions. This was done by the construction of an accessibility measure based on knowledge flows in the form of patent citations between regions. This accessibility measure seems to have some potential endogeneity problems as well, since its value is related to the level of patenting in regions (see also Peri, 2005 p. 318 on this). However, in line with Peri (2005), it can be argued that the use of an actual indicator for knowledge spillovers is to be preferred over a more arbitrary assumption on structure of interaction, which is generally considered an important drawback of the use of distance, or contiguity based weight matrices.

57 Instrumental variables reflecting network potentials between regions would be a more definite solution to this problem, but good instruments are difficult if not impossible to find. Labour mobility (in professions related to the separate industries studied) as an instrument for social networks is a preferred candidate, but data on this detailed level are not available. Within the literature on trade and economic growth (see for example Frankel and Romer 1999), geographical distance is often used as an instrument for patterns on trade between countries and could be used for other patterns of spatial interaction as well. However, as the main interest is in separating localised knowledge spillovers from spillovers carried by university-industry collaboration, it is obvious that this cannot be used here.

6.3.3 Standardisation procedure

In order to make the effects of different weight matrices comparable, it is necessary to standardize them. The choice of the method of standardisation is important, since it implies a specific way of allocating the value of a variable (in this case, R&D spillovers) from one region to other regions (Leenders, 2002). The weight matrix is typically row-standardized in studies applying spatial-econometric techniques in order to take possible spatial autocorrelation into account. Each row element is divided by the sum of the row, and as a result, each row sums up to one. The value of the spatially lagged variable is then a weighted average of all neighbouring regions. This method of standardization is rational if the interest lies in correcting for possible misspecification through spatial dependence; each neighbour influences the size of the possible misspecification in proportion to the total number of neighbours that an observation has. Nonetheless, Abreu et al. (2005) and Leenders (2002) emphasized that the selection of the method of standardisation should ideally be based on the theoretical problem under consideration. Because most studies using spatially lagged variables have done this with the aim of controlling for spatial autocorrelation, and consequently applied row standardisation, only marginal attention has been paid to this issue. Hanes (2002) is one of the few exceptions and provides a theoretical argument to use an unstandardised weight matrix in a study on spillover effects of local rescue services for Swedish municipalities.

The use of a row standardized weight matrix in this chapter implies that the spatially lagged variable is the weighted average of R&D expenditures in neighbouring (defined by space or networks) regions. An increase of the number of neighbours *j* implies that the size of the spillovers that region *i* receives from each individual neighbour *j* automatically decreases. Conceptually, this suggests the presence of limited absorptive capacity of region *i*, to the extent that the size of spillovers from region *j* is less if region *i* is connected or linked with more regions. In the case of row standardisation, the sum of the spillovers from region *i* can be smaller, equal to, or larger than the initial amount of R&D expenditures.[58]

Alternatively, it can be assumed that the size of the R&D spillovers received by region *i* from region *j* is related to the total number of regions that are connected or neighbours with *j*. As such, an increase of the total number of neighbours *i* of the spillover generating region *j* implies a smaller total of spillovers received by each specific region *i*. In this case, column standardization of the weight matrices is more appropriate. Each matrix element is divided by the sum of the column, and consequently, each column sums up to one. Within a column standardized weight matrix, the column of region *i* represents the effect of an increase or decrease in R&D expenditures in region *i* on all other regions *j* (see

58 Suppose region X has two neighbours and region Y has four neighbours. Both regions X and Y are of equal size and have one common neighbour but do not share a common border with each other. This common neighbour Z has a university with a given amount of R&D expenditures and has only two neighbours, X and Y. By row standardizing the weight matrix, the region X with two regions would receive $^1/_2$ (1/(1+1)) of the value of the R&D expenditures in region Z. Compare this with region Y, which has four neighbours and consequently only receives $^1/_4$ (1/(1+1+1+1)) of the value of the R&D expenditures in region Z. The strange phenomenon occurs that the size of the R&D expenditures that spills over from Z to regions X and Y depends on the number of neighbours X and Y have and not so much on the number of neighbours of Z. The fewer neighbours (other than Z) regions X or Y have, the more R&D of region Z they have ‘access’ to. The overall size of the spillovers is $^3/_4$ of the original R&D expenditures.

also Abreu et al., 2005). R&D spillovers from region *i* are in this case conceptualised as a pool of knowledge spillovers partly accessible to other regions *j*. In the case of column standardisation, the sum of all knowledge spillovers always equals the initial amount of R&D expenditures.[59]

As such, column standardisation implies that the knowledge generated in a region is not conceptualised as a public good but as a rival good. This is based on the assumption that a given investment in R&D will be an input in a limited set of patents. Consequently, there is also a limit to the number of patents generated by the knowledge spillovers from a specific region. If more regions have access to the knowledge generated in a specific region, the size of the spillovers that each region receives can be assumed to be smaller. This might be justified by the fact that knowledge spillovers are not 'in the air' but result from mechanisms that are rival in nature to the extent that they involve costs and time (see section 6.2). Therefore, column standardisation seems theoretically more appropriate than row standardisation here. In order to check for the sensitivity of the results, the models have been estimated with column-standardized and row-standardized lagged variables separately.

6.3.4 *The empirical model: an extended knowledge production function*

The network weight matrix, with firms in region *i* in the rows and universities in region *j* in the columns, is defined as follows in the case of column standardization:

$$W_{ij\_network\_column} = \frac{r_{ij}}{\sum_j r_{ij}} \tag{6.1}$$

and as follows in the case of row standardisation:

$$W_{ij\_network\_row} = \frac{r_{ij}}{\sum_i r_{ij}} \tag{6.2}$$

where *rij* stands for the number of collaborations between firms in region *i* and a university in region *j*. In a similar way, the spatial weight matrix that defines the allocation of knowledge spillovers from region *j* to region *i* is defined as:

$$W_{ij\_space\_column} = \frac{d_{ij}^{-1}}{\sum_j d_{ij}^{-1}} \tag{6.3}$$

in the case of column standardisation and as:

$$W_{ij\_space\_row} = \frac{d_{ij}^{-1}}{\sum_i d_{ij}^{-1}} \tag{6.4}$$

in the case of row standardisation, where *dij* stands for the average travel time between regions *i* and *j*. The maximum possible value of *dij* was set to 90 minutes because the size of spillovers through localised mechanisms is considered negligible beyond a travel time of 90 minutes. This is based on Van Ham et al. (2001) who concluded that in the Netherlands,

59 Following the example in the previous, column standardisation implies that regions X and Y both receive $^1/_2$ (Z has two neighbours: 1 / (1+1)) of the R&D expenditures of region Z.

the intensity of commuting and business trips show a strong decay after a travel time of 45 minutes. [60]

Based on these specifications of interregional knowledge spillovers, the following cross-regressive spatial model is estimated:

$$\ln P_{i,k,t} = \alpha_0 + \alpha_1 \ln RDp_{i,k,t-1} + \alpha_2 \ln RDu_{i,k,t-1} + \alpha_3 \ln\left[\sum W_{ij\_space} RDu_{j\neq i,k,t-1}\right] + \alpha_4 \ln\left[\sum W_{ij\_space} RDp_{j\neq i,k,t-1}\right] + \alpha_5 \ln \left[\sum W_{ij\_network,t-2} RDu_{j\neq i,k,t-1}\right] + \alpha_6 \ln X_{i,k,t-1} + \varepsilon \quad (6.5)$$

where $P_{i,k,t}$ stands for economically valuable knowledge as measured by patent applications of firms in region *i* in technology *k* in the period of 1999-2001, and $RDp_{i,k,t-1}$ denotes the private R&D expenditures and $RDu_{i,k,t-1}$ the university R&D expenditures in the period of 1996-1998 (i.e., t-1) in region *i* and technology *k*. Both private and university R&D expenditures in the other regions *j* are spatially lagged using a spatial weight matrix, W_{ij_space}. Furthermore, university R&D is lagged by the network weight matrix $W_{ij\_network,t-2}$, which denotes the spatial structure of university-industry collaboration in the years of 1993-1995 (i.e., t-2). ε is a stochastic error term. The seven technologies have been pooled, leading to a total of 280 observations consisting of 40 NUTS3 regions *i* times seven technologies *k*. Technology dummies have been included to control for possible differences in the rates of patenting between technologies. The variable $X_{i,k,t-1}$ in equation 6.5 refers to region specific conditions that might have influenced the innovative output during the period of 1996-1998 (t-1). The urban density and human capital variables are region specific but have similar values across technologies, whereas the dummy variable for the presence of a relevant TNO institute is region and technology specific. A second set of models includes regional fixed effects, instead of variables for region specific conditions, which control for regional unobserved heterogeneity in conditions that influence the innovative output (although these conditions themselves remain a 'black box').

In equation (6.5), the dependent variable is log transformed because of the transformation of the production function. This raises the issue of dealing with regions with zero patents since the log of zero is undefined. Adding a (small) value to each observation typically solves this problem. Alternatively, several empirical studies have applied a count data model in a knowledge production framework (e.g. Del Barrio-Castro and Garcia-Quevedo, 2005 and Fritsch and Slavtchev, 2007). Both approaches are applied in order to check for the robustness of the results. Patents are a good example of count data to which a Poisson model is typically applied (Hausman et al., 1984). However, a negative binomial regression is used in order to correct for overdispersion. With the application of a negative binomial model, an extra variable alpha is introduced, which corrects for the overdispersion by adjusting the variance independently from the mean (Cameron and Trivedi, 1998). Besides linear regression models with fixed effects, unconditioned pooled negative binomial models

60 Next to this specification, several other specifications of the spatial weight matrix have been applied: first-order contiguity, inverse distance functions with other cut-off points (60 minutes and 120 minutes) and without cut-off points. The results presented later on are robust with regard to these different specifications.

Table 6.1 - Descriptive statistics

	N	Mean	Minimum	Maximum	Std. Deviation	Source and unit of measurement
Patents	280	11.19	0.00	911.72	67.81	European Patent Office (absolute numbers)
University R&D (ln)	280	0.88	0.00	5.38	1.76	Association of universities in the Netherlands – VSNU (million euro's)
Private R&D (ln)	280	1.77	0.00	5.55	1.14	Ministry of Economic affairs (million euros)
W space university R&D – column standardized (ln)	280	2.56	0.00	4.00	1.05	
W space university R&D –row standardized (ln)	280	2.66	0.00	4.07	1.08	
W space private R&D –column standardized (ln)	280	2.19	0.05	4.18	0.89	
W space private R&D –row standardized (ln)	280	2.25	0.16	4.47	0.84	
W network university R&D – column standardized (ln)	280	0.99	0.00	6.03	1.67	
W network university R&D – row standardized (ln)	280	1.40	0.00	5.38	2.13	
Human capital (ln)	280	10.10	8.01	12.34	0.99	Statistic Netherlands (absolute numbers)
Urban density (ln)	280	7.08	6.31	8.43	0.51	Own elaboration on basis of Statistic Netherlands (addresses per square km)
TNO (dummy)	280	0.09				Own elaboration of annual reports of TNO

Table 6.2 - Correlation matrix – including column standardized variables

		1	2	3	4	5	6	7	8
1	University R&D	1.00							
2	Private R&D	0.44*	1.00						
3	W space university R&D – column standardized	-0.15*	0.10	1.00					
4	W space private R&D – column standardized	0.07	0.41*	0.59*	1.00				
5	W network university R&D – column standardized	0.37*	0.58*	0.09	0.19*	1.00*			
6	Human capital	0.57*	0.67*	0.18*	0.40*	0.54*	1.00*		
7	Urban density	0.44*	0.45*	0.31*	0.34*	0.46*	0.75*	1.00*	
8	TNO	0.43*	0.24*	-0.02	0.04	0.37*	0.27*	0.34*	1.00*

* indicates significance at 5% level

with direct estimation of fixed effects by including region dummies have been estimated (Allison and Waterman, 2003).[61]

6.4 Results

The descriptive statistics are presented in Table 6.1. It is clear that the distribution of patents is rather skewed.

Table 6.2 and 6.3 show the correlations of all independent variables with respectively the column standardized and the row standardized variables. The low correlation between the spatially and network lagged university R&D indicates that there are clear differences between the structure of the spatial weight matrix and the network matrix, resulting in different footprints (and hence impacts) of academic knowledge spillovers.

Table 6.4 shows the results of the negative binomial estimations with the region specific variables and the results with regional fixed effects. The first four models include the region specific variables and the models five till eight include regional fixed effects.[62] For each model the results are shown for the specification with row and column standardized weight matrices. The first and fifth model include only the intra-regional R&D expenditures and, in the case of the first model, the variables that denote the region-specific conditions. In the second and sixth model, the inter-regional R&D spillovers through localised mechanisms are included. The third and seventh model include R&D spillovers from university-industry

61 Note that this variant of a fixed effects negative binomial model differs from the one suggested by Hausman et al. (1984), where fixed effects refer to the dispersion parameter alpha, which is the same for all elements in the same group. Since the main goal of applying fixed effects is to control for regional unobserved heterogeneity, the pooled negative binomial model with regional dummies, as suggested by Allison and Waterman (2003), is more appropriate.

62 In order to analyse the sensitivity of the results to the influence of the Philips Corporation, the models for physical science-based technologies (such as telecommunication) have also been estimated excluding the patents owned by Philips. The results remain similar.

Table 6.3 - Correlation matrix – including row standardized variables

		1	2	3	4	5	6	7	8
1	University R&D	1.00							
2	Private R&D	0.44*	1.00						
3	W space university R&D – row standardized	-0.18*	0.09	1.00					
4	W space private R&D – row standardized	0.02	0.40*	0.49*	1.00				
5	W network university R&D – row standardized	0.35*	0.53*	0.05	0.17*	1.00			
6	Human capital	0.57*	0.67*	0.15*	0.36*	0.53*	1.00		
7	Urban density	0.44*	0.45*	0.29*	0.29*	0.43*	0.75*	1.00	
8	TNO	0.43*	0.24*	-0.03	0.02	0.27*	0.27*	0.34*	1.00

* indicates significance at 5% level

research collaboration. The fourth and eighth model includes both types of interregional spillovers.

The first and fifth model is the basic knowledge production function including only intra-regional R&D expenditures. In both models university R&D has a positive and significant relationship with innovation, suggesting the presence of academic knowledge spillovers within the regions having a university, a finding that is in line with previous studies in European countries. Note that the positive relationship of private R&D cannot be interpreted as an indication of localised knowledge spillovers in the region, since it is not possible to distinguish between the internal R&D investments of a firm and possible spillovers from R&D investments of other firms located in the region.

The other models include the variables that denote the presence of interregional spillovers. The main conclusion holds that collaborative networks between universities and firms form an important mechanism for academic knowledge spillovers, irrespective of the method of standardisation. With regard to geographically localised spillovers between regions, the results are less robust. In case of the models that include region-specific variables no significant relationship between the spatially lagged university R&D and innovation was found, suggesting the absence of localised, interregional academic knowledge spillovers. A significant and positive relation for spatial lagged private R&D is found, which can be interpreted as an indication of the existence of geographically localised interregional spillovers from private research. In case of the fixed-effect estimations, the outcomes are opposite. There seems to be a positive and significant relationship between localised academic knowledge spillovers and innovation. Moreover, the insignificant effects of spatially lagged private R&D expenditures suggest the absence of interregional knowledge spillovers from private R&D. These results appear to be robust across the different methods of standardisation. As a further check on the robustness of the results, linear models with similar specifications have been estimated as well.[63] The results are shown in table 6.5 and reveal that the outcomes are similar with regard to the variables of main interest.

63 One patent has been added to each region to avoid zeros (which cannot be log-transformed).

Table 6.4 - Regression results of negative binomial estimations on regional patents

	Negative binomial regression including technology dummies							Negative binomial regression incl. regional fixed effects and technology dummies						
	Model 1	**Model 2**		**Model 3**		**Model 4**		**Model 5**	**Model 6**		**Model 7**		**Model 8**	
Weight matrix	-	*row*	*column*	*row*	*column*	*row*	*column*	-	*row*	*column*	*row*	*column*	*row*	*column*
University R&D	0.134** (0.051)	0.206** (0.057)	0.173** (0.056)	0.151** (0.051)	0.157** (0.047)	0.238** (0.056)	0.206** (0.051)	0.361** (0.069)	0.442** (0.072)	0.448** (0.087)	0.369** (0.068)	0.347** (0.083)	0.450** (0.071)	0.433** (0.085)
Private R&D	0.565** (0.096)	0.541** (0.093)	0.542** (0.093)	0.517** (0.097)	0.349** (0.097)	0.477** (0.094)	0.334** (0.093)	0.350** (0.102)	0.398** (0.099)	0.395** (0.104)	0.333** (0.100)	0.314** (0.099)	0.384** (0.098)	0.360** (0.100)
W space university R&D		0.039 (0.099)	0.025 (0.232)			0.076 (0.097)	0.144 (0.212)		0.490** (0.149)	0.519** (0.178)			0.469** (0.147)	0.514** (0.176)
W space private R&D		0.339** (0.137)	0.308* (0.160)			0.351** (0.134)	0.249* (0.150)		0.073 (0.194)	0.178 (0.179)			0.068 (0.191)	0.178 (0.174)
W network university R&D				0.087** (0.042)	0.154** (0.035)	0.114** (0.042)	0.159** (0.034)				0.100** (0.047)	0.115** (0.051)	0.091** (0.046)	0.117** (0.052)
Human capital	0.749** (0.158)	0.611** (0.161)	0.628** (0.163)	0.654** (0.163)	0.689** (0.144)	0.478** (0.165)	0.565** (0.149)							
TNO	1.148** (0.273)	1.166** (0.264)	1.075** (0.266)	1.033** (0.274)	0.570** (0.270)	1.032** (0.261)	0.482** (0.265)							
Urban Density	-0.945** (0.221)	-0.977** (0.227)	-0.957** (0.231)	-0.948** (0.218)	-0.787** (0.207)	-1.011** (0.223)	-0.830** (0.213)							
Constant	-0.107 (1.313)	-1.524 (1.304)	0.796 (1.333)	0.839 (1.374)	-0.498 (1.232)	-0.083 (1.374)	0.619 (1.256)	-1.317 (1.049)	-2.523** (0.842)	-3.899** (1.025)	0.173 (0.517)	1.132** (0.479)	-2.870** (0.865)	-2.543** (0.951)
Alpha	0.898** (0.117)	0.846** (0.111)	0.859** (0.113)	0.866** (0.115)	0.750** (0.106)	0.805** (0.108)	0.712** (0.101)	0.496** (0.077)	0.448** (0.072)	0.425** (0.069)	0.471** (0.075)	0.435** (0.067)	0.427** (0.071)	0.404** (0.066)
N	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)	280 (7 x 40)
Max likelihood R2	0.688	0.700	0.697	0.693	0.711	0.708	0.721	0.774	0.784	0.808	0.777	0.803	0.787	0.811
Log likelihood	-620.55	-615.10	-616.50	-618.52	-609.79	-611.51	-604.75	-575.68	-569.29	-564.16	-573.43	-567.84	-567.37	-561.97

** indicates significance at 5% level, * indicates significance at 10% level. Standard errors in parentheses

Concerning region-specific conditions, the coefficients and significance levels are stable across the models estimated. The presence of a branch of TNO in the relevant technology fields has a positive relationship with innovative output, as does the human capital variable. There is a negative correlation between urban density and innovative output, suggesting that innovation in science-based technologies does not benefit from city size. This is in line with the findings for the USA reported by Carlino et al. (2007), who concluded that innovation is concentrated in medium-sized cities rather than in the most urbanized areas.

