ESSAYS ON INNOVATION IN GERMANY (1877-1914)

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Abstract

This Ph.D. dissertation studies innovation in Germany from 1877 to 1914. The German patents that had survived for at least ten years are used as a proxy of innovation. The introduction briefly outlines the issues to be investigated. The first chapter examines the successive waves of technological progress during the German industrialization. It discusses the distribution of patents across industries and across regions. The second chapter investigates the regional innovation system (RIS) in Prussia. In particular, it focuses on the determinants of innovation in Prussian regions. The third chapter goes beyond Prussia and studies innovation in German cities (1890-1914). Using firm-level data of Baden region, the fourth chapter tries to study the linkage between clusters and innovation by examining whether firms located in clusters were more innovative. The fifth chapter studies the knowledge spillover from schools to firms and from firms to firms. The sixth chapter uses patent renewal data. Employing Cox regression technique, we explore the question what factors (such as patent's technological class and patentee's nationality) impact patent survival. The concluding part of this dissertation summarizes the main results and points out tentative directions for further research using this patent data set.

Introduction

INNOVATION AND KNOWLEDGE ECONOMY

Technology is a major engine of long-term economic growth.[1] Accordingly, from the birth of modern economics, economists have appreciated the importance of technological progress. Over the past three centuries, the main source of wealth in market economies has shifted from natural assets (notably land), through tangible, man-made assets (such as machinery) to intangible, created assets (notably knowledge and information). With the approach of the knowledge economy (which refers to the use of knowledge to produce economic benefits) accompanied with globalization and internet-driven information revolution, technological innovation plays an increasingly important role in our modern society. As intangible inputs, such as knowledge, gain importance in economic activities, our economy becomes more knowledge-based and "weightless". Alan Greenspan comments that in 1996, America's total output, measured in tons, is little more than it was one century ago, although America's real GDP has increased 20 times.[2] Even the traditional manufacturing sector experiences this shift from brawn to brain. An OECD study in 1996 shows that high-skill industries have doubled their share of manufacturing output to 25 % from 1975 to 1996.[3] The idea that technology is the foundation of our future especially applies to a country such as Germany, which does not have abundant natural resources.

Today, innovation is certainly a topic that draws much interests and enthusiasm. Yet until very recently, innovation was a word with at least some negative denotation and connotation.[4] The positive connotation of innovation, as a valuable improvement, is itself a relatively new idea. This neatly illustrates the ambiguity that underlies the role of innovation in society. Schumpeter's concept of innovation as "creative destruction" (Schumpeter, 1942) highlights this ambiguity: Creative firms bring new products or better

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[1] Theoretical and empirical works supporting the contention that innovative economies are prosperous are too abundant to enumerate. For a few examples, see Jacobs (1969, 1984), Landes (1969), Murphy et al. (1991), Porter (1990), Romer (1986, 1994), Rosenberg and Birdzell (1986), and many more.

[2] "The World Economy Survey", *The Economist*, September 28, 1996, p. 43, cited in Neef (1998), p.4.

[3] "The Knowledge-Based Economy", *OECD*, 1996, cited in Neef (1998), p.4.

[4] Looking up the word "innovation" in the Oxford English Dictionary reveals that the use of the word in English had strongly negative meaning from the 16th century into the 19th century.

technology into the economy, but this destroys stagnant non-innovative firms.[5] This destruction is the downside of innovation. Christensen (1997) articulated his theory of disruptive technology. The term "disruptive technology" was coined to describe a new, lower performance, but less expensive product. The disruptive technology starts by gaining a foothold in the low-end (and less demanding part) of the market, successively moving up-market through performance improvements, and finally displacing the incumbent's product. Therefore, innovation is a mixed blessing and two-edged sword. When the Luddite movement (1811-1816) took place in England, seeking to increase their wages, the Luddites became the machine breakers and wreckers. As a matter of fact, innovation phobia is a rather widespread phenomenon.

The following broad trends are behind the current upsurge of interest in knowledge. Firstly, globalization is reshaping the world economic landscape and is putting great pressure on firms to increase adaptability, which demands innovation.[6] Secondly, in coping with the pressure of globalization, economic agents are increasingly aware of the value of knowledge, which is often embedded in organizational processes and routines (such as corporate culture) and often yields significant market values. Thirdly, networked information technology gives us a powerful tool for working with and learning from each other.

INNOVATION SYSTEM

The innovation system approach has emerged during the last few decades for the study of innovation process as an endogenous part of the economy. The approach is not a formal theory, but a conceptual framework. The idea that lies at the center of this framework is that the economic performance of localities depends not only on how actors perform individually, but also on how they interact with each other in knowledge creation and dissemination. Lundvall (1992) is one of the first works to promote thinking about systems of innovation. It mentioned regionalization in relation to globalization and referred to regional networks, but it did not believe a regional perspective on innovation could be as useful as national systems, even in respect of such geographically contingent

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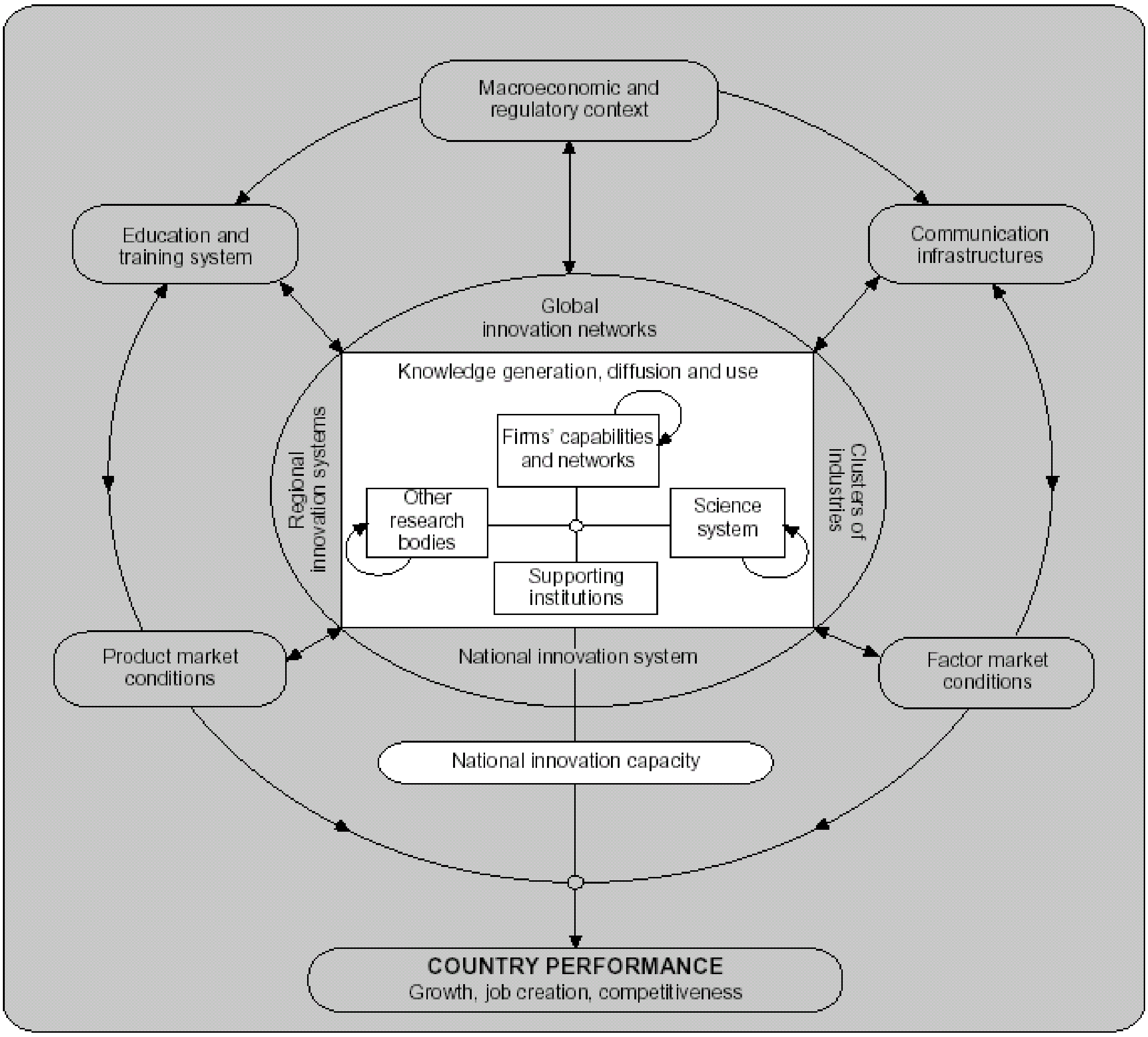
[5] The term Schumpeterian evolution is also used to describe creative destruction. Schumpeterian evolution, like Darwinian evolution, is the survival of the fittest. But in Schumpeterian evolution, firms purposefully make themselves the fittest by investing in innovation.

[6] Hall et al. (1993) show that firms with high R&D spending (input of innovation) have above industry-average financial performance.

processes as tacit knowledge exchange. Contradicting Porter (1990, 1998), Lundvall (1992) suggested that transnational innovation interactions were likely to gain in importance over national ones, but that regional processes were unlikely to. In the literature on innovation, the meaning of the term "system" is not analyzed in great details. Some general definitions of a system of innovation do exist. For example, Lundvall defines a system of innovation as being constituted of a number of elements and by the relationship between these elements (Nelson and Winter 1982; Lundvall 1992; Edquist 1997). It follows that a system of innovation is constituted of elements and relationships that interact in the production, diffusion and use of new and economically useful knowledge (Lundvall 1992). It becomes quite clear that an innovation system is a social system, which means that innovations are the result of social interaction between economic actors. And it is an open system, which interacts with its environment. The National Innovation System (NIS) approach highlights the importance of interactive learning and the role of nation-based institution in explaining the difference in innovation performance and hence, economic growth, across different countries. Freeman (1987) first used the "national innovation system" concept in his analysis of Japan's blooming economy. National innovation systems can be defined as the "... set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provide the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artifacts which define new technologies" (Metcalfe, 1995). From this perspective, the innovative performance of an economy depends not only on how the individual institutions (e.g. firms, research institutes, universities) perform in isolation, but on "how they interact with each other as elements of a collective system of knowledge creation and use, and on their interplay with social institutions (such as values, norms, legal frameworks)" (Smith, 1996). Now, there is an extensive literature on national innovation systems. Some representative works are Lundvall (1992), Nelson (1993), Freeman (1995), and Niosi, et al. (1993). Figure 1 helps us to visualize the various actors and their interactions in a system of innovation.

Figure 1 Actors and linkages in the innovation system



Source: OECD, *Managing National Innovation Systems*, 1999

USING PATENT AS PROXY FOR INNOVATION

Economists often aspire to quantify their variables. Many economists (for instance, Pavitt, 1982 and Griliches, 1990) have been debating about the issue of measuring innovative activity and technological progress, but, not surprisingly, no universal solution has been found. There are at least three basic problems in measuring innovation:

Firstly, innovation is a dynamic process rather than a static point in time. Yet we have to impose a beginning and an end to make our analysis tractable. We have to be reliant on static indicators to measure a dynamic process. What we can track is often only the successful innovation as final product. Secondly, inputs and outputs of innovation are heterogeneous. The quality of R&D effort varies. Some patents have little economic value. Thirdly, we have to acknowledge the unobservability of much innovative activity. Most process innovations are not marketed. Some firms tend to keep their inventions as trade secret.[7]

The empirical literature on innovation most often uses one or more of three quantitative measures of innovative activity. None of these measures is perfect, and the flaws of each are discussed below.

(1). Research and Development (R&D) spending and/or employment

Corporate R&D expenditure/employment is widely used as a measure of a firm's investment in innovation. And the data are often disclosed in annual reports or financial statements of firms. The main methodological criticism of using R&D expenditure and/or employment is that the data measure an input to innovation, not the number or value of the innovations actually produced. We know that firms often invest money and labor in unprofitable projects, so the possibility that most R&D spending and/or employment might be wasted cannot be dismissed. Moreover, R&D data is biased towards large firms and publicly-listed firms.

(2). Innovation counts

Innovation counts are comprehensive lists of innovations made by various firms. They are usually constructed from large surveys. In principle, innovation counts should be the best data, for they clearly measure output, and the survey organizers can apply similar rules in constructing data for different firms, industries and countries. In practice, innovation counting is often criticized as arbitrary. The surveyors must decide what is an "innovation" and what is not. Patent counts also usually try to distinguish "important" from "unimportant" innovations, but this too is a judgment call. Sometimes, the surveyors lack the ability to judgment. Sometimes, they are not inclined to give unbiased judgment because their self interest is involved. Finally, innovation counts are not available at the firm level in most countries.

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[7] A trade secret is an item of information (commonly a customer list, business plan, or manufacturing process) that has commercial value and that the firm possessing the information wants to conceal from its competitors in order to prevent them from duplicating it. A trade secret is not property in the usual sense– the sense it bears in the law of real and personal property or even in such areas of intellectual property law as copyright–because it is not something that the possessor has the exclusive right to use or enjoy. If through accident the secret leaks out, or if a competitor unmasks it by reverse engineering, the law gives no remedy. The law does give a remedy if the secret is lost through a breach of contract–say by a former employee who had promised not to disclose what he learned on the job. But the violation is not of a property right to the secret but of a common law right defined without regard to trade secrets. See Friedman et al. (1991, pp. 61-2).

(3). Patents

In fact, one of the longest lasting debates in the history of economic measurement has been whether the noise and the biases in patent count measures can be minimized enough to make patent counts maximally useful indicator of innovative output in economic studies (see, for example, the papers of Kuznets and Sanders, and the comments of Schmookler, both in Nelson, 1962).

There has been quite noted criticism on using patents to study technological innovation. Patent data can sometimes be misleading and the patent approach does have its limits. Some of the deficiencies are as follows. Firstly, patent laws can be very different in different countries. For example, Japan allowed seven-year patents to be filed for minimal innovations, while most other countries only granted patents for real innovations, and those patents lasted for close to twenty years. Patent laws in different countries are now converging, so these problems will not affect very recent and future years' data. But it is difficult to use historical patent data in cross-country comparisons without controlling carefully for these factors. Different countries often have different classification of patents. Many types of innovation, including software and some biological innovations, are not patentable in many countries. Therefore, it is difficult to compare patents from different countries. Secondly, patents are a measure of invention, not innovation. Innovation is the embodiment of an invention in the productive process. From an economic standpoint, innovation is about applying new ideas and technology to improve human life, not just about having ideas. High patent counts do not necessarily mean a high level of innovation. Thirdly, firms that have a new technology and fear that other firms might try to steal their technology by finding superficially different technological processes that circumvent the innovator's patent are thought to engage in patent thicketing.[8] This involves filing numerous patents on minor variants of the original patent, not because these are real innovations, but because they "might" head off a competitor's attempt to circumvent the original patent. Nevertheless, this practice implies that there is at least one important data hidden behind the inflated patent data pool. Fourthly, there is essentially not an easy way to weight patents by their importance. Pure patent counts allocate the same weight to every patent, no matter whether it has a high or a low economic value for the patentee or the society. Using the number of patents as an indicator for new technological knowledge suitable to foster economic growth therefore

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[8] See Bernstein (2001) for a detailed discussion about this problem.

leads to a potentially very large measurement error.[9] To decrease this measurement error it is necessary to distinguish patents with a high economic value from those with a low one. A possibility to do this is to let the patents be evaluated by experts. Townsend, for example, rated patents related to coal mining according to their importance on a scale from 1 to 4.[10] This procedure might be recommendable for specific industry studies with a small number of observations, but does not work for large patent populations when the careful evaluation of every single patent would be very time consuming and would require engineering competence in a wide range of technological fields. Fifthly, not all important inventions were patented. Some inventors do not want to pay or cannot afford to pay the required fee to register patents. Some inventors prefer to keep their patents secret. Sixthly, the propensity to patent inventions has been declining for most of the 20th century (Wilson, 2003). Thus, long-run time series analysis is hazardous. Seventhly, the propensity to patent varies across industries and firms. Thus, cross-section analysis is difficult. Levin et al (1989), for example, find out that some industries try to appropriate the returns of their inventions primarily by keeping them secret while others, like the chemical or pharmaceutical industries, prefer patenting to reach this goal.[11] Because of industries' different propensities to patent, it might be misleading to interpret a particular industry's comparatively high number of patents automatically as a sign for its alleged above-average innovativeness. In the econometric analysis, however, we can take care of this problem by controlling for industry fixed effects. Eighthly, patent application data is biased towards large firms, manufacturing firms and those firms that are financially more powerful.

Overall, the pros and cons of using patent data to study innovation have been quite thoroughly studied. Two good survey articles are Griliches (1990) and Archibugi (1992). For more recent discussions, see Desrochers (1998, 2001) and Kleinknecht et al. (2002). Scherer (1984) has argued quite convincingly that patents can serve as tangible indicators of inventive activities that are embedded in the innovation processes driving general technological development. Various remedies have been proposed to make patent data more suitable for research. Lanjouw et al. (1998) discuss the imperfection of patent

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[9] The academic debate about the extent of this kind of measurement error is still far from settled. On the one hand, Schankerman and Pakes state that "one cannot draw inferences on changes in the value of cohorts of [European] patents ... from changes in the quantity of patents during this period" [1955-1975]. Schankerman and Pakes (1986), p. 1070. Sullivan, on the other hand, shows that for the 1852-76 period fluctuations of the number and aggregate value of British and Irish patents generally moved in the same direction. See Sullivan (1994), p. 49.

[10] See Townsend (1980), p. 150.

counts as measures of innovative output, and methods of dealing with at least some of the problems listed above.

Therefore, despite all its shortcomings, patent data is a useful source to study innovation. It has several advantages. Patents are easily available in large quantity for long time series. Patented inventions are a good representative sample of the population of inventive activity. Patent records contain information about the place of patentees. Thus, we can map the spatial distribution of innovation. Patent statistics is disaggregated to industry level. Patents offer us even detailed information at the firm level. Thus, we can study the clustering effect of firms, as we will do in chapter 4 of this dissertation. Sullivan (1994) has argued that the variability in patent quality may not be a serious concern for some historical data.

PATENT SYSTEM

A patent is a set of exclusive rights granted by a government to an inventor for a limited amount of time (normally 15-20 years from the filing date). It is the most common form of intellectual property, which is the cornerstone of the modern knowledge economy.[12] Patent laws are a manifestation of the state's police powers designed to prevent other people from "free-riding" on an innovator's idea (Atkinson and Stiglitz, 1980). The patent system tries to solve the paradox of innovation: creation and diffusion.[13] The essence of the patent system is that the state trades patent protection for invention disclosure. In order to use the patented idea and benefit, other people have to get the patentee's permission and pay a license fee.

The word patent comes from the Latin "litterae patentes", meaning an open letter. Such letters were used by medieval monarchs to confer rights and privileges. With a royal seal, the letters served as proof of those rights, for all to see. Although there is evidence suggesting that something like patents was used among some ancient Greek cities, patents

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[11] See also Arundel and Kabla (1998).

[12] Other common forms of intellectual property are copyrights and trademarks. A trademark is a word, name, symbol or device which is used in trade with goods to indicate the source of the goods and to distinguish them from the goods of others. Copyright is a form of protection provided to the authors of "original works of authorship" including literary, dramatic, musical, artistic, and certain other intellectual works, both published and unpublished. For more details, see the United States Patent and Trademark Office web page (http://www.uspto.gov/web/offices/pac/doc/general/whatis.htm).