In order to control for possible autocorrelation, a modified version of Moran's I for count data models introduced by Lin and Zhang (2006) has been applied on the residuals. Whereas the models including no spillover variables and only the network-mediated spillovers exhibit significant levels of spatial autocorrelation in the error terms this is not the case anymore with the inclusion of the variables that denote geographically localised spillovers.[64] This result implies that this specification does not only capture geographically and network-mediated spillovers, but also, by doing so, effectively deals with spatial autocorrelation.

In sum, the robust results with regard to network mediated spillovers indicate that collaborative networks between universities and firms form an important mechanism for academic knowledge spillovers in science-based industries. Given that these networks are not limited to the regional scale, knowledge spillovers are also not bounded to this scale; this would imply that academic knowledge spillovers occur over longer distances as well. The results with regard to the presence of geographically localised knowledge spillovers are less robust between the different specifications. This is possibly the result of unobserved regional heterogeneity, which is not fully controlled for in the first four models presented in table 6.4 and 6.5. Given the fact that the fixed effects models control for this, it is reasonable to assume that these results are more reliable. Based on this, it seems that geographically localised spillovers from academic research are present as well. Given the larger magnitude of the coefficient, they seem even stronger than network mediated spillovers. This might be related to the fact that the geographically localised spillovers capture a range of spillover mechanisms, including the formation of spin-off companies, labour mobility, and informal networks.

6.5 Conclusions

Universities are generally seen as important factors influencing regional differences in innovation due to the occurrence of geographically localised knowledge spillovers. Previous micro-level research on the mechanisms of these spillovers, such as labour mobility and spin-offs, has shown that these, to a large extent, take place at the regional scale. Collaborative networks with academic research organisations, especially in science-based industries are an important mechanism of knowledge exchange. These networks exist over short and longer distances, which means that academic knowledge spillovers are not restricted to the regional level. In order to analyse knowledge spillovers stemming from

64 Results are available on request

Table 6.5 - Regression results of OLS estimations on regional patents

	OLS regression including technology dummies							**OLS regression including regional fixed effects and technology dummies**						
	Model 1	**Model 2**		**Model 3**		**Model 4**		**Model 5**	**Model 6**		**Model 7**		**Model 8**	
Weight matrix	-	*row*	*column*	*row*	*column*	*row*	*column*	-	*row*	*column*	*row*	*column*	*row*	*column*
University R&D	0.152**	0.188**	0.171**	0.153**	0.163**	0.194**	0.189**	0.354**	0.393**	0.387**	0.353**	0.335**	0.392**	0.370**
	(0.033)	(0.035)	(0.036)	(0.033)	(0.031)	(0.035)	(0.033)	(0.050)	(0.051)	(0.053)	(0.049)	(0.050)	(0.051)	(0.053)
Private R&D	0.346**	0.339**	0.337**	0.314**	0.202**	0.301**	0.189**	0.232**	0.231**	0.235**	0.217**	0.205**	0.217**	0.208**
	(0.059)	(0.058)	(0.059)	(0.060)	(0.059)	(0.059)	(0.058)	(0.068)	(0.067)	(0.067)	(0.068)	(0.068)	(0.067)	(0.067)
W space university R&D		0.085	0.075			0.103*	0.122		0.243**	0.191			0.242**	0.202
		(0.056)	(0.136)			(0.056)	(0.126)		(0.108)	(0.136)			(0.107)	(0.135)
W space private R&D		0.103	0.127			0.108	0.120		0.100	0.122			0.097	0.119
		(0.078)	(0.095)			(0.077)	(0.088)		(0.120)	(0.116)			(0.119)	(0.115)
W network university R&D				0.061**	0.156**	0.074**	0.160**				0.060*	0.100**	0.059*	0.103**
				(0.027)	(0.023)	(0.027)	(0.023)				(0.032)	(0.043)	(0.032)	(0.042)
Human capital	0.380**	0.334**	0.327**	0.343**	0.372**	0.287**	0.317**							
	(0.089)	(0.092)	(0.092)	(0.090)	(0.083)	(0.093)	(0.085)							
TNO	0.641**	0.644**	0.628**	0.581**	0.307**	0.573**	0.279**							
	(0.178)	(0.176)	(0.178)	(0.179)	(0.173)	(0.176)	(0.171)							
Urban Density	-0.394**	-0.479**	-0.435**	-0.409**	-0.413**	-0.512**	-0.469**							
	(0.137)	(0.143)	(0.141)	(0.136)	(0.127)	(0.142)	(0.130)							
Constant	-0.001	0.641	0.588	0.458	0.286	0.066	0.971	1.075**	-0.477	-0.326	1.038**	1.056**	-0.561	-0.434
	(0.769)	(0.794)	(0.800)	(0.790)	(0.715)	(0.795)	(0.740)	(0.138)	(0.375)	(0.420)	(0.138)	(0.137)	(0.376)	(0.418)
N	280	280	280	280	280	280	280	280	280	280	280	280	280	280
	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)	(7 x 40)
R2	0.600	0.612	0.609	0.607	0.657	0.623	0.669	0.507	0.526	0.525	0.530	0.550	0.548	0.562

** indicates significance at 5% level, * indicates significance at 10% level. Standard errors in parentheses university-industry research, a cross-section version of a knowledge production function has been estimated that takes into account the extent to which firms in a region collaborate with universities in other regions.

The results of this chapter suggest that both geographically localised mechanisms and collaboration networks generate academic knowledge spillovers. Knowledge spillovers from university research appear to be present at the regional scale, indicating that universities indeed seem to contribute to the innovation output of the region where they are located and of nearby regions. At the same time, social networks based on formal collaborative research over longer distances also provide a channel for knowledge spillovers. Given the fact that these networks are not limited to the regional scale, this means that there is a risk of over-estimating the importance of geography for academic knowledge spillovers. As such, these results suggest that studies on the geographical dimension of knowledge spillovers should not automatically assume these spillovers to be geographically localised. This implies that in order to analyse the impact of university research on regional innovation it is necessary to take into account the presence of spillovers over longer distances as well. Knowledge spillovers occur at different geographical scales, depending on the geographical dimension of the underlying spillover mechanisms. This chapter included explicitly one mechanism of knowledge spillovers into a knowledge production function. Future research in this area could further extend this framework by including additional weight matrices based on the geographical patterns of other mechanisms, such as labour mobility flows, spin-off dynamics and inter-firm R&D alliances. This research direction will shed light at the relative importance of the various mechanisms of knowledge spillovers at the different spatial scales at which these occur.

The outcomes imply that within the Netherlands, academic knowledge spillovers within science-based technologies cannot be attributed solely to one specific geographical scale. If academic knowledge spillovers occur at various geographical scales, the idea that a university can be regarded as a booster of regional development is at least incomplete. Although regions seem to benefit from the presence of a university, this is not a necessity, since knowledge spillovers occur over longer distances as well. This chapter thus suggests that innovation policy measures should not focus on specific regions only. Given the wide geographical range of these spillovers, a larger geographical scale, such as the national or even international scale, seems more appropriate for such policies. Future studies might provide insight into the role of interregional networks for knowledge spillovers in other countries or at the EU level (see Maggioni et al., 2007). In line with these policy implications of this chapter, the Dutch system of university funding and innovation policies are already centrally organised. For countries with a more decentralized system, e.g. Germany, the outcomes of this chapter suggest that a more centralized system might be considered. Related empirical studies for these countries are however needed before such conclusions can be made.

Finally, it is necessary to keep in mind that these conclusions are based on an analysis of science-based technologies. Given the fact that the importance of the different mechanisms of academic knowledge spillovers probably differs between industries, it would be interesting to see whether these conclusions hold for other industries as well.

Chapter 7

Knowledge flows and innovation in clusters: A firm level analysis[65]

7.1 Introduction

The spatial concentration of knowledge intensive industries has been subject of many studies in the field of economic geography. Much attention has been given to the case of biotechnology as a rapidly growing science-based industry that clusters in specific regions (see for example Cooke, 2001). Most studies (see for an overview Acs, 2002; Audretsch and Feldman, 2004) argue that the existence of localised knowledge spillovers is an important force for the spatial clustering of knowledge intensive industries like biotechnology. Relatively small biotechnology firms tend to cluster around research universities together with venture capitalist and research units of pharmaceutical and chemical multinationals. Firms located in such clusters would benefit from geographical proximity to one another and the relevant research institutes since this enhances the probability of knowledge spillovers to occur. This would then result in a better innovative performance of these firms compared to firms located outside a cluster. Supported by this argument and the success stories of exemplary regions as Cambridge, policymakers in various countries try to stimulate knowledge transfer between firms and research organisations in industries such as biotechnology.

Knowledge spillovers are localised to the extent that geographical proximity is important for the underlying mechanisms. Inter-organisational knowledge exchange through formal and informal networks is seen as an important mechanism for knowledge spillovers. Especially within biotechnology, inter-organisational networks are considered to be an important determinant for the innovative performance of firms (Powell et al., 1996). Intentional inter-organisational knowledge flows depend on the presence of mutual benefits for the organisations involved and some form of mutual understanding and trust (Nooteboom, 2004). Trust and mutual understanding are important here since even in a contract based joint research not all contingencies can be formalised. Geographical proximity is often assumed to be important for these inter-organisational contacts, because it reduces the costs associated with the need of the development of mutual trust and frequent face-to-face for knowledge flows between organisations (Gertler, 2003).

Research on the spatial structure of inter-organisational knowledge flows in biotechnology shows, however, that these are not restricted to the regional scale. Rather, several studies show that knowledge flows are frequently taking place at the national and international scale as well (McKelvey et al., 2003; Gertler and Levitte, 2005; Ponds et al, 2007). These findings on the diverse spatial structure of inter-organisational knowledge flows are in line with more recent views on the role of geographical proximity for knowledge exchange.

65 A slightly different version of this chapter has been submitted as Ponds, R and A. Weterings. Knowledge flows and innovation in clusters: A firm level analysis

Several authors (Howells, 2002; Torre and Rallet, 2005; Boschma, 2005; Knoben and Oerlemans, 2006) argue that geographical proximity can only have an indirect role, and is neither a prerequisite nor sufficient for knowledge exchange to take place. Geographical proximity can positively influence the possibility of identifying possible partners and can stimulate the growth of the necessary trust but is not essential for both (Boschma, 2005). Consequently, the role of geographical proximity for knowledge exchange is not as straightforward as sometimes assumed. In line with this, several authors have argued that the role of geographical proximity differs across various types of knowledge flows, because it depends, among other things, on the mechanisms of identifying potential partners and the underlying coordination mechanisms (Coenen et al., 2004; Bell and Zaheer, 2007). Storper (1997) distinguishes between traded and untraded interdependencies where the latter are assumed to be more localised. Storper and Venables (2004) introduce the expression 'buzz' to refer to localised knowledge exchange based on ongoing face-to-face contacts. Owen-Smith and Powell (2004) refer to 'pipelines' as non-local knowledge relationships such as strategic alliances and R&D collaborations based on formalized relationships. Bathelt et al. (2004) combine this to 'local buzz and global pipelines' to refer to the dual structure of local and (inter-) national knowledge flows. Based on these studies it is often argued that the role of the region (and geographical proximity) for knowledge exchange tends to be exaggerated in studies on the spatial clustering of industries. The role of geographical proximity for processes of innovation seems to be rather complex if knowledge flows take place at various spatial scales. Consequently, empirical studies on knowledge spillovers and clustering should not only focus on the regional dimension since this runs the risk of overestimating the importance of the region. Therefore, recent empirical studies have analysed the relation between knowledge flows and the innovative performance of clustered firms by explicitly taking local and non-local knowledge flows into account (see for example Gertler and Levitte, 2005; Boschma and Ter Wal, 2007).

This chapter adds to the insights of these recent empirical studies by comparing two types of inter-organisational knowledge flows of Dutch biotechnology firms. The first concerns formal knowledge exchange in the form of research collaboration and the second concerns informal knowledge exchange in the form of problem solving oriented contacts. The empirical analysis uses a combination of secondary data on research collaboration based on scientific co-publications and data on informal knowledge exchange collected through a telephone survey. The goal of this chapter is to enhance the understanding of the role of geographical proximity for different mechanisms of knowledge spillovers. This is done by the analysis of the spatial structure of the two types of knowledge flows and their effect on the innovative performance of clustered biotechnology firms in the Netherlands. In the following section, the recent literature on the role of geographical proximity, clustering and knowledge flows in the case of biotechnology is discussed. The research design and methodology will be described in the third section. The results are discussed in the fourth section and section five concludes.

7.2 Spatial clustering, knowledge flows and innovation in the biotechnology industry

The biotechnology industry can be viewed as a typical example of a science-based industry as defined by Pavitt (1984). Within science-based industries, innovation is strongly related to the development of scientific and technological knowledge. Consequently, firms in science-based industries invest relatively heavily in basic, scientific research. Individual firms are however generally unable to keep up with the rapid development in relevant scientific fields. Collaboration with academic research organisations and other firms is therefore a frequently occurring phenomenon. This is especially apparent for biotechnology. Next to universities, organisations like pharmaceutical and chemical multinationals hospitals and venture capitalists play pivotal roles in the innovation process.[66] Studies on the organisation of innovation conclude that these networks between small firms and other organisations are nowadays the 'locus of innovation' in the biotechnology industry (Powell et al., 1996).

Inter-organisational knowledge flows are, therefore, typical for the innovation process in the biotechnology industry. Given the strong spatial concentration of the biotechnology industry, it is often assumed that localised inter-organisational knowledge flows are an important agglomerative force. Knowledge flows in this industry are however not limited to the regional scale but also take place at the national or international scale. The spatial structure of knowledge flows is intensively studied by Cooke (2001, 2005) and he concludes that the biotechnology industry is concentrated in local nodes of excellences that are mutually connected through national and international knowledge linkages. This dual structure of regional and (inter-) national knowledge flows makes the biotechnology industry an interesting case with regard to the recent views on the role of geographical proximity for inter-organisational knowledge flows.

This chapter is focussing on formal and informal inter-organisational knowledge flows. Formal knowledge flows are defined as formal research collaboration: a collaborative arrangement between organisations to pool resources for a common R&D goal (Hagedoorn et al., 2000 p. 58). Informal knowledge flows are here referred to as problem oriented knowledge contacts resulting from the need to solve a specific problem and is mainly concerned with practical knowledge on technologies, artefacts or organisations (Cowan et al., 2000). Both types of inter-organisational contacts are expected to function as an important mechanism of knowledge spillovers and, given the importance of inter-organisational networks in biotechnology, to have a positive effect on innovation. A comparison of empirical studies (see for example McKelvey et al., 2003; Dahl and Pedersen, 2004; Ponds et al., 2007; Boschma and Ter Wal, 2007; Giuliani, 2007) suggests that these types of knowledge flows have rather different spatial patterns. This can be related to the characteristics of the knowledge, the process of identifying potential partners and the underlying coordination and exchange mechanisms, as is further explained below.

Formal knowledge exchange in the form of collaborative research is a structural feature of the biotechnology industry. Research collaboration is strongly oriented towards the development of scientific knowledge, which is a fundamental element in innovation

66 This results from what can be called the functional specialization between small biotechnology firms and large chemical, pharmaceutical or agro food multinationals (Cooke, 2005, 2006). Small biotechnology firms (often referred to as 'dedicated biotechnology firms') perform research and develop potential new drugs, treatments etc. These are then further developed (often in license) by multinationals that have the means (such as the financial resources and the distribution channels) that are generally lacking with the smaller biotechnology firms. This has lead to a form of mutual dependence between large multinationals and smaller biotechnology firms. Hospitals play an important role in the clinical trials necessary for the development of new drugs.

processes in science-based industries. As a result, potential partners for research collaboration are likely to be found in the specific scientific field in which the firm is active.[67] It is often alleged that the generation and exchange of scientific knowledge takes place in epistemic communities (see for example Cowan et al., 2000). Epistemic communities can be defined as a group of individuals with the common goal of the enhancement of knowledge on a specific topic and a common framework for communication (Cohendet and Llerena, 2003). This common framework enables knowledge exchange and is based on the characteristics of the scientific discourse including the terminology, methods and the related conventions and practices. Mutual trust and understanding, necessary for knowledge exchange, is derived from a mutual acceptance and use of this framework for communication. Consequently, frequent face-to-face contacts and meetings, which are more easily to maintain with geographically nearby partners, are less important mechanisms for creating the necessary mutual understanding. Geographical proximity is therefore not as important for facilitating knowledge exchange as having the relevant knowledge on the specific field of interest and speaking the same scientific language (Coenen et al., 2004). Empirically, a large range of studies find indeed that research collaboration in these industries largely takes place at the international and national level (see for example McKelvey et al., 2003; Ponds, 2008 and Hoekman et al., 2008). Given the fact that research collaboration requires the investment of scarce resources such as time or money, this type of inter-organisational knowledge flows is often based on some form of formal agreement on the sharing of the tasks, risks and possible benefits, especially in case of inter-firm research collaboration (Tödtling et al., 2006). Although geographical proximity might ease the formation of such agreements it is not a very important factor for the establishment of such agreements. Temporally geographical proximity (through business trips) is often sufficient here (Rallet and Torre, 1999).

Next to formal knowledge exchange in the form of research collaboration, informal inter-organisational knowledge flows based on 'problem solving' oriented knowledge exchange are distinguished. Informal knowledge exchange is considered to be an important factor in innovation processes (Allen, 1983; Von Hippel, 1987). Firms that encounter specific problems might ask advice from organisations that have encountered similar problems in the past or have knowledge about possible solutions. Within biotechnology these problems are typically occurring during research projects and refer to relative minor technological issues, such as the specific adjustment of a laboratory device. The generation of the specific knowledge internally (for example through trial-and-error) can be time-consuming and rather expensive whereas this knowledge might also be acquired externally at relatively low costs. This requires that firms have knowledge on the competences and practical knowledge of other organisations and that these other organisations are willing to exchange their knowledge. The information on the competences and knowledge of other organisations is not readily available but is typically circulating in social networks and is consequently often considered as rather informal and unarticulated knowledge (Dahl and Pedersen, 2004).

This type of information is often gathered at meetings, within business clubs or through contacting former colleagues or classmates. All these contacts form social networks. The

67 Note that, contrary to for example the social science, this community does not merely consists of academic organisations but also of firms (see also Rosenberg, 1990 on this) and governmental organisations such as hospitals and institutes as the National Institutes of Health in the USA.

localised character of such networks implies that information on relevant organisations for a specific problem is to a large extent gathered among organisations located nearby. Consequently knowledge flows of ‘problem solving’ contacts are more likely to be regionally oriented than knowledge flows through research collaboration since the mechanisms of identifying possible ‘partners’ are more affected by geographical distance. Moreover, as often emphasised in the economic geographic literature, ‘problem solving’ knowledge is also often exchanged on the base of reciprocity, instead of through a market transaction (Schrader, 1991). The willingness to exchange knowledge comes from trust-based, reciprocal relations that are in turn often based on localised social networks (see for example Uzzi, 1996 and Giuliani, 2007). However, the willingness of an organisation to exchange the practical knowledge for a specific problem can also simply result from the price set in a market transaction, as is generally the case in specialised consultancy or legal matters. Geographical proximity hardly plays a role for the underlying coordination mechanism, since it concerns a pure market based transaction. The identification of the relevant organisations is however still based on information flows occurring through localised social networks. As a consequence, informal knowledge flows are assumed to be to a large extent localised regardless of the coordination mechanism involved.