[13] The patent system trades off the private property rights that create incentives ex ante versus the welfare costs of restricting an output which could be provided ex post at a relatively low cost, which means that, unfortunately, a single solution that will apply at all times and in all cases cannot be given.

in the modern sense originated in Renaissance Italy. The first recorded patent for an industrial invention is the one granted in 1421 in Florence. In 1474 the Republic of Venice issued a decree in which new and inventive devices, once they had been put into practice, had to be communicated to the Republic in order to obtain legal protection against potential infringements.[14] Such privileged grants to inventors spread from Italy to other European nations over the next few centuries. England followed with the Statute of Monopolies in 1624 under King James I of England. The right of the US Congress to pass laws regulating intellectual property was established in the US Constitution in 1787.[15] The Patent Commission of the U.S. was created in 1790 and issued the first patent in the same year.[16] France enacted its patent system the following year. The French Patent Law of 1844 remained in effect with little change up to the 1960s. By the end of the nineteenth century, all major industrial powers in the world had established patent systems except Switzerland. Today there exist approximately 100 separate jurisdictions regarding patents.

Typically, an application for a patent is examined before a patent is issued or granted for an invention. That is to say, the application is reviewed by a patent examiner for patentability. Different patent systems use different criteria for reviewing patents. In most cases, an invention must be considered novel and useful in order to receive a patent. It must also represent a relatively significant advance in the state of the art and cannot merely be an obvious change from what is already known.[17] While examining patent applications, most countries in the world use first-to-file principle while, granting a patent and all rights to the first person who files a patent application for an invention. The US is quite unusual in that it has first-to-invent principle, granting a patent to the first inventor who conceives the technology or invention.[18] This practice often requires substantial burden of proof.

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[14] *Encyclopedia Britannica*, Standard Edition, 2002.

[15] Article I, Section 8, Clause 8 of the U.S. Constitution stipulates: "Congress shall have power . . . to promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries."

[16] See Nard and Morris (2004) for a survey of the historical development of the US constitutional patent law. The basic structure of the present US patent law was adopted in 1952.

[17] "Copycat" innovation may involve simply replicating another firm's invention and should not get a patent for the crude imitation.

[18] Clause 101 of US Code 35 states: "Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requirements of this title.. . ." This has further been defined by some following case laws.

The patent system is controversial. Several key questions are at the center of the controversy. How long should patent protection be maximally?[19] What items should be entitled to be patented? Is patent system effective in fostering innovation?[20] Do patents allow firms to appropriate the benefit that flows from their intellectual property?[21] Moreover, it is an open question whether patent applications are competently examined and properly issued by trained, skilled and thoughtful patent examiners who often have heavy workload and have to work under pressure. Nevertheless, it is fair to say that the patent system, despite a few faults, continues to make a substantial contribution to the economic well-being of society.

OUR PATENT DATABASE

Patent data is the major data used in this dissertation. It appears in every chapter. We use patents as a proxy of technological innovation. Over the time period under consideration, the patent rules were subjected to several changes. Nevertheless, these changes do not significantly affect our study over this time period. Our prime data source is the annual *Verzeichnis der im Vorjahre erteilten Patente* published by the German patent office (located in Berlin).[22] The directory lists all patents granted in the immediately preceding year. To be exact, in the directory, for each patent we get the

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[19] Nordhaus (1969) developed the first model of optimal patent protection. Longer patent lives give a greater financial incentive to prospective innovators, but also slow the diffusion of an innovation through the economy. The optimal patent life balances these two factors. Economists, for example Scotchmer and Green (1990), Scotchmer (1996), and O'Donoghue et al. (1998), have proposed various interesting models subsequently. Yet little is known about the parameter values needed to operationalize these models. Therefore, we have to admit that we still have little idea about what the optimal patent life should be, whether it is the same across industries and, if not, how it should differ across industries, or whether patent lives should be the same for different innovations in the same industry. Neither do we know whether current patent laws in various countries provide optimal, sub-optimal or super-optimal patent lives.

[20] The question whether the patent system has the desired effect on innovation has proven exceedingly difficult to answer, partially owing to the lack of real experiments (a common problem in social sciences). Most researchers who investigate this topic have looked at historical data when there were changes to the system and examined the consequences for subsequent innovative activities. Moser (2001) argues provocatively that some countries may be better off without strong patent laws. The positive results are presented by Park and Ginarte (1997). Using aggregate data across 60 countries for the 1960-90 period, the paper finds out that the strength of the patent system is positively related with R&D investments in the 30 countries with the highest incomes (that is, G7 countries and other rich nations).

[21] Jaffe (2000, p. 555) concludes that although important, patents are not central to appropriating the returns to R&D in some industries. Yet using a 1994 survey of more than a thousand managers of manufacturing industry R&D laboratories on methods adopted to protect income flows generated by intellectual assets, Cohen et al (2000) suggest that in many industries, in particular pharmaceuticals, patents are indeed highly effective in protecting the firm's competitive advantage gained from innovations.

[22] For a survey on the publications of the Reichspatentamt see Theobald (1927).

following information: (1). patent class code[23], (2). patent number[24], (3). name of the patentee (person or firm)[25], and (4). residence place of the patentee.[26] The directory also contains a short description (often just one or two lines) of invention patented (we do not use this information since it is difficult to quantify).[27] One typical patent is randomly chosen and provided here as one example:

Klasse 21. Elektrotechnik.

21 a. Telegraphie und Fernsprechwesen.

134410. Siemens & Halske Akt.-Ges., Berlin. Gesprächszähler.[28]

The regular directory also contains a list of all patents still in force, which enables us to calculate the life spans of particular patents. We will use patent's life spans to study patent survival in chapter 6.

Between 1877 and 1918, in total 311,019 patents were granted in Germany. The starting year of the observation period is determined by the establishment of the German patent law of 1877[29] that for the first time in German history gave inventors the possibility to apply for patent protection not only in single states but in the whole German Empire.[30] The patent protection could last up to fifteen years but was not for free. Rather, the patentee had to pay at the beginning of each year an increasing renewal fee in order to keep his patent in force. This annual renewal fee came to 50 Marks in the first two years[31], and grew then by 50 Marks each year up to 700 Marks at the beginning of the fifteenth year. Patent holders were supposed to decide to renew their patent only when the costs of doing this were lower than the expected future return of the patent. Following this contemporary assumption about the behavior of patent holders, we will use information on the actual life span of a patent as an indicator for its private economic

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[23] The patents are classified according to a technologically oriented classification system. The system has 89 patents classes (from 1 to 89). From 1900 on, there are sub-classes under each patent class.

[24] The number will not be given to another patent even if the original patent becomes invalid.

[25] The information tells us whether a particular patent was held by an individual or a firm.

[26] From this information, we know whether a patent is held by a German or foreign patentee. In general, the patents filed by large firms might be biased to a certain extent in geographic location, since it is conceivable that some patents were filed by the headquarters of a firm, even though the inventions might be developed in geographically distant subsidies. Yet during the time period under our study, this problem is not serious as not many firms had establishments over many geographic places in Germany at that time.

[27] Please note that patent applications that had been rejected are not public information.

[28] This entry is from the patent directory 1902, p. 96.

[29] See "Patentgesetz vom 25. Mai 1877", *Reichsgesetzblatt,* (1877), pp. 501-510. In 1877 (the year when the patent law was introduced), only 190 patents were registered. In 1878, 4,227 patents were registered.

[30] For the genesis of the German patent law see Heggen (1977).

[31] In the first year the potential patentee had to pay 20 Marks for the application and additional 30 Marks after the patent was granted. 50 Marks were approximately the monthly gross income of the average industrial worker. See Bry (1960), p. 51.

value. One big drawback of using patent data is that patents have various qualities as not all patents are equally important (see, for example, Lanjouw and Schankerman 2001). To address this concern, following Schankerman and Pakes (1986), in this dissertation we use only the patents that have been prolonged for at least ten years.[32] Following the selection criterion of the 10-year renewal, we have 39,343 patents from 1877 to 1918 in our database.[33] Patentees had to pay substantially fees to keep their patents alive. Therefore these long-lived patents can well be regarded as high-value patents. A patent stands for an invention, but a patent that is held for ten years is a good proxy for innovation. Some inventors might register patents for leisure, but they normally would not spend money to renew patents for ten consecutive years. Moreover, the drawbacks of using patent data are more severe when small units (such as firms) and short periods of time are considered.[34] Our use of relatively large regions and of more than three decades of patent data is likely to wipe off most of the problems arising from patent heterogeneity.

GERMAN INDUSTRILIZATION

The patents that we use in this dissertation date from 1877 to 1914. Germany quickly industrialized during this period. The importance of the German industrialization can hardly be exaggerated. However, not much research has been done on innovation in Germany at this time period. As a matter of fact, historical research using patent data in general is scanty. In this dissertation, the author strives to fill this gap.

Industrialization fundamentally changed the trajectory of world history. Correspondingly, one of the most interesting problems of economic history is still the question why some nations were able to industrialize successfully and others were not. England was the first nation to undertake industrialization after the Industrial Revolution. Yet in academia, even the very name “industrial revolution” has been heatedly debated.[35] Is it “industrial revolution” or “industrious revolution?”[36] Is it evolution or revolution? The role of technological innovation and human capital in the British Industrial

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[32] Schankerman and Pakes (1986) found that most of the value of the patent stock in Britain, France and the former West Germany between 1955 and 1981 was represented by the upper five percent of patents.

[33] From 1877 to 1914, there are around 34,300 patents that survived for at least ten years.

[34] Schmookler (1962) specifically argues against the use of annual patent data (which may be influenced by many non-invention related factors) preferring instead 5-year periods.

[35] Coleman (1983) argues rather provocatively that the term “Industrial Revolution” is confusing and too vague to be useful. This view has been echoed by Jones (1988) and Lee (1986).

[36] See DeVries (1994) for a good survey on this debate.

Revolution has also been heatedly debated and no convincing conclusions have been reached.[37]

After the British Industrial Revolution, the German industrialization is a landmark event in human history. It had profound and long-lasting impacts. Accordingly, it stimulates much research.[38] In general, industrialization can be characterized as the transition process that leads an economy from stagnation to sustainable growth.[39] Mokyr suggests that the key factor of this transition is a fundamental change in the behavior of economic actors who have to develop both the willingness and ability to create a permanent stream of innovations that shifts the production frontier determined by the efficient use of the resources land, labor and capital steadily outwards.[40] North and Thomas stress that the willingness to innovate depends on the efficiency of institutional arrangements that are supposed to channel individual economic effort in the socially most profitable activities.[41] According to this view the liberal reforms of the 19th century that defined property rights with respect to land, real capital and finally inventions clearly were a necessary precondition for the industrialization of Germany. Keck (1993) adds that during the German industrialization the ability to innovate was considerably increased by new organizations like an advanced education system, public research organizations or industrial research departments. Despite the general consensus among economic historians that the application of new technological knowledge (rather than increased input of production) was the prime source for overcoming economic stagnation, not much is known about the concrete timing of innovations and their distribution over industries and regions during the German industrialization.[42] We would like to examine the role of technological innovation in the German industrialization and economic development.

STRUCTURE OF THE DISSERTATION

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[37] See Mokyr (1993) for a fine survey on the research on the British Industrial Revolution.

[38] Gerschenkron made his fame by studying the role of universal bank in the German industrialization.

[39] See Landes (1969). See also Rostow (1960).

[40] See Mokyr (1990), p. 4

[41] See North and Thomas (1973), p. 2.

[42] See Metz and Watteler (2002), pp. 37-41. For the patenting activities during the British and American industrialization, see Khan and Sokoloff (1998); MacLeod (1988); and Sokoloff (1988).

This Ph.D. dissertation strives to study innovation during the German industrialization in a systematic and analytical way. Each chapter constitutes an integral facet of the whole structure in the intellectual inquiry.

The role of technological innovation in the German industrialization, an important topic, has not been thoroughly examined so far. In chapter 1, we investigate whether there are some particular waves of patents from certain technological classes that correspond with the development of certain industries during the German industrialization. Since Adam Smith, economists have paid great attention to geography. And there has been growing literature on the topic of geography of innovation. Until recently, relevant literature has focused almost exclusively on the case of the USA. Little work has been done on Germany.[43] Chapter 2 tries to fill the void and study innovation in Prussian regions. Some intriguing questions (such as regional catch-up and convergence) are examined. And the important role of human capital and infrastructure in fostering innovation is confirmed. These research results surely have policy implications. Innovation and cities are inextricably related. Urban residents acquired most of the patents in Germany. Chapter 3 extends the geographic scope to Germany as a whole and studies innovation in German cities.

Knowledge production and spillover occupy the center stage of the innovation system approach. Economists used to believe that there is no free lunch in this world. Many contemporary economists provide counter arguments to this general statement. Mokyr (1990) argues that economic history is full of free lunches, as well as (more frequently) very cheap lunches. Knowledge spillovers are very typical examples for free lunches or cheap lunches as knowledge has the feature of a quasi public good. One important reason behind the phenomenon that firms tend to cluster is that firms can benefit more from knowledge spillover from clustering. This is especially true for knowledge-intensive firms. Therefore, it is impossible to discuss innovation in a sophisticated way without taking clustering and knowledge spillover into account. Are firms in clusters really more innovative? Using firm-level data from Baden region, chapter 4 tries to answer this question empirically. It examines whether firms located in industrial clusters are more innovative than firms located outside these clusters. Chapter 5 is dedicated primarily to the study of knowledge spillover. Interestingly, we confirm that

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[43] Caniels (1997) covered five European countries (Spain, France, Italy, the Netherlands, and the United Kingdom), but missed Germany. The author stated regretfully, “However, it should be kept in mind that the

knowledge spillover is geographically bound as knowledge spillover is facilitated by close interactions among people.

Research (re-search) is accumulative by nature. It is, like innovation, essentially a process that never ends. Any research should open windows towards more research and stimulate further studies. As we stated above, if used properly, patents can serve as good indicator of innovation. From chapter 1 to chapter 5, we have used patents that have survived at least ten years to decrease the noise/signal ratio of patents. Yet we can further improve the quality of the patent data used in our research. In chapter 6, the last chapter of this dissertation, we use patent survival data. Employing Cox regression technique, we study whether patents from different technological classes and different countries have distinct survival rates. Thus, in future, we would be able to attach different values to patents to get weighted patent data, which is a more precise measure of innovation. Moreover, the survival data would enable us to study the value of patent protection, an important and interesting topic.

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sample used in this paper does not include German regions, even though recent studies (Verspagen 1997, Breschi 1995) have found that the most innovative regions of Europe are located in Germany."

Chapter 1

Successive Waves of Technological Progress

1877-1918[44]

Abstract

We demonstrate that technological progress during German industrialization occurred in at least four different technological waves. We distinguish the railway wave (1877-1886), the dye wave (1887-1896), the chemical wave (1897-1902), and the wave of electrical engineering (1903-1918). Evidence is presented that inter-industry knowledge spillovers between technologically, economically and geographically related industries were a major source for innovative activities during the German industrialization. We also show that technological change affected the geographical distribution of innovative regions. Using an index of comparative advantage in technological sectors, we find out that the regions that increased their innovativeness during the waves of technological progress revealed special strength in the technological clusters electrical or mechanical engineering or chemicals.

1.1. INTRODUCTION

It has been argued that the diffusion of new technological knowledge might be as important as its creation to make an economy grow.[45] This is especially true for knowledge spillovers that increase the productivity of firms in the technological or geographical neighborhood of the original inventor.[46] Jacobs (1969) believes that the most important knowledge spillovers take place across industries in highly diversified industrial regions. This argument has received further support by studies that confirm the significance of inter-industry technology flows and point out that technological solutions are often transferred from the sector where they were originally invented to a variety of

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[44] See also Streb, Baten and Yin (2005) on these issues.

[45] See Streb (2003a) as a recent representative work.

[46] For a survey on knowledge spillovers, see Griliches (1992).

industries applying them.[47] In this respect, Lundvall (1988) emphasizes the importance of inter-industry knowledge spillovers between suppliers and customers. However, except for some anecdotal evidence regarding the information exchange between German dye producers and textile firms in the late 19th century,[48] not much is known about the actual impact of knowledge spillovers during the German industrialization.

The purpose of this chapter is to find evidence for important technological and geographical knowledge spillovers during German industrialization. Our research hypotheses are:

1. Patent booms in leading technological sectors accelerated innovating activities in technologically related industries via knowledge spillovers.
2. Knowledge spillovers between technologically related industries were considerably facilitated by geographical proximity.

We organize the remaining chapter in three main sections. Section 2 analyzes the technological distribution of high-value patents over time. We will identify four successive patent waves in industrializing Germany during which knowledge spillovers occurred between technologically related industries. Section 3 discusses how technological change described by these patent waves affected the geographical distribution of innovative regions. It will turn out that the most innovative regions relied on diversified industry clusters in the fields of mechanical or electrical engineering or chemicals. Section 4 concludes the chapter.

1.2 TECHNOLOGICAL DISTRIBUTION OF HIGH-VALUE PATENTS OVER TIME

Patents can generally be assigned to the industry in which they were developed or to the industry that will use or produce the resulting products and whose productivity may thereby increase.[49] New dyes, for example, usually originated in chemical firms but were used by textile producers. The technological classes labelled to the patents by the German patent office rather corresponded to the industry that was supposed to use the respective invention. However, the correspondence between the technological class and the industry that might profit by the patent was far from perfect. A major shortcoming was that patents

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[47] Scherer (1982) finds that as many as 70 percent of inventions in a given industry are applied in other industries. See also Bairoch (1988).

[48] See Beer (1959). See also Streb (2003b), pp. 75-6.

[49] See Scherer (1982), pp. 228-9.

were assigned to only one technological class although they were often useful in several industries. New inventions with respect to steam engines, for example, were allocated to technological class 14 but probably increased the profits in a wide range of industries that used this kind of engine as a source for kinetic energy. Table 1.1 lists the 18 technological classes that contained the most high-value patents of all 89 classes in the period between 1877 and 1918.

Table 1.1 Ranking of technological classes 1877-1918

Rank	**Class**	**Number of high-value patents**	**Share in all high-value patents**	**Cumulated shares**
1	21 Electrical engineering	3350	8.51%	8.51%
2	12 Chemicals (without dyes)	2840	7.22%	15.73%
3	22 Dyes	2206	5.61%	21.34%
4	42 Scientific instruments	1584	4.03%	25.37%
5	15 Printing	1429	3.63%	29.00%
6	49 Metal processing	1202	3.06%	32.06%
7	20 Railway installations	1146	2.91%	34.97%
8	47 Machine parts	1137	2.89%	37.86%
9	72 Firearms	1003	2.56%	40.42%
10	8 Dyeing	928	2.36%	42.78%
11	45 Agriculture	904	2.30%	45.08%
12	52 Sewing	706	1.79%	46.87%
13	80 Earthenware	675	1.72%	48.59%
14	46 Internal combustion engines	627	1.59%	50.18%
15	30 Health care	615	1.56%	51.74%
16	13 Steam boiler	605	1.54%	53.28%
17	81 Transportation	601	1.53%	54.81%
18	14 Steam engine	553	1.41%	56.22%

This ranking could lead to the impression that during German industrialization technological progress mainly relied on electrical engineering, chemicals including dyes and scientific instruments which together included more than one quarter of all high-value patents. Three arguments speak against this simple conclusion. First, we have already mentioned that industries like electrical engineering or chemicals generally seem to have a higher propensity to patent their inventions than, for example, the machine and vehicle industry that above all tries to protect their inventions by keeping secret how to make them. Second, the technological classes of the German patent law considerably differed in the width of the technological field they covered. Patents of the fields of electrical engineering and chemicals were concentrated in classes 21 and 12 or 22 respectively whereas patents with regard to mechanical engineering were spread over several classes like 47 (machine parts), 49 (metal processing), 14 (steam engine) or 63 (vehicles). What is more "machinery patents" could also be found in less obvious classes like 45 (agriculture → agricultural machinery) or 86 (weaving → textile machines) to name just a few. This last finding also implies that it is not advisable to try to calculate the accurate number of "machinery patents" just by aggregating some technological classes like Hoffmann did for "metal working" on basis of all patents granted.[50] Third, our sample is dominated by the many high-value patents of the pre-World War I boom during which electrical engineering patents especially flourished. As a result, electrical engineering has gained the leading position in table 1.1 even though this technological class was not dominating patenting activity in the decades before 1900. These three observations together lead to the conclusion that technological progress in the broad technological field of mechanical engineering played a much greater role during German industrialization than table 1.1 might suggest.