This implies that informal knowledge exchange in the form of problem solving oriented contacts is more likely to be localised than formal knowledge exchange through research collaboration for two reasons. First, the identification of organisations with relevant knowledge takes places through different mechanisms. In case of knowledge flows that are oriented towards problem solving, the identification and selection of potential partners is localised since the information on possible partners circulates in social networks that are to a large extent localised (Dahl and Pedersen, 2004). In case of research collaboration, possible partners are identified and selected on the basis of specific knowledge or competences demonstrated in the relevant scientific community. Due to fact that epistemic communities are characterised by a universal communication framework, possible partners can be found worldwide as long as they understand this framework (see Cowan et al., 2000 and Cohendet and Llerena, 2003). Second, the role of geographical proximity for the underlying coordination mechanisms often differs. Informal knowledge exchange might occur within a market transaction but is typically based on reciprocity. Knowledge is being exchanged on the expectation that this is reciprocated in the future (Schrader, 1991). As a consequence, the basis of this type of knowledge exchange is mutual trust that follows from social networks, which are often localised (Breschi and Lissoni, 2003, 2006). Formal knowledge exchange in the form of research collaboration on the other hand is based on a joint investment of resources for a common R&D goal (Hagedoorn et al., 2000). Consequently, this type of knowledge exchange involves some form of formal agreement in most cases and geographical proximity does not play an important role in the underlying coordination mechanism.

7.3 Research design

The reminder of this chapter consists of an empirical analysis of the spatial structure of both types of knowledge flows and the effect on the innovative performance of biotechnology firms in the Netherlands. In this section, the data collection is further explained. Two sources of data have been used. First, information among biotechnology firms in the Netherlands have been gathered using a telephone survey. Since data on inter-organisational knowledge flows and firm specific characteristics are in general not readily available, studies on this topic often use firm level surveys, conducted among firms located in one or several regions (see for example Kaufman and Tödtling, 2001; Gertler and Levitte, 2005; Boschma and Ter Wal, 2007). Partly, this chapter has followed a similar approach and uses data that is gathered through a firm level telephone questionnaire held in May and June 2006[68]. Using the survey, information on informal knowledge exchange in the form of problem solving knowledge contacts and the innovative performance of biotechnology firms has been gathered. Second, secondary data on formal knowledge exchange through research collaborations of these firms have been gathered, using information from the Web of Science. This dataset provides information on the co-publications of firms and research institutes. Both datasets have been matched, leading to data on the innovative performance of biotechnology firms and formal and informal knowledge flows. Below, the measurement of the innovative performance of firms and their knowledge networks is further elaborated upon.

7.3.1 Data collection: measuring innovation knowledge networks

For most industries, innovative performance can be measured by the share of new products and services in the total sales or total revenue (see Kleinknecht et al., 2002). Biotechnology is a somewhat different case however, since most biotechnology firms do not have revenues (yet), which makes this indicator of rather limited use (Zucker et al., 1998b). Alternatively, the innovative performance of biotechnology firms is typically measured by using patents as indicator for the innovative output (see for example Zucker et al., 1998b; Gertler and Levitte, 2005). Results of R&D activities in biotechnology are generally patented and often licensed to larger firms. Given the fact that most firms are not very willing to give information on the income through licensing of their patents, the best option here seems to be the number of patents of a firm as indicator for innovation (Zucker et al., 1998b). Although the use of patents as indicator is widely discussed in the literature (see Griliches, 1990), in case of biotechnology it is generally considered to be a fairly good indicator of the innovative performance of firms. Therefore, all interviewed biotechnology firms have been asked how many patents their firm has registered in 2005 and 2006 as an indicator of their innovative performance.

Furthermore, the survey has also been used to collect data on firm specific characteristics that may influence the innovative performance such as the R&D intensity and the size of the firm. With these data it is possible to control for heterogeneity between firms. Size and age are commonly used control variables. Larger firms are likely to have more patents due to the pure size effect, which is controlled for by taking the number of employees in fulltime equivalents into account. Older firms are sometimes assumed to be less likely to innovate since new innovative products may interfere with existing products or services that are already in the market. Age, measured in number of years of existence, is therefore included. Finally, firms can differ in their investments in new knowledge and firms that invest more in the generation of new knowledge are more likely to be successful in terms

68 For more details, see Weterings and Ponds (2006).

of innovation. The share of R&D employees in the total number of employees is included to take these differences into account.

As explained above, the survey has also been used to gather data on informal knowledge exchange of the biotechnology firms. Firms were asked if and with which organisations they had contact if they were confronted with a specific problem during the last two years. This has been defined as the occurrence of difficulties or unknown events during daily operations, which could not be handled on the basis of existing knowledge and skills from the employees in the firm. The firms were asked only to mention contacts with other organisations that involved the exchange of knowledge that significantly contributed to solving the problem. The collection of the data on these contacts with other organisations was based on the so-called roster-recall method (see Giuliani, 2007 and Morrison, 2008 for similar approaches), stemming from social network methodology (Wasserman and Faust, 1994). Firms were send a list of names of organisations located in the same region and were asked to indicate whether they had contacted this firm if confronted with a problem during the last year ('the roster part'). This list consisted of all relevant research institutes and the most important firms in the region in the industry. Furthermore, firms were asked to mention if they had contacted other organisations inside or outside the region not mentioned on the list ('the recall part'). In social network analysis, the roster method is considered to be far better than the recall method. However, the roster method is based on the assumption that all potential 'partners' are known. Since this is hardly ever the case, the roster method is generally extended with a recall part (Wasserman and Faust, 1994). For each contact with another organisation, firms were asked to give information on the location of this organisation. It was explicitly emphasized this could also include organisations located outside the region.

Information on formal knowledge exchange in the form of research collaboration has been based on data on scientific publications with multiple organisations. In science-based industries, firms are actively involved in scientific publishing since it is necessary for participation in a scientific community (Rosenberg, 1990). Furthermore, publication of research finding can have an important signalling function to potential investors and collaboration partners. Research collaboration between firms and other organisations often leads to a co-publication. Consequently, co-publications have been intensively used to study research collaboration (see for example Katz and Martin, 1997; Coenen et al., 2004 and Ponds, 2008). Alternatively, data on the announcements of research alliances is often been used as indicator for research collaboration. In comparison with co-publications, the 'literature-based alliance counting' (Hagedoorn, 2002) has the advantage of being applicable for more industries than just science-based industries. Nevertheless, the lack of publicity for specific types of collaborative research and the low profile of certain companies and industries might lead to a specific bias in this indicator as well. Given the focus on science-based industries and the fact that collecting data based on announcement of research collaboration is costly and rather time-consuming, the use of co-publications as indicator for collaborative research is preferred. All publications of the firms that participated in the questionnaires have been retrieved for the years 2005 and 2006 from Web of Science. Research collaboration has been measured by the co-occurrence of a biotechnology firm and another organisation on a publication. This implies that a publication with multiple authors from a single organisation is not considered as a collaboration, whereas a publication with a single author and multiple affiliations is. This results from the practical restriction that within the database format of Web of Science it is not possible to link individuals to organisations and therefore the addresses of the organisations cannot be used to identify the location of individuals. Based on the location of the organisations involved, the spatial scale of the collaboration can be derived.

7.3.2 Survey: research population and response rate

The data have been collected among biotechnology firms that are located in two provinces in the Netherlands that are home to the two largest Dutch clusters in the field of biotechnology: South-Holland (concentrated around the city of Leiden) and Gelderland (concentrated around the city of Wageningen). Biotechnology firms in the region of South Holland are more focused on pharmaceutical applications of biotechnology whereas firms in Gelderland are generally more specialised in the field of agro-food biotechnology. At this moment, biotechnology is no specific subcategory in industrial classification schemes, which makes it hard to determine the size of the industry and to select the relevant firms (see also OECD 2005 on this). To obtain the names and addresses of these firms, two regional life sciences organisations[69] have been contacted. They have provided the names and addresses of firms that are registered with them. Since the goal of these organisations is to support the life sciences and membership is free, it can be assumed that the registered firms form (nearly) the entire biotechnology industry in both regions. The total research population consisted of 135 firms. The telephone questionnaire has been conducted among the owners or managing directors of the firms. After verifying the main activities of the firm, only so-called dedicated biotechnology firms have been selected. The final research population consisted of 120 firms (35 located in the province of Gelderland and 85 in the province of South-Holland). The response rate was relatively high (more than 45%) and the final research sample consisted of 55 firms. It is difficult to determine the representativeness of the sample since no information on the other firms is available. Nonetheless, there are two reasons why it is fair to assume that the firms that participated in the questionnaire are to a large extent representative for the overall population. First of all, the research sample is a relatively large one. According to the life science sector report of Biopartner[70] (2005), the whole of the Netherlands was home to 157 biotechnology companies in 2004. Second, the descriptive statistics in table 7.1 of the firms in the research sample reveals many similarities with the often-described characteristics of the biotechnology industry in general.

This table shows that the final research sample consists of relative small firms (the average size is less then 14 employees) that are rather research intensive (the average share of R&D employees is higher than 50 percent. Furthermore, the average firm seems to be actively involved in inter-organisational knowledge flows. Altogether, the descriptive statistics are in line with the general observation that the biotechnology industry consists to a large extent of small and research-intensive firms (see for example OECD, 2005).

69 Respectively CCLS for South-Holland and Biopartner Wageningen and Foodvalley for Gelderland
70 The governmental organisation responsible for the implication of the policy measures trying to stimulate the life sciences industry in the Netherlands.

Table 7.1 Descriptive statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Patents	55	0	18	1.87	3.31
Size (number of employees)	55	0.4	80	13.72	19.82
Age (in years since entry)	55	0	22	6.20	5.00
Share of R&D employees	55	0	100	53.71	37.14
Number of problem oriented Knowledge contacts	55	0	24	5.53	4.46
Number of research collaborations	55	0	183	8.80	25.40
Share of regional problem oriented knowledge contacts	55	0	1	0.65	0.36
Share of regional research collaborations	55	0	1	0.10	0.22

7.4 Results

The empirical analysis of this chapter consists of two parts. The first part describes the spatial structure and characteristics of formal and informal inter-organisational knowledge flows. The second part analyses the relation between these knowledge flows and the innovative performance of biotechnology firms, controlling for different firm characteristics.

7.4.1 Spatial structure of inter-organisational knowledge flows

In the theoretical considerations discussed in the section two of this chapter, it is argued that informal knowledge flows through problem-oriented contacts are more localised than formal knowledge flows through research collaboration. The main goal of this part of the empirical analysis is to test these claims and thereby gain insights in the role of geographical proximity for both types of knowledge flows. A distinction is made between three spatial scales where knowledge flows can occur: the regional scale (between a firm and an organisation located in the same province), the national scale and the international scale. Although this is not a sophisticated spatial classification due to its dependence on administrative borders, comparing the absolute and relative importance of the regional, national and international scale for both types of knowledge flows can provide insights in the role of geographical proximity. Significant differences between both types of knowledge flows in the relative importance of these three spatial scales can be assumed to indicate differences in role of geographical proximity.

Table 7.2 shows the number of both types of knowledge flows at the three distinguished spatial scales. The regional scale is significantly more important for informal, problem oriented knowledge contacts than for formal knowledge flows through research collaboration. Research collaboration on the other hand is significantly more often occurring at the international scale than informal problem oriented knowledge contacts. Together these findings confirm the idea that informal, problem solving oriented, knowledge flows are more localised than formal research collaboration.

Table 7.2 - The spatial scale of knowledge flows

	Problem oriented knowledge contacts		**Research collaboration**		
	Absolute number	*Share in total*	*Absolute number*	*Share in total*	*Significant differences between the shares*
Total	304	-	484	-	-
Regional	205	68%	150	31%	Yes**
National	65	21%	130	27%	No
International	34	11%	204	42%	Yes**

** Significance level of 0.99, *significance level of 0.90. Based on Chi-square test

Table 7.3 shows a similar descriptive analysis, but focuses on the number of firms that have knowledge flows at different spatial scales. Table 7.2 showed that the number of formal knowledge flows is higher than the total number of informal knowledge flows. At the same time, table 7.3 shows that almost all firms have informal, problem solving oriented contacts but only slightly more than half of the firms are involved in formal knowledge exchange through research collaboration.

In case of problem oriented knowledge contacts, most firms participate in knowledge flows at the regional level. The number of firms with knowledge contacts at the national and especially at the international level is much lower. In case of research collaboration, there are hardly differences between the number of firms participating in collaborative research at a specific spatial scale. This indicates that the geographical distance is less important for this type of knowledge flows compared to informal, problem oriented knowledge contacts.

Altogether, these findings indicate that there are indeed significant differences in the spatial structure of formal and informal knowledge flows. It implies that the hypothesis derived from the theoretical reflections in part two, that more informal, problem oriented knowledge contacts are more localised than formal knowledge exchange through research collaboration can be confirmed.

Table 7.3 - Firms and the spatial structure of knowledge flows

	Problem oriented knowledge contacts		**Research collaboration**		
Number of firms with knowledge flows:	*Absolute number*	*Share in total firms(=55)*	*Absolute number*	*Share in total firms (=55)*	*Significant differences between the shares*
Total	53	96%	31	56%	Yes**
Regional scale	49	89%	22	40%	Yes**
National scale	26	47%	23	42%	No
International scale	15	27%	24	44%	Yes*

** Significance level of 0.99, *significance level of 0.90. Based on Chi-square test

Table 7.4 - Correlations

		1	2	3	4	5	6	7
1	Size (log)	1.00						
2	Age (log)	0.16	1.00					
3	R&D	0.18	-0.42**	1.00				
4	Number of problem oriented contacts (log)	0.05	-0.02	0.16	1.00			
5	Number of research collaborations (log)	0.34*	0.01	0.18	0.21	1.00		
6	Share of regional problem oriented knowledge contacts	-0.19	-0.14	0.08	0.04	0.17	1.00	
7	Share of regional research collaborations	0.09	-0.03	0.14	0.15	0.35**	0.20	1.00

**significant at 0.05 level

7.4.2 Knowledge flows and innovative performance

In order to analyse the relation between the (characteristics of) knowledge flows and the innovative performance of the firms, a regression model has been estimated. The innovative output of a firm is modelled as a function of the size, the age, the share of R&D employees in total employment and the size and (spatial) characteristics of both types of knowledge flows. Contrary to most previous studies on this topic, this chapter does not distinguish between regional and non-regional knowledge flows a-priori but focuses on the effect of inter-organisational knowledge flows in general. Based on the theoretical arguments in section two, there is no specific reason to assume that the effect of a knowledge flow on innovation is different simply because it takes place at a different spatial scale. This could only be the case if knowledge flows at a specific spatial scale were associated with greater benefits than the same type of knowledge flows at another spatial scale. The geographical dimension of specific knowledge flows is however considered to be the outcome of the relative importance of geographical distance for the underlying mechanisms rather than being a specific characteristic of a knowledge flow that influences its effect on innovation. The effect of inter-organisational knowledge flows on innovation is therefore analysed by incorporating the sum of these knowledge flows without differentiating a priori towards a specific spatial scale. In order to test if the geographical dimension of both types of knowledge flows itself has indeed no extra effect on the innovative performance, the share of regional knowledge flows in the total number of knowledge flows is taken into account.

Table 7.4 shows the correlations between the variables. Some variables exhibit a significant, though low, correlation indicating that there seems to be no problem of multicollinearity.

Innovative output is measured by the number of patent applications, which has a count data character. Consequently a Poisson model has been estimated. In order to account for potential differences between the two regions from which the firms in biotechnology are pooled, a regional dummy has been included in the model. However, this variable turned out to be insignificant and is therefore not reported. The variables size, age and the number of both types of knowledge flows have been transformed by taking the log.[71]

Several models have been estimated. Table 7.5 presents the results. The first model includes only the share of employees devoted to R&D activities and the firm specific control variables size and age. The results are straightforward. A higher percentage of R&D employees is related to a better innovative performance. Larger and younger firms also appear to be more innovative. Models two, three and four included respectively the number of research collaborations, the number of problem oriented knowledge contacts and the number of both type of knowledge flows jointly. The results show that the number of both types of knowledge flows has a positive effect on the innovative performance of firms. This suggests that both informal and formal inter-organisational knowledge flows form an important source of external knowledge and contribute to a firm's innovative performance. These findings are in line with the description of the innovation process in biotechnology in general as set out in section two.

In order to test whether the geographical dimension itself has an extra effect on innovation, the share of regional research collaborations and problem oriented knowledge contacts have been included in models five till seven. No significant effect has been found in case of informal, problem oriented knowledge contacts, suggesting that there is no relation between the geographical dimension of these knowledge flows and the innovative performance of firms. Although the majority of these informal knowledge contacts take place at the regional level, no additional effect on the innovative performance of firms of the localised character of these knowledge flows seems to exist. As expected, geographical proximity plays a role in the underlying mechanisms that establish informal, problem oriented, knowledge contacts rather than enhancing the effect on innovation of these contacts directly.

A higher share of regional formal knowledge flows, in the form of research collaboration, does have a positive and significant effect on the innovative performance of firms, despite the fact that research collaboration is less localised than informal problem oriented contacts as shown in table 7.2 and 7.3. This seems to be somewhat surprising given the fact that the underlying mechanisms of selection and coordination of these knowledge flows are less likely to be affected by geographical proximity. It appears as if formal knowledge flows through research collaborations with organisations located in the same region brings along additional benefits compared to research collaboration at the national or international level. Owen-Smith and Powell (2004) found similar results in their study on the Boston biotechnology industry. They suggested that although formal research collaboration is generally embedded in formal contractual agreements, additional benefits might arise if partners are located nearby. This is said to result from the increased likelihood that next to the formal agreements on joining resources, already existent social relations between both partners give rise to additional knowledge spillovers next to the formal agreements on joining resources. This might for example be the case with university spin-offs where the entrepreneurs collaborate in a research project with former university colleagues. Given their already existing social relations, the chances are higher that additional

71 In both types of knowledge flows, a value of one has been added in order to make log transformation possible if a firm does not participate in one or two type(s) of knowledge flows.