We are able to solve most of these problems by analyzing the patenting activities in the 89 technological classes over time. It turns out that the relative number of high-value patents of the technological classes presented in table 1.1 was not constant between 1877 and 1918. In general, different technological classes boomed in different sub periods. Figure 1.1 visualizes this finding by showing the major patent booms between 1877 and 1918. A major patent boom of a specific technological class is defined as the period in which this technological class held an annual rank no less than its average rank[51] in every year and one of the three highest ranks in at least one year of this period.

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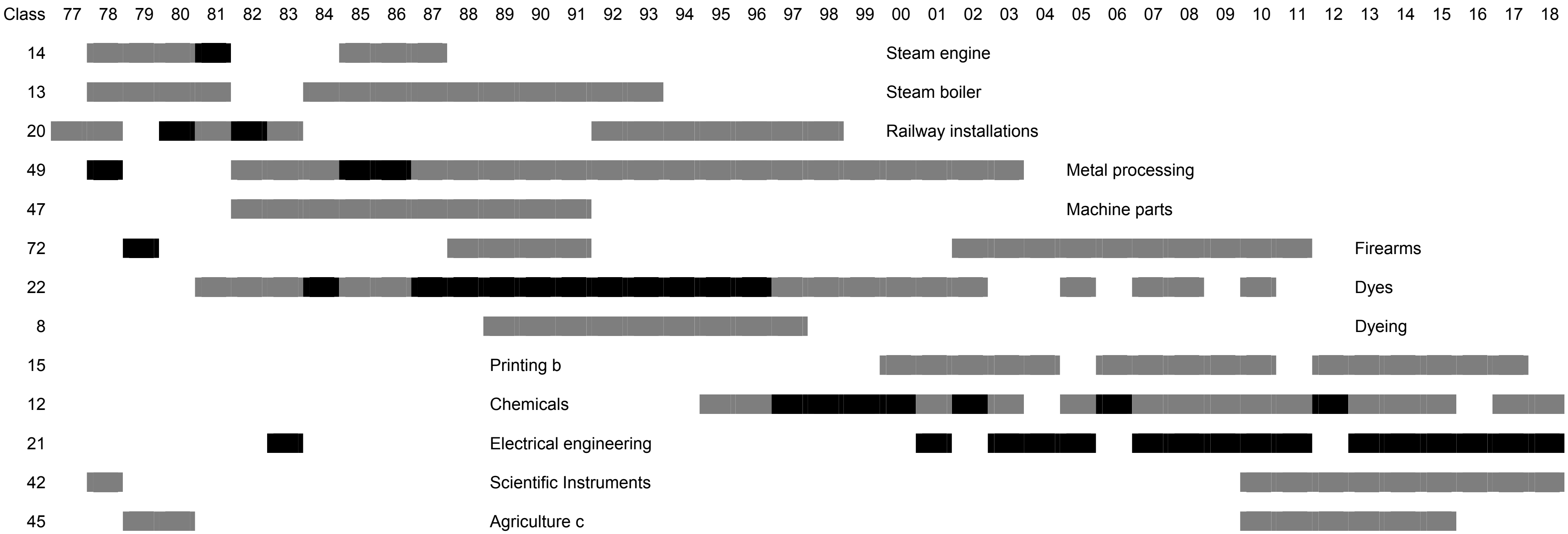
[50] See Hoffmann (1965), pp. 264-9.

[51] The average rank of a technological class is shown in table 1.1.

Figure 1.1 The major patent booms 1877-1918[a]



a Figure 1.1 doesn't contain the less important technological classes 6 (brewery, rank 2 in year 1877, average rank 31), 36 (heating systems, rank 2 in 1878, average rank 35), 68 (metal working, rank 1 in 1877, average rank 40), 76 (spinning, rank 3 in 1881, average rank 25) and 89 (sugar, rank 2 in 1879, average rank 44).

b The highest rank of printing was 4.

c The highest rank of agriculture between 1910 and 1915 was 5.

In figure 1.1, patent booms of specific technological classes were generally marked by grey bars. In years in which a technological class was ranked first, this bar is coloured black. We can discern four distinct waves of technological progress:

1. the railway wave (1877-1886),
2. the dye wave (1887-1896),
3. the chemical wave (1897-1902), and finally
4. the wave of electrical engineering (1903-1918).

The railway wave was dominated by patents in the technological classes steam boiler (class 13), steam engine (class 14), railway installations (class 20) which mainly contained inventions concerning rail tracks, rail switches and signals, machine parts (class 47) and metal processing (class 49). Traditionally, the railway industry is regarded as Germany's leading sector in the middle of the 19th century that, by increasing demand for coal, iron and advanced engineering technology, caused the parallel growth of the German coal mining, iron and steal industry and mechanical engineering.[52] Our finding supports the conjecture that the railway industry generated forward and backward linkages not only by selling or buying tangible goods and services but also played an important role as a focal point for the exchange of intangible new technological knowledge in the field of mechanical engineering indicated by the patent boom in most of the industries of the railway cluster between 1877 and 1886.

The industries of the railway cluster kept to their above-average patenting activities until the beginning of the 20th century. This did not prevent, however, that the new industries of the second industrial revolution, namely chemicals and electrical engineering, took over the technological lead in the midst of the 1880s. According to Murmann's co-evolutionary approach, the meteoric rise of the German dye industry was paradoxically caused both by the absence of a German patent law before 1877 and by its existence afterwards.[53] The absence of patent protection led in the 1860s and 1870s to a much higher number of newly founded dye producers in Germany than in Britain or the United States where entry barriers were substantial because of an already existing patent law. The initially high number of German dye producers resulted in a fierce price competition in which only those firms that were able to cut costs considerably survived. After the establishment of the German patent law in 1877, the winners of this selection process gave up their traditional strategy of imitating new dyes of foreign inventors and

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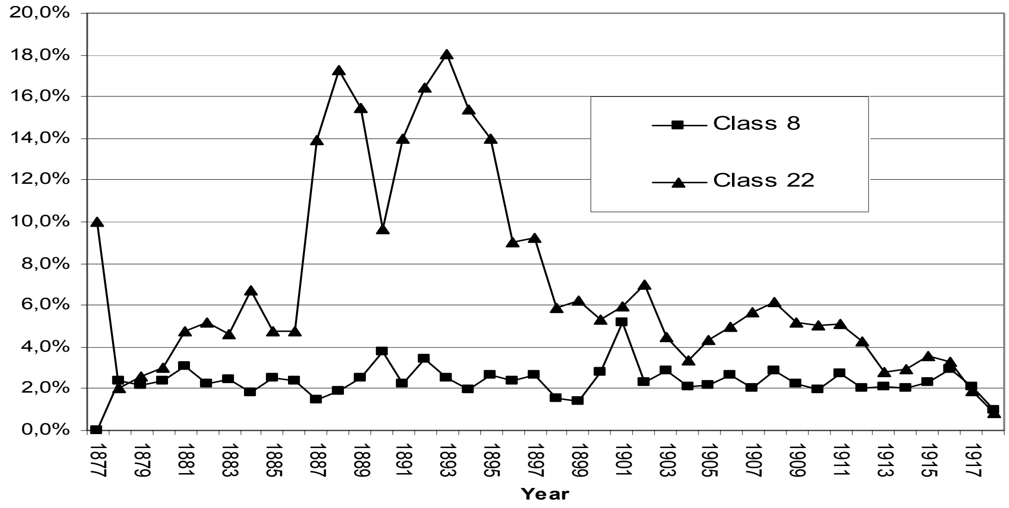
[52] See Fremdling (1975), p. 5.

[53] See Murmann (2003), pp. 84-93.

instead used their increasing profits to build up industrial laboratories in which for the first time in economic history white-collar workers searched systematically and based on the division of labor for economically useful inventions.[54] As a result, the German dye producers considerably accelerated the evolution of the synthetic dye technology by inventing famous dyes like Congo Red or Synthetic Indigo. They also succeeded in shaping their institutional environment by lobbying for the change of patent law in 1891 explained above.

Figure 1.2 Share of the high-value patents of classes 8 and 22 in all high-value patents, 1877-1918, in percent



This fundamental change of innovating strategy first led to the dye wave (1887-1896), in which patents with respect to new dyes (class 22) ranked first in every year. Figure 1.2 reveals that after some time lag the invention of new synthetic dyes also accelerated the development of new and complex chemical and mechanical dyeing procedures patented in technological class dyeing (class 8). In a next step, this new knowledge spilled over to the downstream textile industry. The main channel of this knowledge transfer was the customer consulting service of the German dye producers who regularly informed textile producers about both new dyes and new dyeing methods.[55] Wallusch, Streb and Yin (2003) observe a statistical bi-directional Granger causality

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[54] See Meyer-Thurow (1982).

between German net cloth exports and patents of technological classes dyes and dying, which suggests that during the German Empire the knowledge spillover between chemical and textile firms created an upward circle of endogenous growth. The increasing demand for synthetic dyes of the prospering textile firms initiated further R&D projects of chemical firms that led to new patents and via customer consulting to additional economic benefits of the German textile industry. This process, however, was not infinite but came to an end when the synthetic dyes technology was fully exploited.

Dyestuffs remained the dominating business of the German chemical firms in the 19th century.[56] Nevertheless, the research laboratories also started to explore other new technological fields like inorganic acids, pharmaceuticals or synthetic fertilizers. The growing importance of these new products was revealed during the chemical wave (1897-1902) when the technological field of chemicals without dyes (class 12) mostly gained rank 1 with regard to the number of high-value patents. As we have already mentioned, this development was considerably fostered by the change in the patent law in 1891.