Table 7.5 - Results of Poisson regressions, dependent variable is number of patents per firm

	1	2	3	4	5	6	7
Share of R&D employees	0.013** (0.003)	0.012** (0.004)	0.012** (0.004)	0.012** (0.004)	0.012** (0.004)	0.011** (0.004)	0.012** (0.004)
Size (log)	1.271** (0.199)	0.678** (0.228)	1.160** (0.203)	0.728** (0.236)	0.724** (0.236)	0.855** (0.252)	0.845** (0.252)
Age (log)	-0.520* (0.303)	-0.480* (0.287)	-0.520* (0.291)	-0.484* (0.282)	-0.506* (0.287)	-0.496* (0.286)	-0.515* (0.289)
Research collaborations (log)		0.869** (0.187)		0.844** (0.352)	0.853** (0.350)	0.881** (0.361)	0.882** (0.357)
Problem oriented knowledge contacts (log)			1.332** (0.335)	0.639** (0.201)	0.656** (0.204)	0.497** (0.208)	0.525** (0.212)
Share regional problem oriented knowledge contacts					-0.138 (0.333)		-0.199 (0.339)
Share regional research collaborations						1.050** (0.416)	1.070** (0.418)
Constant	-1.118** (0.393)	-1.138** (0.387)	-1.976** (0.455)	-1.635** (0.447)	-1.555** (0.484)	-1.826** (0.473)	-1.712** (0.508)
N	55	55	55	55	55	55	55
Loglikelihood	-109.245	-98.248	-100.478	-95.160	-95.074	-92.322	-92.150
Maximum likelihood R2	0.755	0.836	0.822	0.853	0.854	0.868	0.868

** indicates significance at 5% level, * indicates significance at 10% level. Standard errors in parentheses

knowledge exchange takes place next to the formally agreed exchange of knowledge and resources. Since these networks of social relations are strongly localised, such additional and unexpected knowledge spillovers are most likely to occur if research collaboration takes places at the regional level. This suggests that formal collaboration might lead to or can be accompanied by informal knowledge exchange as well. The outcomes of the type of analysis performed in this chapter can however not be more conclusive on this due to data limitations. It can however be considered as an interesting future research issue.

7.5 Conclusions

Research on localised knowledge spillovers is increasingly based on the notion that these spillovers are as localised as their underlying mechanisms are. Based on this, an increasing number of studies analyse the role of geographical proximity for the underlying mechanisms of knowledge spillovers with the use of data on micro-economic linkages between economic agents. This chapter builds on this line of research and aims to enhance the understanding of the role of geographical proximity for knowledge exchange by analysing the geographical dimension of inter-organisational knowledge flows and the effect of these flows on the innovative performance of biotechnology firms in the Netherlands. Two different types of inter-organisational knowledge flows have been distinguished, informal knowledge exchange, defined as problem oriented knowledge contacts, and formal knowledge exchange in the form of research collaboration. The empirical analysis is based on a combination of data gathered through a telephone survey among biotechnology firms and an existing database on research collaboration as measured by co-publications.

The results show that informal, problem oriented knowledge flows are more localised than formal knowledge exchange through research collaboration. It is argued that this can be related to the different role of geographical proximity in the mechanisms underlying the identification of potential partners and in the coordination mechanisms of the knowledge exchange. The identification of potential partners in case of problem oriented knowledge contacts is mainly based on information circulating in social networks, which are in turn largely localised. Furthermore, this knowledge is often assumed to be partly exchanged on the base of future reciprocity. The necessary trust generally results from social networks, which are in turn largely localised. Formal knowledge exchange in the form of research collaboration is, within science-based industries like biotechnology, strongly oriented towards the development of scientific knowledge. The identification of potential partners takes place within the relevant scientific field. The organisation of scientific research strongly resembles an epistemic community characterised by a common framework for communication and shared norms and values. As a consequence, geographical proximity is not an important factor for the identification of potential partners and the coordination of the knowledge exchange.

The empirical results show that both types of knowledge flows have a positive effect on the innovative performance of firms. In line with other studies on the biotechnology industry, it is shown that, controlling for firm specific characteristics, inter-organisational knowledge flows play an important role for innovation. Contrary to most previous studies on the relation between the regional dimension of knowledge flows and innovation at the firm level, no a-priori distinction between regional and non-regional knowledge flows has been made. Rather, the regional dimension has been taken into account by analysing the effect of the share of regional knowledge flows in combination with the overall number of knowledge flows. Despite the fact that the majority of problem oriented knowledge contacts takes place at the regional level, no additional effect is found of a more localised dimension of these knowledge flows on the innovative performance of biotechnology firms. This seems to confirm the idea that geographical proximity might have an important facilitating role for the formation of these knowledge flows, but that it does not have any additional benefits for innovation. In case of research collaboration, there seems to be a positive effect of a more localised orientation. This might reflect a higher chance of additional knowledge spillovers, which could result from an already existing social relation between the organisations involved in the research collaboration.

Altogether these findings are in line with recent views on the more indirect effect of geographical proximity for knowledge exchange. It is shown that geographical proximity plays a role for knowledge exchange to the extent that geographical proximity facilitates the underlying mechanisms through which knowledge is exchanged. As a consequence, knowledge spillovers are not limited to the regional scale but depend on the role of geographical proximity in the underlying mechanism. In the case of biotechnology, knowledge spillovers seem to occur at the regional, the national and the international scale due to the fact that both informal and formal inter-organisational knowledge flows matter for the innovative performance of firms. Since geographical proximity plays a different role in the underlying mechanisms of these flows, the spatial dynamics of biotechnology resembles a structure of local nodes and global pipelines, as argued by Gertler and Levitte (2005).

Although this chapter provides valuable empirical insights, more studies on how geographical proximity influences mechanisms of knowledge exchange in relation with their effect innovation are required before more decisive conclusions can be drawn. Future studies might examine the possible differences between firms inside and outside clusters with regard to the number and effect of knowledge flows through inter-organisational contacts. Possibly, firms outside clusters are confronted with more difficulties and higher costs in finding and maintaining knowledge exchange with other organisations. This might be especially the case for informal, problem oriented knowledge contacts. Furthermore, a comparison between different industries on the role and effect of different types of knowledge flows might provide valuable insights in inter-industry differences. Finally, in-depth case studies might provide the necessary insights in the actual process of identifying and selecting potential partners and the subsequent mechanisms of coordination for different types of knowledge flows, which could not be tested with the data used in this chapter.

Chapter 8

Summary and conclusions

8.1 Introduction

This study is motivated by the need for a better understanding of the role of geographical proximity for knowledge spillovers. Although the presence of knowledge spillovers is generally considered to be a strong force behind the spatial agglomeration of industries and economic growth, the understanding of the geographical scale and scope of knowledge spillovers is still limited. Given the increasing focus of policymakers at the regional, national, and international levels on the geographical dimension of innovation processes, this topic also has policy relevance. The goal of this study is to broaden the understanding of the role of geographical proximity for knowledge spillovers that result from collaborative research in science-based industries. This is done by (1) analysing the role of geographical proximity in collaborative research and by (2) analysing the effect of collaborative research on the innovation rate of regions and firms. In this concluding chapter, the most important research findings are summarized. The conclusions are discussed in relation to the existing literature. The policy implications are also outlined. This chapter concludes with a discussion of the limitations of this study and suggests directions for further research.

8.2 Summary and research findings

Following insights dating back to Marshall (1920), localised knowledge spillovers are generally considered to be important agglomerative forces. Knowledge spillovers have consequently become an important research theme in regional economics and economic geography. A large number of econometric studies has found indirect evidence of the presence of geographically localised knowledge spillovers, but their conclusions on the size and geographical range of these spillovers strongly differ. To understand why this is the case, research on localised knowledge spillovers is increasingly focusing on the underlying mechanisms. Within this line of research, three mechanisms of localised knowledge can be distinguished: labour mobility, entrepreneurship and spin-off dynamics, and inter-organisational knowledge relationships. The geographical dimension of knowledge spillovers is determined by the role of geographical proximity for each of these spillover mechanisms. However, empirical insights on this matter are only slowly emerging and conclusions on the role of geographical proximity are far from decisive. The goal of this study has been to contribute to the understanding of the role of geographical proximity for one specific mechanism for knowledge spillovers: collaborative research. The focus is on science-based industries because collaborative research is considered to be especially important in these industries.

The following two research questions were formulated:

1 What is the role of geographical proximity for research collaboration in science-based industries in the Netherlands?

2 Does collaborative research constitute a mechanism for knowledge spillovers in science-based industries in the Netherlands?

Science-based industries are of particular interest because these are highly innovative and exhibit a strong tendency towards geographical concentration. The focus on collaborative research as a mechanism for knowledge spillovers is motivated by the importance of research collaboration between firms, and especially between firms and academic research organisations in science-based industries. In chapter three, the distinct features of science-based industries are described. The introduction of new products and services is strongly related to developments in scientific research in fields like applied physics and biochemistry. Consequently, firms in science-based industries invest relatively heavily in R&D compared to other industries. Firms are actively involved in scientific research and participate in those scientific communities that are considered relevant to their innovative capacity. Research collaboration with universities and other academic research organisations is a central element of innovation processes within these industries and is considered as the most important mechanism for knowledge spillovers. Collaborative research with both academic organisations and between firms has been increasing over time in science-based industries. The main reason for this is the inability of individual firms to keep pace with rapid developments in relevant scientific fields. This is further enhanced by governments, which are increasingly stimulating collaborative research in science-based industries to promote the transfer of knowledge between academic organisations and firms. Based on the relative importance of scientific knowledge for different technology fields, eight science-based technologies that constitute the fields of innovation for science-based industries are selected.

Chapters four and five focus on the first research question of this study and analyse the role of geographical proximity in collaborative research. Based on a distinction between academic organisations, governmental organisations, and firms, six different types of collaborations have been identified; three homogeneous types (collaboration between similar organisations) and three heterogeneous types (collaboration between different types of organisations). The main premise is that the role of geographical proximity is likely to be related to the types of collaboration. Institutional differences between academic and non-academic organisations regarding the underlying incentive structures create possible obstacles to successful collaborative research. Given the complexity of collaborative arrangements for joint research, not all contingencies can be encoded in enforceable legal contracts. Consequently, research collaboration is partly based on less formal mechanisms to lower the risk of opportunism, such as mutual trust. This trust is more difficult to establish between organisations with different incentive structures and institutional backgrounds. Because trust is typically created by frequent meetings involving face-to-face contacts and by common culture and institutions, the costs of collaboration are likely to rise with geographical distance. Collaboration between organisations with the same institutional background occurs within a similar framework of incentives and constraints and the necessary trust is consequently more easily established. By distinguishing between different types of collaboration (defined by the type of organisations involved) and analysing each technology separately, the role of geographical proximity is isolated from institutional and technological proximity.

Chapter four analyses the international dimension from 1988 until 2004. Over time, collaborative research has been increasing in all science-based technologies. The majority of collaborative research involving an organisation from the Netherlands is international. The relative importance of the international dimension, expressed by the share of international collaborations, is stable over this period, indicating that there was no increase in the level of internationalisation. The rise of international collaboration equals the pace of the rise in national collaboration, exemplifying the increasingly collaborative nature of research rather than a tendency towards internationalisation. International research collaboration is mainly driven by academic collaboration, which reflects the international dimension of scientific communities. International academic-industry collaboration also occurs and can be considered to be a mechanism for international knowledge spillovers from academic research. If foreign firms collaborate disproportionately more with Dutch academic organisations than Dutch firms collaborate with foreign academic organisations, this might generate asymmetric benefits of these international spillovers. It is shown that these asymmetric benefits might have occurred in the beginning of the period under investigation but largely disappeared as a result of a more balanced pattern of international academic-industry collaboration. Next to this, it is found that heterogeneous collaboration (e.g. academic-industry) and subsequent knowledge spillovers are more likely to occur at the national level than homogenous collaboration (e.g. university-university). Research collaboration between organisations with different institutional backgrounds and incentive structures seems to be facilitated by co-location in the same country. These findings are consistent with propositions from the proximity framework, which holds that geographical proximity is helpful in overcoming possible difficulties related to differences in incentive structure – referred to as a lack of institutional proximity.

To determine if the advantages of geographical proximity regarding this type of research collaboration are present at a lower geographical scale as well, chapter five focuses on the regional dimension of collaborative research in the Netherlands. By aggregating individual collaborations to the level of functional urban regions – NUTS 3 regions – the role of geographical proximity in different types of collaborations is analysed by estimating the effect of travel time on the intensity of collaboration between two regions with the application of a spatial interaction model. Consistent with the conclusion of chapter four, geographical proximity is found to be more important for collaborative research between different types of organisations than for collaborative research between the same types of organisations. However, this does not mean that academic-industry collaboration is necessarily a regional phenomenon. Within the Netherlands, the role of geographical proximity is more pronounced for collaboration between academic organisations and governmental organisations than for academic-industry collaboration where the national scale seems more important.

Chapters six and seven focus on the role of research collaboration as a spillover mechanism at the level of regions and firms, respectively, and answer the second research question. A large number of empirical studies on knowledge spillovers are based on the regional knowledge production framework where different regional knowledge inputs are related to regional differences in knowledge output. Within knowledge production function studies, the presence of interregional knowledge spillovers is tested with the inclusion of weighted averages of knowledge inputs from other regions. The construction of the weighted average is based on assumed patterns of interaction between regions, which are formally expressed in a spatial weight matrix. The non-zero elements in this matrix reflect the potential interaction between regions. Based on the assumption that knowledge spillovers are largely localised, the majority of the studies apply weight matrices that are contiguity or distance-based, implying that nearby regions have higher weights than regions further away. This is theoretically underpinned by assuming that all mechanisms of these spillovers are geographically localised due to the importance of face-to-face contacts for tacit knowledge transfer. Chapters four and five, however, show that at least one possibly important mechanism for knowledge spillovers is far less geographically localised than often assumed. This implies that by only including the weighted average of knowledge inputs from nearby regions into this empirical framework, the possible presence of spillovers over longer distances is ignored. To formally test the presence of spillovers through collaborative research, a cross-sectional regression of the knowledge production function at the level of NUTS3 regions in the Netherlands is estimated in chapter six. This is done by including two different versions of the weighted average of university R&D from other regions into the knowledge production function. The first is based on a spatial weight matrix reflecting the spatial structure of academic-industry collaboration to account for knowledge spillovers through research collaboration. The second is based on a weight matrix following a distance decay function, reflecting possible spillovers resulting from geographically localised mechanisms. The results of chapter six suggest that academic knowledge spillovers cannot be easily attached to a specific geographical scale. Knowledge spillovers occur through collaborative research, where the national scale is more important (see chapters four and five) and through mechanisms that are geographically more localised.

In chapter six, the mechanisms of knowledge spillovers other than formal collaboration are assumed to be geographically localised. In chapter seven, this assumption is further investigated by analysing the geographical dimension and the effect of informal knowledge exchange on innovation. This chapter has a firm level approach and focuses on the biotechnology firms in two regions in the Netherlands. The empirical research is based on a combination of data on informal knowledge exchange gathered by a telephone firm survey and co-publication data on research collaboration. Informal knowledge flows are referred to as problem oriented knowledge contacts resulting from the need to solve a specific problem. Informal knowledge exchange is mainly concerned with practical knowledge on technologies, artifacts, or organisations, in contrast to formal research collaboration, which is based on a collaborative arrangement between organisations to pool resources for a common R&D goal. Informal knowledge exchange is often considered to be localised for two reasons. Information on the competences and knowledge of other organisations is not readily available but is typically circulating in localized social networks. Additionally, it is often assumed that this type of knowledge exchange occurs through reciprocal relationships. Empirical studies have found that these social relationships are largely localised and, as a result, subsequent knowledge spillovers are also assumed to be localised. In chapter seven, this claim is tested by comparing the geographical dimension of collaborative research and informal knowledge exchange. It was found that informal problem oriented knowledge flows are indeed more localised than collaborative research. This suggests that the 'black box' of localised spillovers in chapter six consists, at least in part, of informal knowledge exchange. The contribution of spillovers through these mechanisms to the innovative performance of biotechnology firms in the Netherlands is formally tested. After controlling for firm specific characteristics, it is shown that both formal and informal collaboration have a positive effect on the innovative performance of firms.

In sum, the results of chapters six and seven show that collaborative research indeed constitutes an important mechanism for knowledge spillovers in science-based industries in the sense that it contributes to the innovative performance of regions and firms. As shown in chapters four and five, collaborative research between universities and firms is more likely to occur at the national level than at the regional level. In addition to the presence of knowledge spillovers over relatively long distances through collaborative research, the results of chapter six suggest that knowledge spillovers through more localised mechanisms also occur. This is confirmed by the outcomes in chapter seven on the differences in the spatial structure of informal knowledge exchange and collaborative research. Taken together, the results presented in these chapters imply that knowledge spillovers occur at various spatial scales due to the different geographical configurations of the underlying mechanisms.

8.3 Research contributions

The aim of this study was to develop further insight into the role of geographical proximity in collaborative research and into the role of collaborative research as a mechanism for knowledge spillovers. The results contribute to the existing literature on the geographical dimension of knowledge spillovers in three ways.

First, this study is the first to empirically test the role of geographical proximity as opposed to other forms of proximity in research collaboration in an explicit econometric framework. By focusing on a specific spillover mechanism and differentiating it from other dimensions of proximity, the effect of geographical proximity can be isolated from other forms of proximity. It is shown that if institutional proximity is lacking, e.g. in case of university-industry collaboration, geographical proximity is more important than in cases of collaboration between similar types of organisations. This suggests that geographical proximity plays an important indirect role in overcoming possible difficulties due to a lack of other forms of proximities. This provides an explanation for the common observation that knowledge spillovers through a similar spillover mechanism can simultaneously occur at different spatial scales. These results suggest that the empirical application of the 'proximity-framework' can increase the understanding of the circumstances under which geographical proximity plays an important role for knowledge spillovers. Moreover, it shows that geographical proximity is neither necessary nor sufficient for knowledge spillovers to occur (Boschma, 2005).

Second, this study is among the first to include information on the pattern of one of the mechanisms of knowledge spillovers in a knowledge production function analysis (the first was Maggioni et al., 2007). In earlier studies, localised knowledge spillover effects could be detected, but the mechanisms underlying these spillovers remained unknown. The results of chapter six show that the use of empirical data on spillover mechanisms to construct a weight matrix – here, research collaboration – is a promising way to tackle this problem.

Third, this study provides a possible explanation for the lack of consensus in the empirical literature on the spatial range of knowledge spillovers as shown in several overviews (see Audretsch and Feldman, 2004; Döring and Schnellenbach, 2006). The geographical dimension of knowledge spillovers is related to how geographical proximity influences the occurrence and intensity of the mechanisms underlying these spillovers. This study showed that the role of geographical proximity can be very different across the various spillover mechanisms. The relative importance of different spillover mechanisms within a specific industry therefore indirectly influences the spatial range of knowledge spillovers in this industry. In the case of science-based industries, this leads to the simultaneous presence of localised knowledge spillovers through mechanisms such as informal knowledge exchange and the presence of knowledge spillovers over longer distances through collaborative research. The different role of geographical proximity between spillover mechanisms is therefore likely to explain the somewhat paradoxical spatial concentration of science-based industries in a limited number of regions in combination with the important role of knowledge flows at the national and international level as described by Bathelt et al. (2004), Gertler and Levitte (2005) and Cooke (2006), among others.

8.4 Policy implications

This study shows that, in case of science-based industries, university-industry collaboration constitutes an important mechanism for knowledge spillovers, which seems to justify the increasing attention of policymakers on research collaboration. As argued in the introduction, cluster policies for science-based industries are often aimed at stimulating collaboration and knowledge exchange networks between firms, universities, and other research organisations. However, geographical proximity plays a role for knowledge spillovers to the extent that it facilitates the underlying mechanisms. This study shows that different spillover mechanisms take place at different spatial scales and are not limited to the regional level. Innovation policies need to address the presence of multiple spillover mechanisms occurring at multiple spatial scales. Selecting a limited number of regions to stimulate high-tech clusters, as in the case of the Peaks in the Delta program in the Netherlands (Ministry of Economic Affairs, 2004), neglects the multi-level nature of the geography of knowledge spillovers.

In the Netherlands, it is shown that the national and international scales are more important for research collaboration than the regional scale. The stimulation of research collaboration in science-based industries should therefore not be restricted to specific regions or a specific spatial scale. Subsidies for collaboration at specific spatial scales might even induce undesired effects if organisations are drawn towards less valuable collaboration partners due to these subsidies. It is unlikely that the best partners for collaboration are found at the spatial scale for which these subsidies were designated. Consequently, if research collaboration is to be stimulated, it should be done without limitations towards the location of the partner, even if this implies that portions of these subsidies go to organisations located outside the region or country.[72]

Regarding the role of universities for regional innovation, the idea of a university as a regional booster for innovation needs to be qualified for two reasons. First, although regions seem to benefit from the presence of a university, geographical proximity is not a necessary condition for knowledge spillovers. Academic knowledge spillovers occur over longer distances, thereby generating additional benefits for other regions. Given the large geographical range of knowledge spillovers from academic research, the national scale seems more appropriate than the regional scale if such spillovers are to be stimulated. Furthermore, geographical proximity is not a sufficient condition for knowledge spillovers. The geographical co-location of firms, universities, and other research organisations does not automatically lead to knowledge spillovers. Stimulating geographical co-location, e.g. in the form of science-parks, to stimulate knowledge exchange and research collaboration is based on a rather simplistic view on the role of geographical proximity for knowledge spillovers.[73] Universities cannot be considered to have automatically positive impact on the innovation of nearby firms. Although universities can generate important spillover effects for some regional firms in specific industries, many other regional firms are likely not to benefit at all.

8.5 Limitations of this study and future research directions.

This study contributes to the understanding of the role of geographical proximity for knowledge spillovers, but it also has limitations. Some of these limitations serve as possible starting points for future research in this area. In this section, the most important limitations of this study are discussed. Based on these limitations, several suggestions for future research are given.

This study focused on science-based industries where collaboration is an important mechanism for knowledge spillovers. Since research collaboration is less influenced by geographical proximity than other spillover mechanisms such as labour mobility and spin-offs, knowledge spillovers in these industries may not be as localised as in other industries. It remains unclear to what extent the results of this study can be generalized to other industries. It is likely that the relative importance of different spillover mechanisms varies across industries. For example, it is often suggested that in knowledge-intensive services such as financial services, informal face-to-face meetings are important mechanisms for knowledge spillovers, leading in a strong concentration of

72 Without a doubt, this is unlikely to be welcomed by politicians or policymakers, as illustrated by the following example in Nooteboom and Stam (2008 p.350): 'The University of Hasselt, in Belgium, cooperated with the University of Maastricht, in the Netherlands, in the development of an instrument to measure a plant's vitality by the state of it schlorophyll, and they needed a development subsidy. Dutch authorities did not want to subsidize cross-border collaboration, and, likewise, Belgian authorities required subsidies to be spent only on Belgian firms and institutes' (Financieele Dagblad 2007).

73 Regional policies in science-based industries have been proven to be difficult. Such policies 'recall many not-so-distant and unfortunate experiences with science parks, growth poles and the likes' (Breschi and Lissoni, 2001b p. 977).

these industries in particular places within large cities. Similarly, the relative importance of different spillover mechanisms might vary across countries. Labour mobility might be less important as a spillover mechanism in countries with strict secrecy and disclosure rules in labour contracts. Consequently, there is a need to compare different types of industries and countries in a systematic way regarding the relative importance of different spillover mechanisms and the role of geographical proximity for each.

This study focused mainly on collaborative research as a mechanism for knowledge spillovers, but it was shown in chapters six and seven that mechanisms other than research collaboration were also important. The analysis in chapter six grouped these under the heading of localised spillovers without providing insights into the actual underlying mechanisms. Ideally, all different spillover mechanisms and their geographical dimensions are identified, measured, and related to patterns of innovation. An interesting future direction of research built upon the knowledge production function approach might be the incorporation of patterns of labour mobility and other mechanisms. In a somewhat paradoxical way, one can argue that the ultimate goal of an approach that incorporates the geographical dimension of different spillover mechanisms into an empirical model is to render the remaining geographically localised spillovers an insignificant factor by explicitly incorporating all relevant spillover mechanisms.

Chapter four showed that the international level is at least as important as the national level for research collaboration in science-based industries. Nonetheless, this study mainly focused on the national level. Consequently, no attention has been paid to the effect of possible international knowledge spillovers, which are likely to play an important role for small countries such as the Netherlands. The Netherlands is sometimes even considered to function as one economic entity, referred to as an urban field. Although this does not seem to be the case regarding innovation in science-based industries, it is necessary to bear in mind that the conclusions drawn here about the role of geographical proximity for research collaboration are largely based on the Netherlands. Similar analyses in larger countries or at the international level might lead to somewhat different conclusions. To draw decisive conclusions about the role of geographical proximity for collaborative research, comparing outcomes of similar analyses to the conclusions of this study is necessary. Related research on this topic is slowly emerging (see Hoekman et al., 2008).

Collaborative research is measured using the number of co-publications in this study. This indicator is widely used and generally considered to be a very good, if not the best, indicator of research collaboration (Katz and Martin, 1997). This seems to be further confirmed by a recent empirical study based on a questionnaire given to researchers in both public and private R&D facilities by Goddard and Isabelle (2006). This study shows that joint publications are the most important by-product of collaborative research between firms and academic research organisations and can consequently be considered as one of the most reliable indicators of collaborative research. Nevertheless, the use of co-publications is likely to underestimate inter-firm research collaboration. Although chapters four and five showed that co-publications between firms also occur, research collaboration between firms is less likely to result in a scientific co-publication. This is related to the lower incentive that firms have to publish their research results compared to academic research organisations. As an alternative, data on R&D alliances and research joint ventures might be collected from systematic tracking of public announcements of these forms of collaborative research. Although this is potentially a better indicator than co-publications for inter-firm collaboration, it suffers from a lack of consistency resulting from the wide variety of collaborations that form the basis of these announcements. There does not seem to be a specific reason to assume that there is a geographical bias in the likelihood that collaborative research between firms leads to co-publication. Therefore, it can be assumed that the possible under-estimation of inter-firm collaboration does not affect the results of this study. However, it implies that future studies on inter-firm knowledge spillovers through collaborative research should ideally combine both types of indicators. Moreover, future studies using co-publications might consider the use of citations to differentiate the weight attached to individual collaborations derived from the use of this data.

The largest part of this study, with the exception of chapter four, is based on a static, cross-sectional regression research design. Although this provides valuable contributions to understanding the relationship between geographical proximity and knowledge spillovers, future research in this area should include a dynamic perspective. Three related and important research directions can be identified in this regard.

The first concerns possible changes in the role of geographical proximity in knowledge spillovers over time. The results of chapter four suggest that the relative importance of geographical proximity for collaborative research remained more or less the same between 1988 and 2004. It might be that the time period is too short or that research collaboration is a distinct case. It seems very unlikely that the role of geographical proximity did not change with the rise of ICT possibilities and the decline of transportation costs. Not much is known, however, about the possible changing role of geographical proximity over time for collaborative research or for other mechanisms of knowledge spillovers.

The second important research direction concerns the analysis of the relative importance of different knowledge spillover mechanisms relative to the product life cycle of industries and technologies. It can be assumed that some mechanisms such as spin-off dynamics might be more important in the early stages of a new technology or industry, whereas other mechanisms might become more important in later stages (see Neffke et al., 2008).

The third research direction is related to the second and focuses on the relative importance of knowledge spillovers as possible drivers for the growth of agglomerations. This can be considered an important element of the broader research agenda in the field of regional and urban economics and regional science. This research agenda consists of the analysis of the relative importance of different agglomeration externalities, including knowledge spillovers, for the existence, growth, and the decline of agglomerations of economic activities.

List of references

Abramowitz, M. and P. A. David. (1996) Measuring performance of knowledge-based economy. In: OECD. Employment and growth in the knowledge-based economy: 35-60. Paris: OECD.

Abreu, M., H. de Groot and R. Florax (2005) Space and growth: a survey of empirical evidence and methods. Region ét Development 21: 13-44.

Acs, Z.J. (2002) Innovation and the growth of cities. Cheltenham: Edward Elgar.

Acs, Z.J., L. Anselin and A. Varga (2002) Patents and innovation counts as measures of regional production of new knowledge. Research Policy 31(7): 1069-1085.

Acs, Z.J. and D.B. Audretsch (1988) Innovation in large and small firms: an empirical analysis. American Economic Review 78: 678-690.

Acs, Z.J and D.B. Audretsch (1990) Innovation and small firms. Cambridge: MIT Press.

Acs, Z.J., D.B. Audretsch, P. Braunerhjelm and B. Carlsson (2005) The knowledge spillover theory of entrepreneurship. CEPR Discussion Papers 5326. London: Centre for Economic Policy Research.

Acs, Z.J., D.B. Audretsch and M. P. Feldman (1992) Real effects of academic research: comment. American Economic Review 82 (1): 363-367.

Acs, Z.J. and A. Varga (2002) Geography, endogenous growth and innovation. International Regional Science Review 25: 132-148.

Adams, J.D (2002) Comparative localisation of academic and industrial spillovers. Journal of Economic Geography 2: 253-278.

Agarwal, R., R. Echambadi, A.M. Franco and M.B. Sarkar (2004) Knowledge transfer through inheritance: spin-out generation, development and survival. Academy of Management Journal 47: 501-522.

Aghion, P. and P. Howitt (1992) A model of growth through creative destruction. Econometrica 60: 323-351.

Agrawal, A., I.M. Cockburn and J. McHale (2006) Gone but not forgotten: labour flows, knowledge spillovers, and enduring social capital. Journal of Economic Geography 6 (5): 571-591.

Agrawal, A., D. Kapur and J. McHale (2008) How do spatial and social proximity influence knowledge flows? Evidence from patent data. Journal of Urban Economics 64 (2): 258-269.

Alcácer, J. and M. Gittelman (2006) Patent citations as a measure of knowledge flows: the influence of examiner citations. The Review of Economics and Statistics 88(4): 774-779.

Allen, R.C. (1983) Collective invention. Journal of Economic Behaviour and Organisation 4: 1-24.

Allison, P.D. and R.P. Waterman (2002) Fixed-effects negative binomial regression models. Sociological Methodology 32: 247-265.

Almeida, P. and B. Kogut (1997) The exploration of technological diversity and the geographic localisation of innovation. Small Business Economics 9(1): 21-33.

Almeida, P. and B. Kogut (1999) Localisation of knowledge and the mobility of engineers in regional networks. Management Science 45: 905-916.

Amin, A. and N. Thrift (1995) Globalisation, institutional thickness and the local economy. In: Healey P., S. Cameron, S. Davoudi, S. Graham and A. Madani-Pour (eds.) Managing Cities, the New Urban Context: 91-108. Chichester: Wiley.

Andersson, M. and U. Grasjo (2008) Spatial dependence and the representation of space in empirical models. Annals of Regional Science: forthcoming.

Andersson, M. and C. Karlsson (2007) Knowledge in regional economic growth – the role of knowledge accessibility. Industry and Innovation 14 (2): 129-149.

Andersson, R., J.M. Quigley and M. Wilhelmson (2004) University decentralization as regional policy: the Swedish experiment. Journal of Economic Geography 4: 371-388.

Anselin, L. (1998) Spatial Econometrics: Methods and Models. Dordrecht: Kluwer.

Anselin, L., A. Varga and Z.J. Acs (1997) Local geographical spillovers between university research and high technology innovations. Journal of Urban Economics 42: 422-448.

Anselin, L., A. Varga and Z.J. Acs (2000) Geographic and sectoral characteristics of academic knowledge externalities. Papers in Regional Science 79: 435-445.

Archibugi, D. and S. Iammarino (1999) The policy implications of the globalisation of innovation. Research Policy 28: 317-336.

Archibugi, D. and J. Michie (1997) Technological globalization or national systems of innovation. Futures 29 (2): 121-137.

Armington C. and Z.J. Acs (2002) The determinants of regional variation in new firm formation. Regional Studies 36(1): 33-45.

Arrow, K. (1959) Economic welfare and the allocation of resources for invention. Rand research paper 1856. Santa Monica: Rand Corporation.

Arrow, K. (1962a) The economic implications of learning by doing. Review of Economic Studies 29: 155-173.

Arrow, K. (1962b) Classificatory notes on the production and transmission of technological knowledge. American Economic Review 59(2): 29-35.

Arthur, W.B. (1994) Increasing returns and path dependence in the economy. Ann Arbor: University of Michigan Press.

Audretsch, D.B. (1998) Agglomeration and the location of innovative activity. Oxford Review of Economic Policy 14(2): 18-29.

Audretsch, D.B. and M.P. Feldman (1996) R&D spillovers and the geography of innovation. American Economic Review 86: 630-640.

Audretsch D.B. and M.P. Feldman. (2004) Knowledge spillovers and the geography of innovation. In: Henderson, J.V. and J.F. Thisse (eds.) Handbook of Urban and Regional Economics 4: 2713-2739. Amsterdam: Elsevier.

Audretsch, D.B. and E. Lehmann (2005) Does the knowledge spillover theory of entrepreneurship hold for regions. Research Policy 34:1191-1202.

Audretsch D.B. and P. Stephan (1996) Company-scientist locational links: the case of biotechnology. The American Economic Review 86 (3): 641-652.

Autant-Bernard, C. (2001) Science and knowledge flows: evidence from the French case. Research Policy 30(7): 1069-1078.

Bathelt, H., A. Malmberg and P. Maskell (2004) Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. Progress in Human Geography 28 (1): 31-56.

Bell, G.G. and A. Zaheer (2007) Geography, networks and knowledge flow. Organisation Science 18: 955-972.
Biopartner (2005) The Netherlands life sciences sector report 2005. The Hague: Biopartner.
Bode, E. (2004) The spatial pattern of localised R&D spillovers: an empirical investigation for Germany. Journal of Economic Geography 4: 43-64.
Boix, R. and J. Trullen (2007) Knowledge, networks of cities and growth in regional urban systems. Papers in Regional Science 86(4): 551-574.
Boschma, R.A. (2005) Proximity and innovation: a critical assessment. Regional Studies 39(1): 61-74.
Boschma, R.A., R. Eriksson and U. Lindgren (2008) Labour mobility, related variety and the performance of plants: a Swedish study. Forthcoming in: Journal of Economic Geography.
Boschma, R.A. and K. Frenken (2006) Why is economic geography not an evolutionary science? Towards an evolutionary economic geography. Journal of Economic Geography 6(3): 273-302.
Boschma, R.A. and A.L.J. ter Wal (2007) Knowledge networks and innovative performance in an industrial district: the case of a footwear district in the South of Italy. Industry and Innovation 14 (2): 177-199.
Boschma, R.A. and R. Wenting (2007) The spatial evolution of the British automobile industry: does location matter? Industry and Corporate Change 16 (2): 213-238.
Botazzi, L. and G. Peri (2003) Innovation and spillovers in regions: evidence from European patent data. European Economic Review 47: 687-710.
Breschi, S. and F. Lissoni (2001a) Localised knowledge spillovers vs. innovative milieux: knowledge 'tacitness' reconsidered. Papers in Regional Science 80(3): 255-273.
Breschi, S. and F. Lissoni (2001b) Knowledge spillovers and local innovation systems: a critical survey. Industrial and Corporate Change 10: 975-1005.
Breschi, S. and F. Lissoni (2003) Mobility and social networks: localised knowledge spillovers revisited. CESPRI Working Paper 142. Milan: Bocconi University.
Breschi, S. and F. Lissoni (2006) Mobility of inventors and the geography of knowledge spillovers. New evidence on US data. CESPRI Working Paper 184. Milan: Bocconi University.
Breschi, S. and F. Malerba (2001) The geography of innovation and economic clustering: some introductory notes. Industrial and Corporate Change 10(4) 817-833.
Bresnahan, T. F. and M. Trajtenberg (1995) General purpose technologies 'engines of growth'? Journal of Econometrics 65(1): 83-108.
Brouwer, E., H. Budil-Nadvornikova and A. Kleinknecht (1999) Are urban agglomerations a better breeding place for product innovation? An analysis of new product announcements. Regional Studies 33 (6): 541-549.
Buenstorf, G. and S. Klepper (2005). Heritage and agglomeration: The akron tire cluster revisited. Papers on Economics and Evolution 0508. Jena: Max Planck Institute of Economics.
Bunnell, T.G and N.M. Coe (2001) Spaces and scales of innovation. Progress in Human Geography 25: 569-589.
Caloghirou, Y., A. Tsakanikas and N.S. Vonortas (2001) University-industry cooperation in the context of the European framework programmes. Journal of Technology Transfer 26: 153-161.
Camagni, R. (1991) Innovations networks: spatial perspectives. London: Belhaven.

Cameron, A. and P. Trivedi (1998) Regression analysis of count data. Cambridge and New York: Cambridge University Press.
Caniels, M. and H. Romijn (2003) Agglomeration advantages and capability building in industrial clusters: the missing link. The Journal of Development Studies 39(3): 129-154.
Canton, E., D. Lanser, J. Noailly, M. Rensman and J. Van de Ven (2005) Crossing borders; when science meets industry. The Hague: Netherlands Bureau for Economic Policy Analysis (CPB).
Carlino, G.A., S. Chatterjee and R.M. Hunt (2007) Urban density and the rate of invention. Journal of Urban Economics 61(3) 389-419.
Carlsson, B. (2006) Internationalisation of innovation systems: a survey of the literature. Research Policy 35 (1): 56-67.
Chung, S. (2002) Catching up through international linkages: science, technology and the Korean experience. Science and Public Policy 29 (6): 431-437.
Cockburn, I.A. and R.M. Henderson (1998) Absorptive capacity, coauthoring behavior, and the organisation of research in drug discovery. Journal of Industrial Economics 46 (2): 157-182.
Coenen, L., J. Moodysson and B.T. Asheim (2004) Nodes, networks and proximities: on the knowledge dynamics of the Medicon Valley biotech cluster. European Planning Studies 12: 1003-1018.
Cohen, W.M. and D.A. Levinthal (1990) Absorptive capacity: a new perspective on learning and innovation. Administrative Science Quarterly 35 (1): 128-152.
Cohen, W.M., R.R. Nelson and J.P. Walsh (2000) Protecting their intellectual assets: appropriability conditions and why U.S. manufacturing firms patent (or not). NBER Working Paper 7552. Washington: National Bureau of Economic Research (NBER).
Cohen, W.M., R.R. Nelson and J.P. Walsh (2002) Links and impacts: the influence of public research on industrial R&D. Management Science 48(1): 1-23.
Cohendet, P. and P. Llerena (2003) Routines and incentives: the role of communities in the firm. Industrial and Corporate Change 12: 271-297.
Combes, P.P and G. Duranton (2006) Labour pooling, labour poaching, and spatial clustering. Regional Science and Urban Economics 36(1): 1-28.
Combes, P.P. and H. Overman (2004) The spatial distribution of economic activities in the European Union. In: Henderson, J.V. and J. F. Thisse (eds.) Handbook of Regional and Urban Economics 1 (4): 2845-2909. Amsterdam: Elsevier.
Cooke, P. (2001) New economy innovation systems: biotechnology in Europe and the USA. Industry and Innovation 8: 267-289.
Cooke, P. (2005) Rational drug design, the knowledge value chain and bioscience megacentres. Cambridge Journal of Economics 29: 235-341.
Cooke, P. (2006) Global bioregional networks: a new economic geography of bioscientific knowledge. European Planning Studies 14: 1266-1285.
Cooke, P., M.G. Uranga and G. Etxebarria (1997) Regional innovation systems: institutional and organisational dimensions. Research Policy 26: 475-491.
Cörvers, F., M. Hensen and D. Bongaerts (2008) Delimitation and coherence of functional and administrative regions. Forthcoming in: Regional Studies.
Cowan, R., P.A. David and D. Foray (2000) The explicit economics of knowledge codification and tacitness. Industrial and Corporate Change 9 (2): 211-253.