Surprisingly enough, the wave of electrical engineering (1903-1918) was not dominated by the two gigantic companies Siemens and AEG. In the period between 1901 and 1916, for example, Siemens and AEG got only 10.7 percent and 7.9 percent respectively of 2,607 high-value patents in the technological class of electrical engineering (class 21), although the combined market share of these two giants was surely more than 20%. Our data set enables us to identify other important inventors that were for example Felten & Guilleaume AG in Cologne, Robert Bosch in Stuttgart, Hartmann & Braun AG in Frankfurt a/m, or Eisenbahn-Signalbau-Anstalt Max Jüdel & Co. AG in Braunschweig. In Berlin, several innovative firms like C. Lorenz Telephon- & Telegrafenwerke AG and Deutsche Telephonwerke GmbH used the opportunity offered by the new telephone technology to enter the market. These observations suggest that the Schumpeterian hypothesis that firm size is a necessary pre-condition for outstanding innovativeness might not have been generally true during German industrialization.[57]

To test our hypothesis econometrically, we compare the ranking of the one hundred largest German firms of 1907 measured by employment[58] with their ranking with

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[55] See Beer (1959), p. 91.

[56] See Hippel (2002), p. 47.

[57] Following Schumpeter (1950, p. 135), Galbraith states: “Thus, in the modern industry shared by a few large firms, size and the rewards accruing to market power combine to ensure that resources for research and technical development will be available. ... The net of all this is that there must be some element of monopoly in an industry if it is to be progressive.” Galbraith (1957), p. 88.

[58] See Fiedler (1999), pp. 44-48.

respect to the number of high-value patents. It turns out that the Spearman's rank correlation coefficient is not positive, but has the negative value –0.242. In the sample of the one hundred largest German firms of 1907, the smaller ones were rather the more innovative ones. This finding can be explained by the fact that this sample was dominated by the very large mining, metals and railway companies like Bergwerksgesellschaft Hibernia, Röchling'sche Eisen- und Stahlwerke or Preussisch-Hessische Staatseisenbahn that could not profit from the technological waves of the second industrial revolution and had therefore only a very small number of high-value patents.[59]

A very interesting facet of the wave of electrical engineering is the patent boom of the technological class of scientific instruments (class 42) that started (similar to the timing of the patent booms in dyes and dyeing) with some time lag to the preceding boom in electrical engineering. Generally, the number of patents in the field of scientific instruments that are needed to develop innovations in most of the other technological fields can be interpreted as an excellent indicator for the innovative potential of an economy. In this respect, the high number of this kind of patents between 1910 and 1918 might indicate that in this period the German industry was well-equipped to produce another generation of high-value patents.

It has been widely assumed that the German industrialization took place in the transition period between two long Kondratieff cycles of which the first was dominated by the railway sector, the second by chemicals and electrical engineering.[60] Our analysis confirms this view and reveals more details about the complexity of the technological development during these cycles. In each of the four technological waves depicted in figure 1.1, the outburst of innovative activities was not limited to the leading sector but occurred with some time lag in a couple of other industries which were technologically and economically linked to the original creator of the basic innovations. In this process, new knowledge spilled over both from the leading sectors to their customers and suppliers and back from the latter to the former. Firm size was not a necessary precondition for successful patenting activities. This is especially true for the patent booms of dyes and electrical engineering that weren't driven by already long-established firms but by newcomers that then grew because of their above-average innovativeness.

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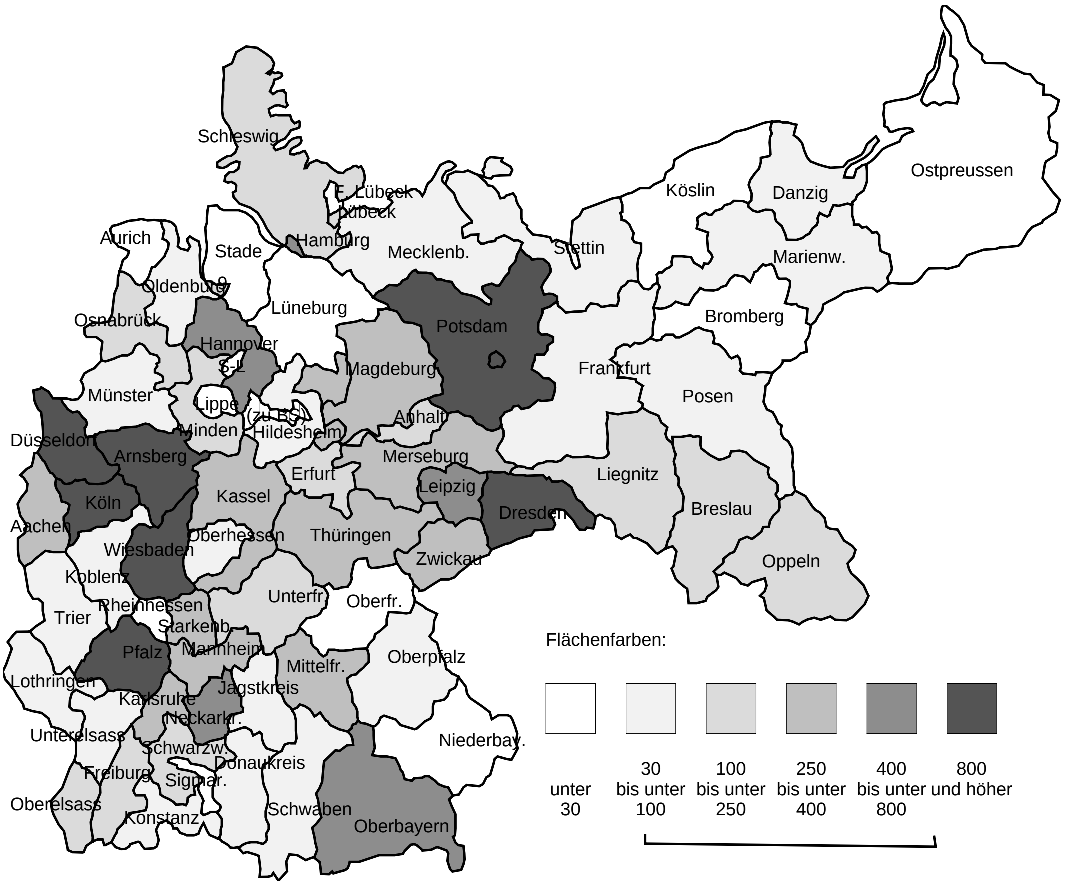
[59] We will come back to the Schumpeterian hypothesis in the context of German industrialization in chapter 2 and chapter 4. In chapter 2, we discover that firm size does not seem to have statistically significant impact on innovation in Prussian regions. In chapter 4, using a data set based on Kocka and Siegrist (1979), we will discuss the largest firms and their representation among the most innovative firms in Germany.

[60] See, for example, Freeman, Clark, and Soete (1982).

1.3. GEOGRAPHIC DISTRIBUTION OF PATENTS

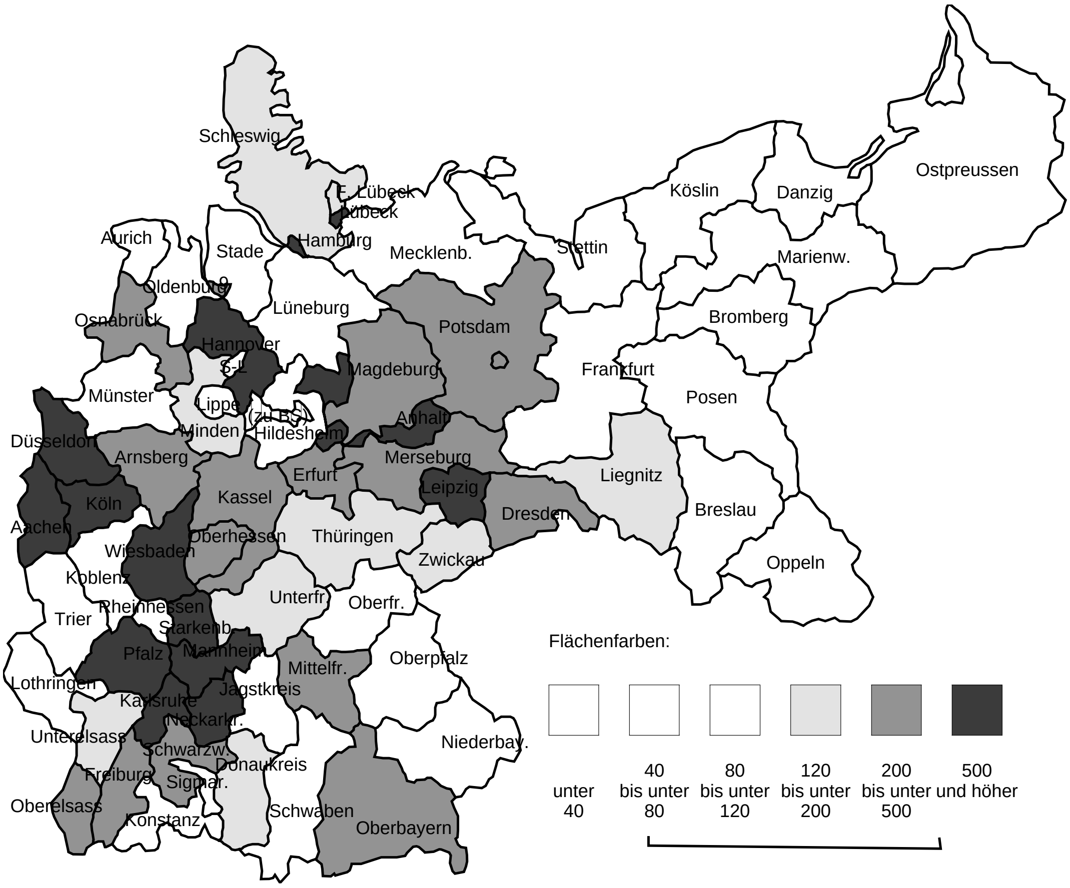
Map 1.1 shows that during German industrialization the high-value patents were not more or less uniformly distributed over the different German regions but were geographically clustered in a broad belt that reached from the districts neighboring the river Rhine in the West to Greater Berlin and Saxony in the center.