Crescenzi, R., A. Rodriguez-Pose and M. Storper (2007) The territorial dynamics of innovation: a Europe-United States comparative analysis. Journal of Economic Geography 7: 673-709.
Criscuolo, P. and B. Verspagen, B. (2008) Does it matter where patent citations come from? Inventor vs. examiner citations in European patents. Forthcoming in: Research Policy.
Dahl, M.S. and C.Ø.R. Pedersen (2004) Knowledge flows through informal contacts in industrial clusters: myth or reality? Research Policy 33: 1673-1686.
Dahl, M.S. and O. Sorenson (2007) Home sweet home: social capital and location choice. Paper presented at the Academy of Management Annual Meeting 2007, Philadelphia USA.
Dalgin, M., V. Trindade and D. Mitra (2008) Inequality, nonhomothetic preferences, and trade: a gravity approach. Southern Economic Journal 74(3): 747-774.
Dasgupta, P. and P.A. David (1994) Toward a new economics of science. Research Policy 23: 487-521.
Del Barrio-Castro, T. and J.A. Garcia-Quevedo (2005) Effects of university research on the geography of innovation. Regional Studies 39(9):1217-1229.
DeSolla Price, D. (1984) The science/technology relationship, the craft of experimental science, and policy for the improvement of high technology innovation. Research Policy 13: 3-20.
Dixit, A. and J. Stiglitz (1977) Monopolistic competition and optimum product diversity. American Economic Review 67: 297-308.
Döring, T. and J. Schnellenbach (2006) What do we know about geographical knowledge spillovers and regional growth?: A survey of the literature. Regional Studies 40 (3): 375-395.
Edler, J. (2008) Creative internationalisation: widening the perspectives on analysis and policy regarding international R&D activities. Journal of Technology Transfer 33 (4): 337-352.
Edler, J. and P. Boekholt (2001) Benchmarking national public policies to exploit international science and industrial research: a synopsis of current developments. Science and Public Policy 28 (4): 313-321.
Etzkowitz, H. and L. Leydesdorff (1997) Universities and the global knowledge economy: a triple helix of university-industry-government relations. London: Pinter.
Etzkowitz, H. and L. Leydesdorff (2000) The dynamics of innovation: from national systems and 'mode 2' to a triple helix of university-industry-government relations. Research Policy 29(2): 109-123.
Etzkowitz, H., A. Webster, C. Gebhardt and B.R.C. Terra (2000) The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. Research Policy 29: 313-330.
Fallick, B., C.A. Fleischman and J.B. Rebitzer (2006) Job-hopping in Silicon Valley: some evidence concerning the microfoundations of a high-technology cluster. The Review of Economics and Statistics 88 (3) 472-481.
Faulconbridge, J.R. (2006) Stretching tacit knowledge beyond a local fix? Global spaces of learning in advertising professional service firms. Journal of Economic Geography 6: 517-540.
Feldman, M.P. (1999) The new economics of innovation, spillovers and agglomeration: a review of empirical studies. Economics of Innovation and New Technology 8: 5-25.

Fischer P.A., E. Holm, G. Malmberg and T. Straubhaar (1998) Why do people stay? The insider-advantages approach: empirical evidence from Swedish labour markets. CEPR discussion paper 1952. London: Centre for Economic Policy Research (CEPR).
Fischer, M. and A. Varga (2003) Spatial knowledge spillovers and university research: evidence from Austria. The Annals of Regional Science 23: 303-322.
Florax, R.J.G.M. (1992) The university: a regional booster? Economic impacts of academic knowledge infrastructure. Ashgate: Aldershot.
Florax, R.J.G.M. and H. Folmer (1992) Knowledge impacts of universities on industry: an aggregate simultanous investment model. Journal of Regional Science 32(4): 437-466.
Foray, D. and B.A. Lundvall (1996) The knowledge-based economy: from the economics of knowledge to the learning economy. In: OECD Documents: Employment and Growth in the Knowledge-based Economy: 11-32. Paris: OECD.
Fornahl, D. and H. Graf (2003) Standortfaktoren und Gründungsaktivitäten in Jena. In: Cantner U., R. Helm and R. Meckl (eds.) Strukturen und Strategien in einem Innovationssystem: Das Beispiel Jena: 97-123. Sternenfels: Verlag Wissenschaft & Praxis.
Frankel, J.A. and D. Romer (1999) Does trade cause growth? American Economic Review 89(3): 379-399.
Frenken, K. (2002) A new indicator of European integration and an application to collaboration in scientific research. Economic Systems Research 14(4): 345-361.
Frenken, K., J. Hoekman, F.G. van Oort (2007) Towards a European Research Area. Rotterdam/The Hague: NAi Publishers/RPB.
Frenken, K., W. Hölzl and F. de Vor (2005) The citation impact of research collaborations: the case of European biotechnology and applied microbiology (1988-2002). Journal of Engineering and Technology Management 22: 9-30.
Frenken, K. and F.G. Van Oort (2004) The geography of research collaboration: theoretical considerations and stylised facts in biotechnology in Europe and the United States. In: Cooke, P. and A. Piccaluga (eds.) Regional Economies as Knowledge Laboratories: 38-57. Cheltenham UK and Northampton MA: Edward Elgar.
Fritsch, M. (2001) Co-operation in regional innovation systems. Regional Studies 35(4): 297-307.
Fritsch, M. and V. Slavtchev (2007) Universities and innovation in space. Industry and innovation, 14(2): 201-218.
Gambardella, A., D. Harhoff and B. Verspagen (2008) The value of patents. European Management Review 5: 69-84.
Gertler, M. (2003) Tacit knowledge and the economic geography of context, or The undefinable tacitness of being (there). Journal of Economic Geography 3: 75-99.
Gertler, M. and Y.M. Levitte (2005) Local nodes in global networks: the geography of knowledge flows in biotechnology innovation. Industry and Innovation 12: 487-507.
Gibbons, M., C. Limoges, H. Nowotny, S. Schwartzman, P. Scott and M. Trow (1994) The new production of knowledge: the dynamics of science and research in contemporary societies. London: Sage.
Gittelman, M. and B. Kogut (2003) Does good science lead to valuable knowledge? Biotechnology firms and the evolutionary logic of citation patterns. Management Science 49 (4): 366 -382.
Giuliani, E. (2007) The selective nature of knowledge networks in clusters: evidence from the wine industry. Journal of Economic Geography 7: 139-168.

Glänzel, W. (2001) National characteristics in international scientific co-authorship relations. Scientometrics 51: 69-115.
Glänzel, W. and A. Schubert (2004) Analysing scientific networks through co-authorship. In: Moed, H., W. Glänzel and U. Schmoch (eds.) Handbook of quantitative science and technology research: the use of publication and patent statistics in studies of S&T systems: 257-276. Dordrecht: Kluwer.
Goddard, J.G. and M. Isabelle (2006) How do public laboratories collaborate with industry? New survey evidence from France. Working Paper Series 2006/02. Paris: Imri – Université Paris Dauphine.
Godin, B. (1995) Research and the practice of publication in industries. Research Policy 25: 587-606.
Godin, B. and Y. Gingras (2000) The place of universities in the system of knowledge production. Research Policy 29 (2): 273-278.
Gomes-Casseres, B., J. Hagedoorn and A.B Jaffe (2006) Do alliances promote knowledge flows? Journal of Financial Economics 80(1) 5-33.
Gordon, I.R. and I. Molho (1995) Duration dependence in migration behaviour: cumulative inertia versus stochastic change. Environment and Planning A 27: 1961-1975.
Gordon, M.D. (1980) A critical reassessment of inferred relations between multiple authorship, scientific collaboration, the production of papers and their acceptance for publication. Scientometrics 2: 193-210.
Granovetter, M. (1973) The strength of weak ties. American Journal of Sociology 78 (6): 1360-1380.
Greunz, L. (2003) Geographically and technologically mediated knowledge spillovers between European regions. Annals of Regional Science 37: 657-680.
Griliches, Z. (1979) Issues in assessing the contribution of research and development to productivity growth. Bell Journal of Economics 10: 92-116.
Griliches, Z. (1984) R&D, patents, and productivity. Chicago: University of Chicago Press.
Griliches, Z. (1990) Patent statistics as economic indicators: a survey. Journal of Economic Literature 28: 1661-1707.
Groot, de H., P. Nijkamp and Z.J. Acs (2001) Knowledge spillovers, innovation and regional development. Papers in Regional Science 80: 249-253.
Grossman, G.M and E. Helpman (1991) Innovation and growth in the global economy. Cambridge, Massachusetts: MIT press.
Hagedoorn, J. (2002) Inter-firm R&D partnerships: an overview of major trends and patterns since 1960. Research Policy 31: 477-492.
Hagedoorn, J., A.N. Link and N.S. Vonortas (2000) Research partnerships. Research Policy 4-5: 567-586.
Hagedoorn, J. and J. Schakenraad (1990) Inter-firm partnerships and cooperative strategies in core technologies. In: Freeman, C. and L. Soete (Eds.) New Explorations in the Economics of Technological Change: 3-38. London: Pinter Publishers.
Hägerstrand, T. (1953). Innovationsförloppet ur korologisk synpunkt. Lund: C.W.K Gleerup. Translated as: Hägerstrand, T. (1967) Innovation diffusion as a spatial process. Chicago: University of Chicago Press.
Hanes, L. (2001) Spatial spillover effects in the Swedish local rescue services. Regional Studies 36(5): 531-539.
Harrison, B. (1992) Industrial districts: old wines in new bottles. Regional Studies 26: 469-483.

Hausman, J., B.H. Hall and Z. Griliches (1984) Econometric models for countdata with an application to the patents-R&D relationship. Econometrica 59: 909-938.
Helpman, E. (1998) General purpose technologies and economic growth. Cambridge, Massachusetts: MIT press.
Helsley, R.W. and W.C. Strange (1990) Matching and agglomeration economies in a system of cities. Regional Science and Urban Economics 20(2): 189-212.
Henderson, R., A.B. Jaffe and M. Trajtenberg (2005) Patent citations and the geography of knowledge Spillovers: a reassessment: comment. American Economic Review 95(1): 461-464.
Hoekman, J., K. Frenken and F.G. Van Oort (2008) The geography of collaborative knowledge production in Europe. Forthcoming in: Annals of Regional Science.
Howells, J.R.L. (2002) Tacit knowledge, innovation and economic geography. Urban Studies 39 (5): 871-884.
Huber, F. (2007) Social networks and knowledge spillovers. Networked knowledge workers and localised knowledge spillovers. Frankfurt am Main: Peter Lang.
Hussler, C. and P. Ronde (2007) The impact of cognitive communities on the diffusion of academic knowledge: Evidence from the networks of inventors of a French university. Research Policy 36(2): 288-302.
Jacobs, J. (1969) The economy of cities. New York: Vintage.
Jaffe, A.B. (1989) Real effects of academic research. American Economic Review 79 (5): 957-970.
Jaffe, A.B., M.S. Fogarty and B.A. Banks (1998) Evidence from patents and patent citations on the impact of NASA and other federal labs on commercial innovation. Journal of Industrial Economics 46 (2): 183-206.
Jaffe, A.B. and M. Trajtenberg (2002) Patents, citations and innovations. A window on the knowledge economy. Cambridge: MIT Press.
Jaffe, A.B., M. Trajtenberg M. and R. Henderson (1993) Geographic localisation of knowledge spillovers as evidenced by patent citations. Quarterly Journal of Economics 108: 577-598.
Johnson, D.K.N, A. Siripong and A.S. Brown (2006) The demise of distance? The declining role of physical proximity for knowledge transmission. Growth and Change 37 (1): 19-33.
Katz, J.S. (1994) Geographical proximity and scientific collaboration. Scientometrics 31: 31-43.
Katz, J.S. and B.R. Martin (1997) What is research collaboration? Research Policy 26 (1): 1-18.
Kleinknecht, A., K. van Montfort and E. Brouwer (2002) The non-trivial choice between innovation indicators. Economics of Innovation and New Technology 11: 109-121.
Klepper, S. (2001) Employee startups in high-tech industries. Industrial and Corporate Change 10(3): 639-674.
Klepper, S. (2007) Disagreements, spinoffs, and the evolution of Detroit as the capital of the U.S. automobile industry, Management Science, 53(4): 616-631.
Klepper, S. and S.D. Sleeper (2005) Entry by spinoffs. Management Science 51(8): 1291-1306.
Klevorick, A.K., R.C. Levin, R.R. Nelson and S.G. Winter (1995) On the sources and significance of interindustry differences in technological opportunities. Research Policy 24 (2): 185-205.
Knight, F.H. (1921) Risk, uncertainty and profit. Boston: Houghton Mifflin.

Knoben, J. and L. Oerlemans (2006) Proximity and inter-organisational collaboration: a literature review. International Journal of Management Reviews 8 (2): 71-89.
Krugman, P. (1991) Geography and trade. Cambridge: MIT Press.
Laudel, G. (2001) Collaboration, creativity and rewards: why and how scientists collaborate. Journal of Technology Management 22 (7-8): 762-781.
Leenders, R. (2002) Modelling social influence through network autocorrelation: contructing the weight matrix. Social Networks 24: 21-47.
Levy, R., P. Roux and S. Wolff (2008) An analysis of science-industry collaborative patterns in a large European university. Forthcoming in: Journal of Technology Transfer.
Liang, L. and L. Zhu (2002) Major factors affecting China's inter-regional research collaboration: regional scientific productivity and geographical proximity. Scientometrics 55 (2): 287-316.
Lin, G. and T. Zhang (2007) Loglinear residual tests of Moran's I autocorrelation and their applications to Kentucky breast cancer data. Geographical Analysis 39: 293-310.
Lindgren, U. and R. Eriksson (2008) Localised mobility clusters: impacts of labour market externalities on firm performance. Forthcoming in: Journal of Economic Geography.
Lissoni, F. (2001) Knowledge codification and the geography of innovation: the case of Brescia mechanical cluster. Research Policy 30(9): 1479-1500.
Long, J.S. (1997) Regression models for categorical and limited dependent variables. Thousand Oaks: Sage.
Long, J.S. and J. Freese (2003) Regression models for categorical dependent variables using stata. College Station: Stata Press.
Lucas, R.E.B. (1988) On the mechanics of economic development. Journal of Monetary Economics 22: 3-42.
Lundberg, J., G. Tomson, I. Lundkvist, J. Skar and M. Brommels (2006) Collaboration uncovered: exploring the adequacy of measuring university-industry collaboration through co-authorship and co-funding. Scientometrics 69 (3): 575-589.
Luukkonen, T., O. Persson and G. Sivertsen (1992) Understanding patterns of international scientific collaboration. Science, Technology and Human Values 17(1): 101-126.
Luukkonen, T., R.J.W. Tijssen, O. Persson and G. Sivertsen (1993) The measurement of international scientific collaboration. Scientometrics 28: 15-36.
Maggioni, M.A., M. Nosvelli and T.E. Uberti (2007) Space versus networks in the geography of innovation. A European analysis. Papers in Regional Science 86 (3): 471-494.
Maggioni, M.A. and T.E. Uberti (2007) International networks of knowledge flows: an econometric analysis. In: Frenken, K. (eds) Applied Evolutionary Economics and Economic Geography: 230-255. Cheltenham: Edward Elgar.
Malerba, F. (2005) Sectoral systems: how and why innovation differs across industries. In: Fagerberg, J., D.C. Mowery and R.R. Nelson (eds.) The Oxford Handbook of Innovation: 380-406. Oxford: Oxford University Press.
Malmberg, A. and P. Maskell (2002) The elusive concept of localisation economies: towards a knowledge-based theory of spatial clustering. Environment and Planning A 34(3): 429-449.
Manski, C.F. (2000) Economic analysis of social interactions. The Journal of Economic Perspectives 14 (3): 115-136.
Markusen, A. (1996) Sticky places in slippery space: a typology of industrial districts. Economic Geography 72 (3): 293-313.

Marshall, A. (1920) Principles of economics. London: MacMillan.
Marsili, O. (2001) The anatomy and evolution of industries: technological change and industrial dynamics. Cheltenham: Edward Elgar.
Martin, R. and P. Sunley (1996) Paul Krugman's geographical economics and its implications for regional development theory: a critical assessment. Economic Geography 72 (3): 259-292.
Maurseth, P.B. and B. Verspagen (2002) Knowledge-spillovers in Europe: a patent citation analysis. Scandinavian Journal of Economics 104: 531-545.
McKelvey, M., H. Alm and M. Riccaboni (2003) Does co-location matter for formal knowledge collaboration in the Swedish biotechnology-pharmaceutical sector? Research Policy 32(3): 483-501.
Meyer, M. (2000) Does science push technology? patents citing scientific literature. Research Policy 29: 409-434.
Meyer, M., T. Sinilainen and J. Timm Utecht (2003) Towards hybrid triple helix indicators: a study of university-related patents and a survey of academic inventors. Scientometrics 58 (2): 321-350.
Meyer-Krahmer, F. and U. Schmoch (1998) Science-based technologies: university-industry interactions in four fields. Research Policy 27(8): 835-851.
Ministry of Economic Affairs (2004) Nota Pieken in de Delta; ruimtelijk economische perspectieven – Peaks in the Delta; territorial economic perspectives. The Hague: Ministry of Economic Affairs.
Ministry of Economic Affairs (2007) Evaluatie WBSO 2001-2005 (in Dutch). The Hague: Ministry of Economic Affairs.
Moen, J. (2005) Is mobility of technical personnel a source of R&D spillovers? Journal of Labour Economics 23(1): 81-114.
Moodysson, J., L. Coenen and B. Asheim (2008) Explaining spatial patterns of innovation: analytical and synthetic modes of knowledge creation in the Medicon Valley life-science cluster. Environment and Planning A 40(5): 1040-1056.
Moreno, R., R. Paci and S. Usai (2005) Spatial spillovers and innovation activity in European regions. Environment and Planning A 37: 1793-1812.
Morgan, K. (1997) The learning region: institutions, innovation and regional renewal. Regional Studies 31(5): 491-503.
Morgan, K. (2004) The exaggerated death of geography: learning, proximity and territorial innovation systems. Journal of Economic Geography 4 (1): 3-21.
Morrison, A. (2008) Gatekeepers of knowledge within industrial districts: who they are, how they interact. Regional Studies 42: 817-835.
Mowery, D.C. (1998) The changing structure of the US national innovation system: implications of international conflict and cooperation in R&D policy. Research Policy 27: 639-654.
Mowery, D.C., J.E. Oxley and B.S. Overman (1996) Strategic alliances and interfirm knowledge transfer. Strategic Management Journal 17: 77-91.
Narin, F., K. Hamilton and D. Olivastro (1997) The increasing linkage between U.S. technology and public science. Research Policy 26: 317-330.
Narin, F. and E. Noma (1985) Is technology becoming science? Scientometrics 7: 369-381.
Narin, F., K. Stevens and E.S. Whitlow (1991) Scientific cooperation in Europe and the citation of multinationally authored papers. Scientometrics 21 (3): 313-323.