Map 1.1 The geographical distribution of high-value patents 1878-1914



To control for population, we divided the number of high-value patents by regions' population.

Map 1.2 The geographical distribution of high-value patents per capita 1878-1914 per million residents (population of 1910)



As a result of this calculation, especially some regions in the southwest like Neckarkreis or Mannheim improved their relative innovativeness while other regions like Potsdam or Dresden fell behind. We should keep it in mind that map 1.2 is also not a perfect representation for regions' relative innovativeness because their number of residents increased with different growth rates during the period under consideration. However, since both maps show nearly the same geographical distribution of patenting activity, we are confident that in the following we can use the absolute number of high-value patents to identify the development Germany's most innovative regions correctly.

The dominance of the Rhine region and Greater Berlin well goes with Sokoloff's seminal finding that the patenting activities in early 19th century America were concentrated in metropolitan areas and along waterways (Sokoloff 1988). Sokoloff explains this geographical clustering of patents mainly by demand factors. He bases his argument on the assumption that the profitability of a patent was the higher the larger the market where the respective innovation could be sold. Because of this correlation, Sokoloff concludes that firms which were either located near highly populated metropolitan areas or could transport their products at low costs along navigable waterways to distant markets faced considerably higher incentives to patent than firms in more remote areas. As a result, patents were concentrated in the former regions. Demand factors, however, also determine the original choice of location. That is why it is necessary to distinguish clearly between a firm's choice of location and its decision to patent.

Sokoloff is well aware of this problem and therefore controls for the division of the labour force between agriculture and manufacturing. It turns out that his estimated positive relationship between firms' proximity to navigable waterways and the intensity to patent is robust to the inclusion of this variable supposed to measure the level of industrial activity in a region. Hence, in Sokoloff's sample, demand factors really seem to influence the geographical distribution of patents independently from the original choice of location.

The German case, however, suggests that, because of industries' uneven geographical distribution, the aggregated level of industrial activity might not be the adequate variable to distinguish between the demand effects on the firms' location and patenting decision respectively. Obviously, the broad west-east strip of German regions with an above-average number of high-value patents was also the favored location of those industries in which most of the high-value patents originated. Long before the German patent law of 1877 actually came into force, these industries' original choice of location might have been influenced by a variety of factors like the expected market size or the availability of raw materials and intermediate products. Large chemical firms like BASF or Bayer, for example, preferred to settle at the banks of the river Rhine which was not only an important navigable waterway but was also used as a water source and to get rid of effluents. It is therefore conceivable that the great majority of all chemical firms located themselves along waterways. Consequently, waterway areas had an above-average density of chemical firms and because of this industry's high patenting activity also a higher number of patents than regions with a similar industrial activity level that were dominated by industries that patented less than the average. The same argument holds for mechanical and electrical engineering. Firms engaged in the field of mechanical engineering were especially concentrated in the geographical neighborhood of iron and steal producers, namely in the Greater Ruhr area, and near textile firms, namely in

Saxony.[61] Berlin was the center of German electrical engineering. The fact that the German industries with an apparently above-average propensity to apply for high-value patents were geographically clustered might have led quite to a similar geographical distribution of high-value patents. To check the robustness of the relationship between firms' proximity to metropolitan areas or mass transportation infrastructure and the intensity to patent proposed by Sokoloff, it would therefore be advisable not to control just for the general level of industrial activity but for the activity levels of different industries located in the regions under consideration. Using our patent sample, our research outcome in chapter 2 supports Sokoloff's hypothesis by showing that railway density had a statistically significant impact on innovations in Prussian regions no matter patents with respect to chemicals and electrical engineering were excluded or not.[62]

Following Feldman (1994), we employ a Chi-squared test on the independence of the location and technological class of the patents.[63] In our contingency table of high-value patents per region and per technological class, rows are German regions while columns are technological classes of patents. We use the following formula to obtain the expected frequency

$$e_{ij} = \frac{R_{iT} \cdot C_{Tj}}{T}$$

where R_{iT} and C_{Tj} are the row total (marginal sum) for *i*th row (region) and the column total (marginal sum) for *j*th column (technology class), and T is the total frequency calculated with marginal sums. Our contingency table has dimensions r*c (rows * columns).

The Chi-squared test formula is

$$x^2 = \sum_i \sum_j \frac{(o_{ij} - e_{ij})^2}{e_{ij}}$$

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[61] See Barth (1973), pp. 73-83.

[62] In chapter 2 of this dissertation, we will see that human capital formation, measured by the number of students of technical and commercial schools, also significantly influenced the geographical distribution of high-value patents in Prussia.

[63] As a matter of fact, there are several tests of independence although Chi-squared test is the most versatile one and is most widely used. The general rule of selection is that if the highest expected frequency (m) is larger than 10, Chi-squared test is used; if m is between 5 and 10, Yates' correction for continuity is used; if m is smaller than 5, Fisher's exact test is used. We choose Chi-squared test because our highest expected frequency (m) has always exceeded 10. The results of a chi-squared test do not solve problems, but they do point out whether we can proceed further. In our case, the answer is positive. For technical details, see R. Myers, R. Walpole, "Tests of hypotheses", in Myers and Walpole (1978), pp. 268 – 273.

where O_{ij} is the observed frequency and E_{ij} is the expected frequency as defined above. The degree of freedom is (r-1)*(c-1)=(85-1)*(89-1)=7392.

The rationale behind this Chi-squared test is that if the probability of patenting in the technological class and the probability of patenting in the region are found to be not independent, then geography affects inventive activities. There is evidence that geography affects inventive activity. Our Chi-square statistic is very high (21435). As we have very high degree of freedom (7392), the p-values of the χ^2 statistics are even less than 0.005. Thus, we reject the null hypothesis that the probability of patenting in the technological class and the probability of patenting in the region are independent. The base for further inquiry is firmly established.

The outcome reveals that the distribution of innovative activity is not random. With respect to the number of all high-value patents, the ranking of the most innovative German regions changed during the four waves of technological progress. Table 1.2 allows us to distinguish regions with continuous, decreasing and increasing relative innovativeness. Berlin and Duesseldorf kept their leading position during the whole period under consideration but it is interesting to note that Duesseldorf, first, was able to catch up to Berlin with respect to the number of high-value patents during the dye period, and then, considerably fell behind in the period of electrical engineering. Wiesbaden and Palatinate also increased their innovativeness during the dye period while Potsdam developed its innovative potential mainly during the period of electrical engineering. Dresden and Leipzig that ranked three and four respectively during the railway period displayed decreasing relative innovativeness in the following waves of technological progress.

Table 1.2 The most innovative regions during the four waves of technological progress, numbers and shares in all high-value patents of the respective wave

Railway 1877-1886			Dyes 1887-1896			Chemicals 1897-1902			Electrical Engineering 1903-1914		
Region	Patent	Share	Region	Patent	Share	Region	Patent	Share	Region	Patent	Share
Berlin	320	11,7%	Berlin	512	10,7%	Berlin	521	11,7%	Berlin	3159	14,2%
Düsseldorf	155	5,6%	Düsseldorf	512	10,7%	Düsseldorf	414	9,3%	Düsseldorf	1982	8,9%
Dresden	105	3,8%	Wiesbaden	300	6,2%	Wiesbaden	241	5,4%	Wiesbaden	1252	5,6%
Leipzig	103	3,8%	Palatinate	186	3,9%	Dresden	124	2,8%	Potsdam	935	4,2%
Wiesbaden	91	3,3%	Dresden	142	3,0%	Palatinate	120	2,7%	Palatinate	573	2,6%
Arnsberg	78	2,8%	Cologne	128	2,7%	Arnsberg	101	2,3%	Arnsberg	515	2,3%
Cologne	74	2,7%	Arnsberg	119	2,5%	Cologne	98	2,2%	Cologne	511	2,3%
Magdeburg	72	2,6%	Leipzig	102	2,1%	Potsdam	96	2,2%	Dresden	483	2,2%
Hamburg	61	2,2%	Chemnitz	95	2,0%	Hamburg	95	2,1%	Leipzig	456	2,0%

Karlsruhe	57	2,1%	Hamburg	81	1,7%	Leipzig	92	2,1%	Neckar	401	1,8%

To check if these changes in the ranking of the most innovative regions could be caused by the transition from one technological wave to the next, we calculated for every technological class an index of location quotient (LQ), where *n* denotes the number of patents, subscript *i* the region, subscript *j* the technological class, and n_G the total number of high-value patents granted to German patentees in the period between 1877 and 1918:[64]

$$LQ_{ij} = \frac{n_{ij} / n_i}{n_j / n_G}$$

If LQ_{ij} is equal 1, patents in technological class *j* are equally represented in the region *i* and in Germany. If LQ_{ij} is larger than 1, region *i* specialized in technological class *j*.

Table 1.3 presents for every region named in table 1.2 the five technological classes with the highest location index. In some regions, these technological classes formed a cluster of economically and technologically related industries that are named in the last column of table 1.3. Bold letters indicate clusters of three or more related industries; normal letters refer to clusters of two related industries.

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[64] See Feldman (1994). Some scholars refer to this LQ as "technological revealed comparative advantage" (e.g., Malerba et al. 1997; Archibugi and Pianta 1992).