Neffke, F., M. Svensson Henning, R. Boschma, K.J. Lundquist and L.O. Olander (2008). Who needs agglomeration? Varying agglomeration externalities and the industry life cycle. Papers in Evolutionary Economic Geography (PEEG) 0808. Utrecht: Utrecht University, Section of Economic Geography.
Nelson, R.R. (1959) The simple economics of basic scientific research. Journal of Political Economy 67: 297-306.
Nelson, R.R. (1982) The role of knowledge in R&D efficieny. Quarterly Journal of Economics 97 (3): 453-470.
Nelson, R.R. and S.G. Winter (1982) An evolutionary theory of economic change. Cambridge Massachusetts: Harvard University press.
Nijkamp, P. and J. Poot (1998) Spatial perspectives on new theories of economic growth. Annals of Regional Science 32: 7-37.
Niosi, J. and B. Bellon (1994) The global interdependence of national innovation systems: evidence, limits and implications. Technology in Society 16 (2): 173-197.
Nooteboom, B. (2004) Inter-firm collaboration, learning and networks; an integrated approach.London: Routledge.
Nooteboom, B. and E. Stam (2008) Micro-Foundations for Innovation Policy. Amsterdam/ Chicago: Amsterdam University Press/Chicago University Press.
Nooteboom, B., W. Vanhaverbeke, G. Duysters, V. Gilsing and A. van den Oord (2007) Optimal cognitive distance and absorptive capacity. Research Policy 36(7): 1016-1034.
OECD (1996) OECD Economic Outlook, No. 60. Paris: OECD.
OECD (2005) A framework for biotechnology statistics. Paris: OECD.
Oerlemans, L.A.G. and M.T.H Meeus (2005) Do organisational and spatial proximity impact on firm performance? Regional Studies 39(1), 89-104.
Ostry, S. and R. Nelson (1995) Techno-nationalism and techno-globalism: conflict and cooperation. Washington DC: Brookings Institution.
Overman, H. (2004) Can we learn anything from economic geography proper? Journal of Economic Geography 4 (5): 501-516.
Owen-Smith, J. and W.W. Powell (2004) Knowledge networks as channels and conduits: the effects of spillovers in the Boston biotechnology community. Organisation Science 15(1): 5-21.
Owen-Smith, J., M. Riccaboni, F. Pamolli and W.W. Powell (2002) A comparison of US and European university-industry relations in life-sciences. Management Science 48: 24-43.
Østergaard, C.R. (2007) Knowledge flows through social networks in a cluster: interfirm versus university- industry Contacts. DRUID Working Papers 07-19. Copenhagen Business School, Department of Industrial Economics and Strategy/Aalborg University, Department of Business Studies.
Paci, R. and S. Usai (2000) Technological enclaves and industrial districts: an analysis of the regional distribution of innovative activity in Europe. Regional Studies 34(2): 97-114.
Pavitt, K. (1984) Sectoral patterns of technical change: towards a taxonomy and a theory. Research Policy 13: 343-373.
Pavitt, K. (1987) The objectives of technology policy. Science and Public Policy 14 (4): 182-188.
Peri, G. (2005) Determinants of knowledge flows and their effect on innovation. The Review of Economics and Statistics 87(2): 308-322.
Polanyi, M. (1966) The tacit dimension. New York: Doubleday.

Ponds, R. (2008) The limits to internationalisation of scientific research collaboration. Forthcoming in: The Journal of Technology Transfer.
Ponds, R. and F.G. Van Oort (2008). Spatial patterns of innovation in science-based technologies in the Netherlands. Tijdschrift voor Economische en Sociale Geografie (TESG) 99, 238-247.
Ponds, R., F.G. Van Oort. and K. Frenken (2007) The geographical and institutional proximity of research collaboration. Papers in Regional Science 86: 423-443.
Poot, T. (2004) Determinanten van kennisintensieve onderzoeks- en ontwikkelingssamenwerking. Phd-thesis (in Dutch). Delft: Delft University Press.
Powell, W.W., K. Koput and L. Smith-Doerr (1996) Interorganisational collaboration and the locus of innovation: networks of learning in biotechnology. Administrative Science Quarterly 41: 116-145.
Power, D. and M. Lundmark (2004) Working through knowledge pools: labour market dynamics, the transference of knowledge and ideas, and industrial clusters. Urban Studies 41: 1025-44.
Rallet, A. and A. Torre (1999) Is geographical proximity necessary in the innovation networks in the era of global economy? Geojournal 49(4): 373-380.
Rodriguez-Pose, A. and R. Crescenzi (2008) R&D, spillovers, innovation systems and the genesis of regional growth in Europe. Forthcoming in: Regional Studies.
Roijakkers, N. and J. Hagedoorn (2006) Inter-firm R&D partnering in pharmaceutical biotechnology since 1975: trends, patterns, and networks. Research Policy 35(3): 431-446.
Romer, P. (1986) Increasing returns and long run growth. Journal of Political Economy 94: 1002-1037.
Romer, P. (1990) Endogenous technological change. Journal of Political Economy 98: 71-102.
Romer, P. (1994) The origins of endogenous growth. Journal of Economic Perspectives 8 (1): 3-22.
Rosenberg, N. (1982) Inside the black box: technology and economics. New York: Cambridge University press.
Rosenberg, N. (1990) Why do firms do basic research (with their own money)? Research Policy, 19: 165-174.
Rosenkopf, L. and P. Almeida (2003) Overcoming local search through alliances and mobility. Management Science 49 (6): 751-766.
Rosenthal, S.S. and W.C. Strange (2004) Evidence on the nature and sources of agglomeration economies. In: Henderson, J.V and J.F. Thisse (Eds.) Handbook of Urban and Regional Economics 4: 2119-2172. Amsterdam: Elsevier.
Saxenian, A.L. (1994) Regional advantage, culture and competition in Silicon Valley and Route 128. Cambridge MA: Harvard University Press.
Scherer, F.M. (1982) Inter-industry technology flows and productivity Growth. The Review of Economics and Statistics 64 (4): 627-634.
Schmoch, U. (1997) Indicators and the relations between science and technology. Scientometrics 38(1): 103-116.
Schrader, S. (1991) Informal technology transfers between firms: cooperation through information trading. Research Policy 20:153-170.
Scitovsky, T. (1952) Two concepts of external economies. Journal of Political Economy 60: 143-151.

Shane, S. and S. Venkataraman (2000) The promise of entrepreneurship as a field of research. The Academy of Management Review 25: 217-226.
Singh, J. (2005) Collaborative networks as determinants of knowledge diffusion patterns. Management Science 51(5): 756-770.
Slaughter, S. and L.L. Leslie (1997) Academic capitalism: politics, policies and the entrepreneurial university. Baltimore: The John Hopkins University Press.
Solow, R.M. (1956) A contribution to the theory of economic growth. Quarterly Journal of Economics 70: 65-94.
Sorenson, O. (2003) Social networks and industrial geography. Journal of Evolutionary Economics 13(5): 513-527.
Sorenson, O. and P.G. Audia (2000) The social structure of entrepreneurial activity: geographic concentration of footwear production in the US, 1940-1989. American Journal of Sociology 106(2): 424-461.
Sorenson, O. and J. Singh (2007) Science, social networks and spillovers. Industry & Innovation 14: 219-238.
Sorenson, O. and T.E. Stuart (2001) Syndication networks and the spatial distribution of venture capital investments. American Journal of Sociology 106 (6): 1546 -1588.
Stichweh, R. (1996) Science in the system of world society. Social Science Information 35: 327-340.
Storper, M. (1995) The resurgence of regional economies, ten years later. The region as a nexus of untraded interdependencies. European Urban and Regional Studies 2 (3): 191-221.
Storper, M. and A. Venables (2004) Buzz: face-to-face contact and the urban economy. Journal of Economic Geography 4: 351-370.
Stuart, T.E. (2000) Interorganisational alliances and the performance of firms: A study of growth and innovation rates in a high-technology industry. Administrative Science Quarterly 43: 668-698.
Stuart, T.E. and O. Sorensen (2003) The geography of opportunity: spatial heterogeneity in founding rates and the performance of biotechnology firms. Research Policy 32: 229-253.
Sung, T.K. and B. Carlsson (2003) The evolution of a technological system: the case of CNC machine tools in Korea. Journal of Evolutionary Economics 13 (4): 435-460.
Thompson, P. and M. Fox-Kean (2005a) Patent citations and the geography of knowledge spillovers: a reassessment. American Economic Review 95(1): 450-460.
Thompson, P. and M. Fox-Kean (2005b) Patent citations and the geography of knowledge spillovers: a reassessment: reply. American Economic Review 95(1): 464-465.
Tödtling, F., P. Lehner and M. Trippl (2006) Innovation in knowledge intensive industries: the nature and geography of knowledge links. European Planning Studies 14: 1035-1058.
Torre, A. and A. Rallet (2005) Proximity and localisation. Regional Studies 39(1): 47-59.
Trajtenberg, M. (1998) General purpose technologies and economic growth. Cambridge MA: MIT Press.
Uzzi, B. (1996) Social structure and competition in interfirm networks, the paradox of embeddedness. Administrative Science Quarterly 42: 35-67.
Van Ham, M., P. Hooimeijer and C.M. Mulder (2001) Urban form and job access: disparate realities in the Randstad. Tijdschrift voor Economische en Sociale Geografie (TESG) 92(2): 231-146.

Van Looy, B., E. Zimmerman, R. Veugelers, E. Verbeek, J. Mello and K. Debackere (2003) Do science-technology interactions pay off when developing technology? Scientometrics 57(3): 355-367.
Van Oort, F.G. (2004) Urban growth and innovation. Spatially bounded externalities in the Netherlands. Ashgate: Aldershot.
Varga, A. (1998) University research and regional innovation: a spatial econometric analysis. Boston: Kluwer Academic Publishers.
Varga, A. (2000) Local academic knowledge spillovers and the concentration of economic activity. Journal of Regional Science 40: 289-309.
Verbeek, A., J. Callaert, P. Andries, K. Debackere, M. Luwel and R. Veughelers (2002) Linking science to technology – bibliographic references in patents. Brussels: Report to the EC DG Research.
Verspagen, B. (1992) Endogenous innovation in neo-classical growth models: a survey. Journal of Macroeconomics 14: 631-662.
Verspagen, B. (2005) Innovation and economic growth. In: Fagerberg, J., D.C. Mowery and R.R. Nelson (eds.) The Oxford Handbook of Innovation: 487-513. Oxford: Oxford University Press.
Verspagen, B. and W. Schoenmakers (2004) The spatial dimension of multinational firm patenting in Europe. Journal of Economic Geography 4: 23-42.
Von Hippel, E. (1987) Cooperation between rivals: informal know-how trading. Research Policy 16: 291-302.
Von Hippel, E. (1994) Sticky information and the locus of problem solving. Management Science 40 (4): 429-439.
VSNU (2007) Wetenschappelijk onderwijs personeels informatie – WOPI (in Dutch). The Hague: Vereniging Samenwerkende Nederlandse Universiteiten/Association Universities the Netherlands.
Wagner, C. (2001) The elusive partnership: science and foreign policy. Science and Public Policy 29 (6): 409-417.
Wagner, C. (2005) Six case studies of international collaboration in science. Scientometrics 62 (1): 3-26.
Wagner, C., I. Brahmakalum, B. Jackson, T. Yoda and A. Wong (2001) Science & technology collaboration: building capacity in developing countries? Santa Monica: Rand Corporation.
Wagner, C. and L. Leydesdorff (2005) Mapping the network of global science comparing international co-authorships from 1990 to 2000. International Journal of Technology and Globalization 1(2): 185-208.
Wagner-Doebler, R. (2001) Continuity and discontinuity of collaboration behaviour since 1800 – from a bibliometric point of view. Scientometrics 52: 503-517.
Wasserman, S. and K. Faust (1994) Social network analysis: methods and applications. Cambridge: Cambridge University Press.
Weibull, J. (1976) An axiomatic approach to the measurement of accessibility. Regional Science and Urban Economics 6: 357-379.
Weibull, J. (1980) On the numerical measurement of accessibility. Environment and Planning A 12: 53-67.
Weingart, P. (1997) From 'finalization' to 'mode 2': old wine in new bottles? Social Science Information 36 (4): 591-613.

Wenting, R. (2008) The evolution of a creative industry: the industrial dynamics and spatial evolution of the global fashion design industry. PhD Thesis. Utrecht: Utrecht University, faculty of Geosciences.
Weterings, A. (2006) Do firms benefit from spatial proximity? Netherlands Geographical Studies nr. 336. PhD Thesis. Utrecht: Koninklijk Nederlands Aardkundig Genootschap/ Utrecht University, faculty of GeoSciences.
Weterings, A. and R. Ponds (2006) Regionale kennisnetwerken en innovatie (In Dutch) – Regional knowledge networks and innovation. Rotterdam/The Hague: NAi Publishers/ RPB.
Wooldridge, J.M. (2003) Introductory econometrics – a modern approach. Second edition. Mason: Thomson South-Western.
Yeung, H.W. (2005) Rethinking relational economic geography. Transactions of the Institute of British Geographers 30 (1): 37-51.
Zitt, M. and E. Bassecoulard (2004) Internationalisation in science in the prism of bibliometric indicators. In: Moed, H., W. Glänzel and U. Schmoch (eds.). Handbook of quantitative science and technology research: the use of publication and patent statistics in studies of S&T systems: 407-436. Dordrecht: Kluwer.
Zucker, L.G. and M.R. Darby (2001) Capturing technological opportunity via Japan's star scientists: evidence from Japanese firms' biotech patents and products. The Journal of Technology Transfer 26(1-2), 37-58.
Zucker, L.G., M.R. Darby and J. Armstrong (1998b) Geographically localised knowledge: spillovers or markets? Economic Inquiry 36 (1): 65-86.
Zucker, L.G., M.R. Darby and M.B. Brewer (1998a) Intellectual human capital and the birth of U.S. biotechnology enterprises. American Economic Review 88 (1): 290-306.

Summary in Dutch – Samenvatting in het Nederlands

Economische groei en welvaart zijn onevenwichtig over regio's verdeeld en sectoren concentreren zich vaak in een beperkt aantal gebieden. De belangrijkste theoretische verklaring voor deze ruimtelijke concentratie van economische activiteiten in bepaalde regio's is de aanwezigheid van agglomeratievoordelen: economische externaliteiten met een beperkte geografische reikwijdte die voortkomen uit de fysieke co-locatie van bedrijven en andere organisaties. Met de opkomst van de endogene groeitheorie eind jaren tachtig van de vorige eeuw worden ruimtelijke verschillen in economische ontwikkeling in toenemende mate gerelateerd aan regionale verschillen in kennis en innovatie. De aanwezigheid van kennis-externaliteiten of kennisspillovers op lokaal en regionaal schaalniveau wordt hierbij als belangrijke factor voor de ruimtelijke concentratie van innovatie beschouwd. Kennisspillovers ontstaan als bedrijven de baten van nieuw ontwikkelde kennis en innovatie niet volledig internaliseren en er kennisoverdrachten plaatsvinden naar andere bedrijven zonder dat daar een volledige (financiële) vergoeding tegenover staat. Het wordt vaak verondersteld dat deze kennisspillovers ruimtelijk gelokaliseerd zijn door het belang van face-to-face contacten voor de overdracht van kennis met een 'tacit' of stilzwijgend karakter. Omdat face-to-face contacten makkelijker en goedkoper zijn wanneer organisaties en individuen in elkaars nabijheid zijn gevestigd is de geografische reikwijdte van deze kennisspillovers beperkt. De aanwezigheid van gelokaliseerde kennisspillovers genereert ruimtelijke gebonden externe schaalvoordelen voor bedrijven. Dit kan leiden tot toenemende meeropbrengsten op het gebied van innovatie en economische groei in bepaalde regio's, waarbij agglomeratienadelen in de vorm van hogere huren en lonen en afnemende bereikbaarheid als tegenkracht dienen.

Hoewel Marshall al in 1920 op de rol van kennisspillovers voor het ontstaan van ruimtelijke concentraties van bepaalde sectoren wees, heeft de opkomst van de endogene groeitheorie de aandacht voor kennisspillovers in de ruimtelijke economie weer sterk doen groeien. In hoofdstuk twee wordt een overzicht gegeven van de literatuur over de ruimtelijke dimensie van kennisspillovers. Een groot aantal econometrische studies (zie ondermeer Jaffe 1989, Audretsch en Feldman 1996, Varga 1998) hebben indirect empirisch bewijs geleverd voor de geografisch beperkte reikwijdte van kennisspillovers aan de hand van zogenaamde kennis-productiefuncties op regionaal niveau. Hierbij is veel aandacht voor de rol van kennisspillovers van universiteiten en andere kennisinstellingen vanwege hun expliciete focus op de ontwikkeling en diffusie van kennis. Tegelijkertijd verschillen deze studies sterk in hun conclusies over de omvang en de exacte geografische reikwijdte van deze spillovers (zie voor een overzicht bijvoorbeeld Döring en Schnellenbach 2006). Dit suggereert dat de rol van ruimtelijke nabijheid voor kennisspillovers sterk verschilt tussen landen, sectoren en tijdsperioden. Om hier meer inzicht in te krijgen is het noodzakelijk om de feitelijke ruimtelijke dimensie van de verschillende mechanismen van kennisspillovers te bepalen. Binnen de literatuur worden drie typen mechanismen onderscheiden (Boschma en Frenken

2006): arbeidsmobiliteit (1), ondernemerschap en spin-offs (2) en samenwerking tussen organisaties (3). Dit onderzoek richt zich op samenwerking tussen organisaties.

Kennisontwikkeling vindt in toenemende mate plaats binnen samenwerkingsverbanden (Roijakkers and Hagedoorn, 2006) en dit is in het bijzonder het geval voor science-based sectoren waar innovatie sterk gerelateerd is aan wetenschappelijke kennis (Pavitt, 1984). Bedrijven in deze sectoren doen relatief veel aan onderzoek en ontwikkeling (R&D) en werken intensief samen met publieke onderzoeksorganisaties zoals universiteiten. Gezamenlijk onderzoek wordt dan ook als één van de belangrijkste mechanismen voor kennisspillovers in sience-based sectoren gezien. Door de tijd is het belang van samenwerking in onderzoek toegenomen, voornamelijk als gevolg van de snelle ontwikkeling binnen verschillende wetenschapsvelden, waardoor het zo goed als onmogelijk is voor individuele bedrijven om dit te blijven volgen op basis van eigen kennisontwikkeling alleen. Binnen de life-sciences industrie werken kleine biotechnologie bedrijven nauw samen in onderzoeksprojecten met universiteiten, ziekenhuizen en grote multinationals op het gebied van chemie en farmacie (Powell e.a. 1996, Cockburn en Henderson 1998 en Cooke 2005, 2006). Dezelfde ontwikkeling doet zich voor in andere science-based sectoren zoals de halfgeleider industrie waar onderzoekssamenwerking tussen organisaties een belangrijk kenmerk van innovatie is geworden (Stuart 2000). Als gevolg hiervan worden inter-organisatorische onderzoeksnetwerken in toenemende mate gezien als 'het brandpunt van innovatie' (Powell e.a. 1996).

Verschillende studies (zie bijvoorbeeld Audretsch en Feldman 1996, Paci en Usai 2000) laten zien dat innovatie in science-based sectoren een sterke ruimtelijke concentratie kent. De grote rol van onderzoekssamenwerking in science-based sectoren suggereert dat de hiermee gepaard gaande kennisspillovers een belangrijke agglomeratiekracht vormen voor deze sectoren. Empirisch onderzoek naar de ruimtelijke patronen van onderzoekssamenwerking laat echter zien dat de regionale dimensie niet overschat moet worden, het nationale en internationale schaalniveau lijkt minstens even belangrijk (McKelvey e.a. 2003, Hoekman e.a. 2008). Dit impliceert dat de met onderzoekssamenwerking geassocieerde kennisspillovers minder ruimtelijk gebonden zijn als vaak ondersteld wordt. Verschillende studies (Cooke 2001, 2005; Owen-Smith en Powell 2004 en Gertler en Levitt 2005) laten zien dat science-based sectoren worden gekenmerkt door een, in eerste instantie wellicht wat paradoxale, ruimtelijke concentratie in een beperkt aantal regio's en een toenemend belang van onderzoekssamenwerking op nationaal en internationaal niveau. Hierbij is gesuggereerd dat dit verklaard kan worden door de gelijktijdige aanwezigheid van gelokaliseerde kennisspillovers (door spillover mechanismen met een beperkte ruimtelijke reikwijdte) en kennisspillovers die over langere afstanden plaatsvinden (door onderzoekssamenwerking). Deze dissertatie heeft als doel om het inzicht in de rol van geografie voor kennisspillovers te vergroten en richt zich op de ruimtelijke dimensie van kennisspillovers door onderzoekssamenwerking binnen science-based sectoren in Nederland. De volgende twee onderzoeksvragen zijn geformuleerd:

1 Wat is de rol van ruimtelijke nabijheid voor onderzoekssamenwerking in science-based sectoren in Nederland?
2 In welke mate vormt onderzoekssamenwerking een belangrijk mechanisme voor kennisspillovers in science-based sectoren in Nederland?

De ruimtelijke dimensie van onderzoekssamenwerking

De rol van ruimtelijke nabijheid voor onderzoekssamenwerking is onderzocht in hoofdstuk vier en vijf waarbij de nadruk ligt op respectievelijk de internationale en de regionale dimensie van samenwerking in onderzoek. Samenwerking in onderzoek is geanalyseerd aan de hand van co-publicaties. Publicaties waarbij meerdere organisaties betrokken zijn worden hierbij beschouwd als een indicator voor samenwerking in het onderzoek, wat eveneens is gedaan in een groot aantal andere studies (zie bijvoorbeeld Cockburn en Henderson, 1998; Zucker e.a., 1998a en Wagner-Doebler 2001). In beide hoofdstukken is de rol van ruimtelijke nabijheid getest door de toepassing van een analytisch raamwerk waarbinnen verschillende vormen van nabijheid worden onderscheiden. Hierbij is geanalyseerd of samenwerking tussen verschillende organisaties wordt gekenmerkt door een groter belang van ruimtelijke nabijheid dan samenwerking tussen organisaties met dezelfde institutionele achtergrond. Het belangrijkste theoretische uitgangspunt is de gedachte dat de rol van de ruimtelijke nabijheid is gerelateerd aan de mate waarin er institutionele nabijheid aanwezig is. Op basis van een onderscheid tussen academische instellingen, overheidsorganisaties en bedrijven, zijn zes verschillende soorten samenwerkingsrelaties onderscheiden, drie gevormd door samenwerking tussen vergelijkbare organisaties en drie door verschillende soorten organisaties. Institutionele verschillen tussen academische organisaties, bedrijfsleven en overheidsgerelateerde organisaties op het gebied van de onderliggende structuur van prikkels kunnen aanleiding geven tot problemen binnen onderzoekssamenwerking. Zo zijn universiteiten en overheden vooral geïnteresseerd in het openbaar maken van kennis, terwijl bedrijven kennis liever niet openbaar maken uit concurrentie-overwegingen. Hiernaast zijn universiteiten voornamelijk bezig met fundamentele kennisproductie, terwijl overheden en bedrijven meer de nadruk leggen op toepassing van kennis in specifieke contexten. Gezien de complexiteit van de coördinatie van gezamenlijk onderzoek zullen niet alle mogelijk situaties van te voren kunnen worden vastgelegd in juridische en afdwingbare contracten. Als gevolg hiervan zal samenwerking in onderzoek deels gebaseerd zijn op minder formele coördinatie mechanismen die de risico's van opportunistisch gedrag moeten verminderen, zoals wederzijds vertrouwen. Wederzijds vertrouwen komt over het algemeen voort uit frequente face-to-face ontmoetingen en een gemeenschappelijke achtergrond en cultuur, waardoor de kosten van samenwerking snel zullen stijgen naarmate de geografische afstand toeneemt. Samenwerking tussen organisaties met dezelfde institutionele achtergrond vergemakkelijkt het noodzakelijke vertrouwen vanwege de overeenkomsten in prikkels en de daaraan gelieerde normen en waarden. Door onderscheid te maken tussen de ruimtelijke en institutionele nabijheid (gedefinieerd als de samenwerking tussen dezelfde soorten organisaties) en het analyseren van verschillende science-based technologieën afzonderlijk, is de rol van ruimtelijke nabijheid voor onderzoekssamenwerking geïsoleerd van cognitieve (of technologische) nabijheid en institutionele nabijheid.

Hoofdstuk vier analyseert de internationale dimensie van onderzoekssamenwerking voor de periode 1988 tot 2004. Over deze periode is het belang van samenwerking in onderzoek toegenomen in alle science-based technologieën op zowel nationaal als internationaal niveau. De toename van internationale samenwerking loopt gelijk op met de toename van nationale samenwerking. Dit impliceert dat samenwerking in onderzoek een belangrijke trend is, maar dat hierbij geen sprake lijkt te zijn van een toenemende internationalisering. Internationale samenwerking in onderzoek wordt vooral gedreven door academische samenwerking, hetgeen een weerspiegeling vormt van de internationale dimensie van wetenschappelijke gemeenschappen. Hiernaast vind er eveneens internationale samenwerking tussen universiteiten en bedrijven plaats, hetgeen kennisspillovers van universitair onderzoek op het internationale niveau genereert. Als buitenlandse bedrijven stelselmatig meer (of minder) samenwerken met Nederlandse academische organisaties dan Nederlandse bedrijven met buitenlandse academische organisaties kan dit leiden tot een negatieve (of positieve) 'balans' op het gebied van internationale kennisspillovers. Uit hoofdstuk vier blijkt dat zowel een negatieve als positieve balans weliswaar heeft bestaan in het begin van de periode die onderzocht is, maar dat dit door de tijd grotendeels is verdwenen als gevolg van een evenwichtiger patroon van internationale onderzoekssamenwerking tussen universiteiten en het bedrijfsleven. Tegelijkertijd laat hoofdstuk vier zien dat samenwerking tussen verschillende soorten organisaties (bijvoorbeeld tussen universiteiten en het bedrijfsleven) eerder plaatsvindt binnen Nederland dan samenwerking tussen dezelfde soorten organisaties. Dit suggereert dat de voordelen van een locatie in hetzelfde land een belangrijke rol spelen voor onderzoekssamenwerking tussen organisaties met verschillende institutionele achtergronden en prikkelstructuren. Deze bevindingen zijn in lijn met de ideeën van het 'nabijheidsraamwerk', waarin wordt gesteld dat ruimtelijke nabijheid een belangrijke factor kan zijn voor het verminderen van problemen die kunnen voortkomen uit een gebrek aan institutionele nabijheid – hier gedefinieerd als verschillende prikkelstructuren. Om te bepalen of de voordelen van ruimtelijke nabijheid voor samenwerking in onderzoek eveneens aanwezig zijn op een lagere geografische schaal, richt hoofdstuk vijf zich op de regionale dimensie van onderzoekssamenwerking in Nederland. Hiervoor zijn de individuele samenwerkingsrelaties geaggregeerd naar de 40 NUTS3 (Corop) regio's. De rol van ruimtelijke nabijheid voor verschillende typen samenwerkingsverbanden is hierbij geanalyseerd door het effect van reistijd te schatten op de intensiteit van verschillende vormen van samenwerking tussen regio's aan de hand van een ruimtelijk interactie-model. In lijn met de conclusie van hoofdstuk vier blijkt dat de ruimtelijke nabijheid van groter belang is voor onderzoekssamenwerking tussen verschillende soorten organisaties dan voor onderzoekssamenwerking tussen dezelfde soorten organisaties. Tegelijkertijd betekent dit echter niet dat samenwerking tussen academische instellingen en het bedrijfsleven een duidelijke regionale oriëntatie kent. Binnen Nederland lijkt de rol van ruimtelijke nabijheid belangrijker voor onderzoekssamenwerking tussen academische instellingen en overheidsorganisaties dan voor samenwerking tussen academische instellingen en het bedrijfsleven, waar het nationale schaalniveau relevanter lijkt. De rol van ruimtelijke nabijheid voor onderzoekssamenwerking en kennisoverdracht in het algemeen, is daarmee niet eenvoudig te duiden. De ruimtelijke dimensie van kennisoverdracht is gerelateerd aan de wisselwerking tussen ruimtelijke en andere vormen van nabijheid.

Onderzoekssamenwerking als mechanisme voor kennisspillovers

Hoofdstuk zes en zeven analyseren de rol van onderzoekssamenwerking als een mechanisme voor kennisspillovers en geven hiermee antwoord op de tweede onderzoeksvraag. Een groot aantal empirische studies naar de ruimtelijke dimensie van kennisspillovers zijn gebaseerd op een regionale variant van een kennis-productiefunctie. Hierbij worden verschillende regionale kennisinputs gerelateerd aan regionale kennisoutput. De aanwezigheid van ruimtelijk gebonden kennisspillovers tussen regio's wordt hierbij getest door het meenemen van het gewogen gemiddelde van kennisinputs uit andere regio's. De constructie van deze gewogen gemiddelden is gebaseerd op de veronderstelde ruimtelijke patronen van de mechanismen van kennisspillovers, die formeel worden uitgedrukt in een ruimtelijke gewichtenmatrix. De waarden van elk element in deze matrix is een afspiegeling van de veronderstelde omvang van de interactie tussen de regio's. Op basis van de theoretische aanname dat kennisspillovers grotendeels ruimtelijk gelokaliseerd zijn, wordt in de grote meerderheid van deze studies een gewichtenmatrix gebruikt die gebaseerd is op aangrenzendheid of op een afstandsvervalfunctie. Hierbij wordt er aan nabij gelegen regio's een hoger gewicht toegekend dan aan regio's die op grotere afstand liggen hetgeen in lijn is met de aanname dat ruimtelijke nabijheid van belang is voor de mechanismen van kennisspillovers. Hoofdstuk vier en vijf tonen echter aan dat tenminste één potentieel belangrijk mechanisme van kennisspillovers veel minder ruimtelijk gelokaliseerd is dan vaak wordt verondersteld. Door alleen het gewogen gemiddelde van kennisinputs uit de nabij gelegen regio's mee te nemen in een kennisproductie functie wordt de mogelijkheid dat kennisspillovers over langere afstanden kunnen plaatsvinden genegeerd. In hoofdstuk zes wordt de mogelijke aanwezigheid van kennisspillovers door onderzoekssamenwerking formeel getest op basis van een kennis-productiefunctie op het niveau van NUTS3 (corop) regio's. Hierbij worden twee verschillende versies van het gewogen gemiddelde van universitaire R&D uit andere regio's mee genomen. De eerste variant is gebaseerd op een ruimtelijke gewichtenmatrix die wordt gevormd door de feitelijke ruimtelijke structuur van onderzoekssamenwerking tussen het bedrijfsleven en universiteiten. De tweede variant maakt gebruik van een ruimtelijke gewichtenmatrix gebaseerd op een afstandsvervalcurve die de mogelijke aanwezigheid van kennisspillovers door mechanismen die sterker ruimtelijk gebonden zijn weerspiegelt. De resultaten van hoofdstuk zes laten zien dat kennisspillovers zowel op het nationale schaalniveau door onderzoekssamenwerking plaatsvinden als op het regionale schaalniveau door meer ruimtelijk gelokaliseerde mechanismen. Dit betekent dat kennisspillovers van universiteiten niet gemakkelijk kunnen worden verbonden aan een specifiek ruimtelijk schaalniveau maar op verschillende ruimtelijke schaalniveaus tegelijk plaatsvinden.

In hoofdstuk zes is verondersteld dat kennisspillovers door andere mechanismen dan formele onderzoekssamenwerking vooral op regionaal niveau plaatsvinden. In hoofdstuk zeven wordt onderzocht in hoeverre deze veronderstelling correct is door de ruimtelijke dimensie van een ander mechanisme, dat vaak als ruimtelijk gelokaliseerd wordt verondersteld, te analyseren. Dit hoofdstuk analyseert de ruimtelijke dimensie en het effect op innovatie van informele kennisoverdracht en onderzoekssamenwerking op het niveau van bedrijven. De focus ligt hierbij op bedrijven in de biotechnologie in de twee provincies in Nederland waar zich een sterke ruimtelijke concentratie van deze bedrijven bevindt, te weten Zuid-Holland (met als zwaartepunt de regio Leiden) en Gelderland (met als zwaartepunt de regio Wageningen). De empirische analyse is gebaseerd op een combinatie van gegevens over informele kennisuitwisseling die verkregen zijn via een telefonische enquête en gegevens over onderzoekssamenwerking op basis van co-publicaties zoals in de hoofdstukken vier, vijf en zes. Informele kennisoverdracht is hier gedefinieerd als contacten tussen organisaties waar kennis wordt uitgewisseld gericht op het oplossen van een specifiek probleem bij één van de betrokken bedrijven. Hierbij gaat het met name om praktische kennis op het gebied van specifieke technologieën, apparatuur of management.

Formele samenwerking in onderzoek kan worden gedefinieerd als een overeenkomst voor het wederzijds investeren van middelen voor een gezamenlijk onderzoeksdoel. In tegenstelling tot onderzoekssamenwerking, dat zoals in hoofdstuk vier en vijf is aangetoond voornamelijk op nationaal en internationaal niveau plaatsvindt, wordt er vaak verondersteld dat meer informele kennisuitwisseling een sterkere regionale dimensie heeft. Dit heeft twee redenen. Allereerst is het noodzakelijk om informatie te hebben over de specifieke competenties en kennis van andere organisaties over het specifieke probleem. Deze informatie is echter niet vrij beschikbaar maar circuleert in sociale netwerken. Ten tweede wordt vaak aangenomen dat de uitwisseling van deze kennis plaats vindt op basis van wederkerige, langdurige relaties die eveneens voortkomen uit sociale netwerken. Omdat verschillende empirische studies aantonen dat dit type sociale netwerken voor een groot deel ruimtelijk gebonden zijn, kan worden verondersteld dat de hiermee geassocieerde spillovers dat eveneens zijn. In hoofdstuk zeven wordt deze aanname getest door de ruimtelijke dimensie van onderzoekssamenwerking te vergelijken met de ruimtelijke dimensie van informele kennisuitwisseling. Informele, probleem georiënteerde kennisuitwisseling blijkt inderdaad een veel sterkere regionale en locale dimensie te kennen dan onderzoekssamenwerking. Dit suggereert dat in elk geval één mechanisme voor de in hoofdstuk zes gevonden ruimtelijke gebonden kennisspillovers bestaat uit informele kennisuitwisseling. Om hier meer inzicht in te krijgen is het effect van spillovers door beide mechanismen op de innovatieprestaties van biotechnologie bedrijven getest. Gecontroleerd voor verschillende bedrijfskenmerken, laat deze analyse zien dat zowel samenwerking in onderzoek als informele kennisuitwisseling een positief effect heeft op innovatie, hetgeen suggereert dat beiden een mechanisme voor kennisspillovers zijn.

De resultaten die gepresenteerd zijn in deze hoofdstukken geven aan dat kennisspillovers kunnen plaatsvinden op verschillende ruimtelijke schaalniveaus binnen één sector door de verschillende ruimtelijke configuratie van de onderliggende mechanismen. Daarmee geeft deze studie een verklaring voor het ontbreken van consensus in de literatuur over de ruimtelijke dimensie van kennisspillovers zoals beschreven in verschillende overzichtsstudies (zie bijvoorbeeld Audretsch en Feldman, 2004; Döring en Schnellenbach, 2006). De ruimtelijke dimensie van kennisspillovers is gerelateerd aan de invloed van ruimtelijke nabijheid voor de intensiteit van de onderliggende mechanismen waardoor deze spillovers plaatsvinden. Zoals uit deze studie blijkt, verschilt de rol van ruimtelijke nabijheid sterk tussen verschillende mechanismen voor kennisspillovers. Het feit dat het relatieve belang van de verschillende mechanismen verschilt tussen sectoren vormt daarmee een mogelijke verklaring voor de verschillen in de ruimtelijke dimensie van kennisspillovers in het algemeen. In het geval van science-based sectoren is er sprake van het gelijktijdig voorkomen van ruimtelijk gelokaliseerde kennisspillovers door middel van mechanismen als informele kennisuitwisseling en de aanwezigheid van kennisspillovers over langere afstanden door middel van onderzoekssamenwerking. Dit lijkt daarmee een belangrijk verklaring voor de, in eerste instantie enigszins paradoxale, gelijktijdige ruimtelijke concentratie van de science-based sectoren in een beperkt aantal regio's en het grote belang van kennisintensieve samenwerkingsrelaties op nationaal en internationaal niveau zoals beschreven door Bathelt e.a. (2004), Gertler en Levitte (2005) en Cooke e.a. (2006).

Curriculum Vitae

Roderik Ponds was born on 1 May 1981 in the city of Hengelo (O), the Netherlands. He studied International Economics and Economic Geography at Utrecht University and graduated in 2004 as MSc. After graduation, he combined a job as researcher economics at the Netherlands Institute for Spatial Research (renamed after a merger in 2008 as the Netherlands Environmental Assessment Agency) and a position as PhD student at the department of Economic Geography, faculty of Geosciences at Utrecht University. At the Netherlands Institute for Spatial Research, he was involved in several research projects for the national government in the field of regional innovation, locational behaviour of firms and the housing market. Roderik Ponds has published several articles in the field of economic geography in national and international journals.