Table 1.3 Technological revealed comparative advantages and innovative cluster

Region	Revealed Comparative Advantage					Innovative cluster
	1	2	3	4	5	
Continuous innovativeness						
Berlin	Electrical engineering (21) 3.2	Signalling (74) 3.1	Lighting (4) 2.4	Printing (15) 2.3	Railway instal-lations (20) 2.0	**Electrical Engineering**
Dusseldorf	Firearms (72) 4.2	Cutting Tools (69) 4.1	Metal sheets (7) 2.7	Iron production (18) 2.5	Dyes (22) 2.4	**Mechanical Engineering**
Wiesbaden	Dyes (22) 4.3	Metal-lurgical Engineering (40) 3.0	Shoes (71) 2.6	Chemicals (12) 2.5	Ore preparing (1) 2.1	Chemicals + Metal-lurgical Engineering
Arnsberg	Pumps (59) 11.3	Fuel (10) 9.1	Drying and Roasting (82) 8.9	Tools (87) 6.8	Mining (5) 6.7	**Mining**
Cologne	Rope making (73) 13.7	Ore preparing (1) 7.7	Harnesses (56) 7.4	Writing Implements (70) 5.6	Internal combustion engines (46) 8.3	
Increasing relative innovativeness						
Palatinate	Dyes (22) 5.3	Chemicals (12) 3.8	Dyeing (8) 2.5	Shoes (71) 2.4	Chemical metal processing (48) 1.5	**Chemicals including dyes**
Potsdam	Toys (77) 4.9	Photography (57) 4.8	Vehicle construction (63) 2.5	Railway construction (19) 2.2	Burning systems (24) 2.0	**Mechanical Engineering**
Neckar	Internal combustion engines (46) 8.3	Bakery (2) 7.9	Tanning (28) 5.3	Book-bindery (11) 4.7	Cutting tools (69) 3.6	Mechanical engineering
Decreasing relative innovativeness						
Dresden	Glass (32) 11.8	Tobacco (79) 11.5	Control engineering (60) 8.9	Paper processing (54) 4.6	Food stuff (53) 3.5	
Leipzig	Book bindery (11) 13.7	Musical instruments (51) 9.9	Harnesses (56) 7.4	Spinning (76) 3.9	Printing (15) 3.3	Books
Magde-burg	Salt works (62) 30.4	Hat making (41) 12.4	Control engineering (60) 9.0	Harnesses (56) 7.6	Ore preparing (1) 6.6	
Hamburg	Haber-dashery (44) 6.7	Ship building (65) 6.4	Sewing (52) 5.3	Food stuff (53) 4.7	Harnesses (56) 4.4	
Karlsruhe	Haber-dashery (44) 8.9	Harnesses (56) 8.3	Travelling equipment (33) 6.4	Water-supply (85) 5.8	Explosives (78) 5.2	

The striking result of this calculation is the fact that most of the regions with continuous innovativeness and all of the regions with increasing innovativeness possessed at least one innovative cluster while the regions with decreasing innovativeness generally did not. This observation is evidence for the hypothesis that inter-industry knowledge spillovers between geographically concentrated firms were a major source for innovation activities. Berlin specialized in electrical engineering including signalling and alarm systems as well as lighting that perfectly explains its great innovative outcome during the wave of electrical engineering. Wiesbaden and Palatinate had technological revealed comparative advantages in chemicals and did especially well during the waves of dyes and chemicals. Regions like Duesseldorf or Potsdam heavily depended on mechanical engineering but were nevertheless able to keep or even improve their rank under the most innovative regions after the railway wave had ended. The development of the regions Cologne, Potsdam and Neckar suggests that in the early 20th century a fifth wave of technological progress with respect to vehicle construction and internal combustion engines started.[65]

The fact that the German regions with a high number of high-value patents often specialized in particular technological fields does not imply that these regions displayed their innovativeness only in a few technological classes. Rather the opposite was true. As figure 1.3 shows, the German regions with a high number of high-value patents usually relied on a comparatively high diversity of technological classes measured by the following version of the Herfindahl-Hirschman-Index (HHI)[66].

$$HHI_i = \sum_{j=1}^{89} \left(\frac{n_{ij}}{n_i} \right)^2 \cdot 100$$

Again, *n* denotes the number of high-value patents summed up for the years 1877 to 1918, *i* the region and *j* the technological class. Here, the Herfindahl-Hirschman-Index would be 100 when a region patented in only one technological class and 1.1 when the patents of a region were equally distributed over the 89 technological classes used by the German patent office.

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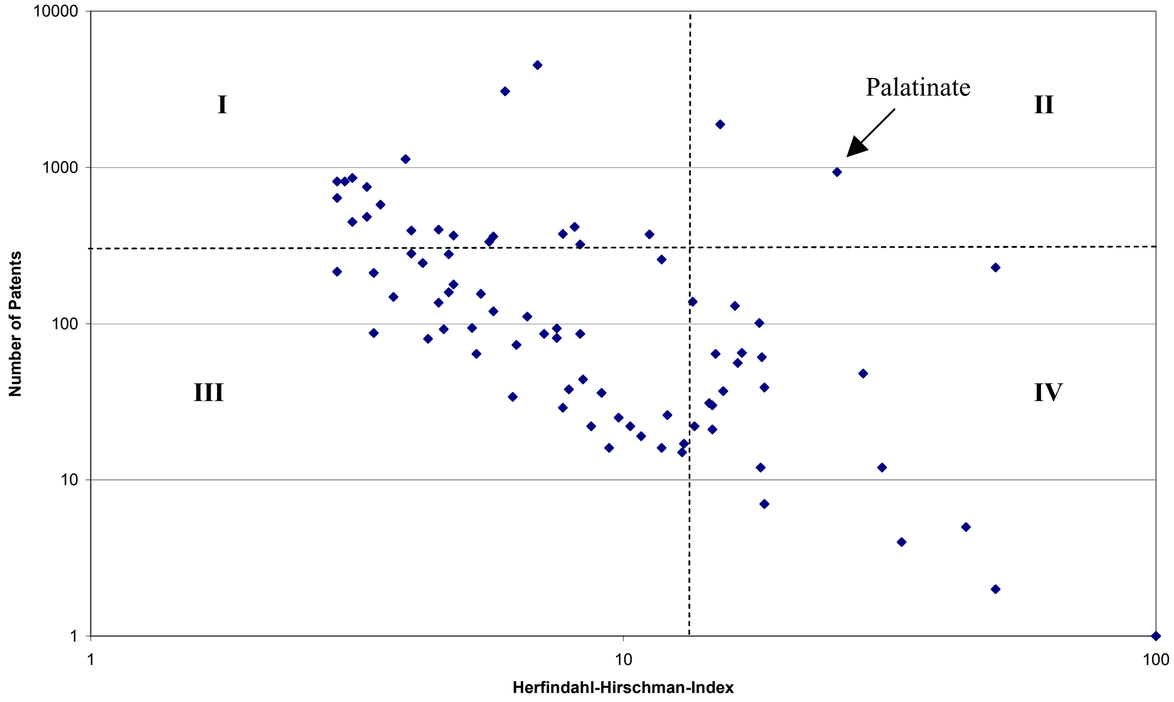
[65] In the mid of the 1920s, the classes internal combustion engines (46) and vehicle construction (63) were ranked sixth and second respectively with respect to the number of patents applied for. See Wernekke (1927), p. 414.

[66] The HHI is a commonly accepted measure of market concentration.

Figure 1.3 The technological Herfindahl-Hirschman-Index of the 85 German regions



In this figure 1.3, every point represents the combination of the number of high-value patents and the Herfindahl-Hirschman-Index of a particular region. The dotted lines that indicate the mean of the regions' number of high-value patents (302) and the mean of their HHI (13.3) respectively divide the diagram into four sectors. Sector I represents regions with both a high number and a high technological diversity of patents, sector II regions that had a lot of patents in comparatively few technological classes, sector III regions with a below-average number of high-value patents in various technological classes, and sector IV regions that had a small number of patents in only a few technological classes. Almost all regions with an above-average number of high-value patents were located in sector I. The great exception is the region Palatinate that heavily depended on the patents and knowledge spillovers that originated in the chemical firm BASF.

1.4 CONCLUSION

Our in-depth analysis of the high-value patents revealed that technological progress was not a continuous process but came in at least four different waves during the German industrialization. We were able to identify clearly the railway wave (1877-1886), the dye wave (1887-1896), the chemical wave (1897-1902) and the wave of electrical engineering (1901-1918). In addition, there might have been the beginning of the fifth wave with respect to vehicle construction not fully disclosed by our data. These successive waves of technological progress had a visible impact on the geographical distribution of high-value patents. Regions like Berlin, Wiesbaden or Palatinate that specialized in the new technologies of the second, third and fourth waves showed increasing innovativeness while other regions like Dresden and Leipzig that were not especially engaged in these technological fields fell behind. We found ample evidence that inter-industry knowledge spillovers between technologically, economically and geographically related industries were a major source for innovative activities during the German industrialization. In a first step, we discovered that most of the parallel patent booms of the successive waves of technological progress occurred in technologically closely related fields. This is, for example, true for steam engines, steam boilers, railway installations, metal processing and machine parts in the first wave, dyes and dyeing in the second wave, or scientific instruments and electrical engineering in the fourth wave. In a second step, we were able to show that these innovative, technologically related industries were often geographically clustered too. Nearly all regions that maintained or improved their above-average innovativeness over time had at least one innovative cluster in the fields of mechanical or electrical engineering or chemicals.

Chapter 2

Regional Innovation System in Prussia

Abstract

Regions play a key role in innovative activities. Consequently, studying regional innovation system help us answer the big question “why are some regions innovative while other regions are bad innovators?” Using data on Prussian regions from 1877 to 1914, this chapter examines the temporal-spatial patterns of Prussian patents. We observe the catch-up and convergence of patents across Prussian regions over time as lagging states of innovation enjoyed fast growth in patenting. As no region had been rising rapidly and persistently over time, we can perceive the catch-up as systematic rather than the isolated cases of a few regions. Then we move on to investigate the extent that various regional factors affect innovation. We find that both human capital and infrastructure have economically and statistically significant impact on innovation in Prussian regions. Furthermore, we exclude patents from special industries such as chemical and electrical industries and from special regions such as Berlin and run the regression again. The results remain robust. Our analysis of regional innovation systems surely has implications for innovation policy and regional policy.

2.1 INTRODUCTION

It is seemingly paradoxical that as international competition intensifies in an increasingly integrated world economy[67], scholars have shown more interest and paid more attention to regional innovation systems (RIS)[68], which can be defined as “the set of economic, political and institutional relationships occurring in a given geographic area which generates a collective learning process leading to the rapid diffusion of knowledge

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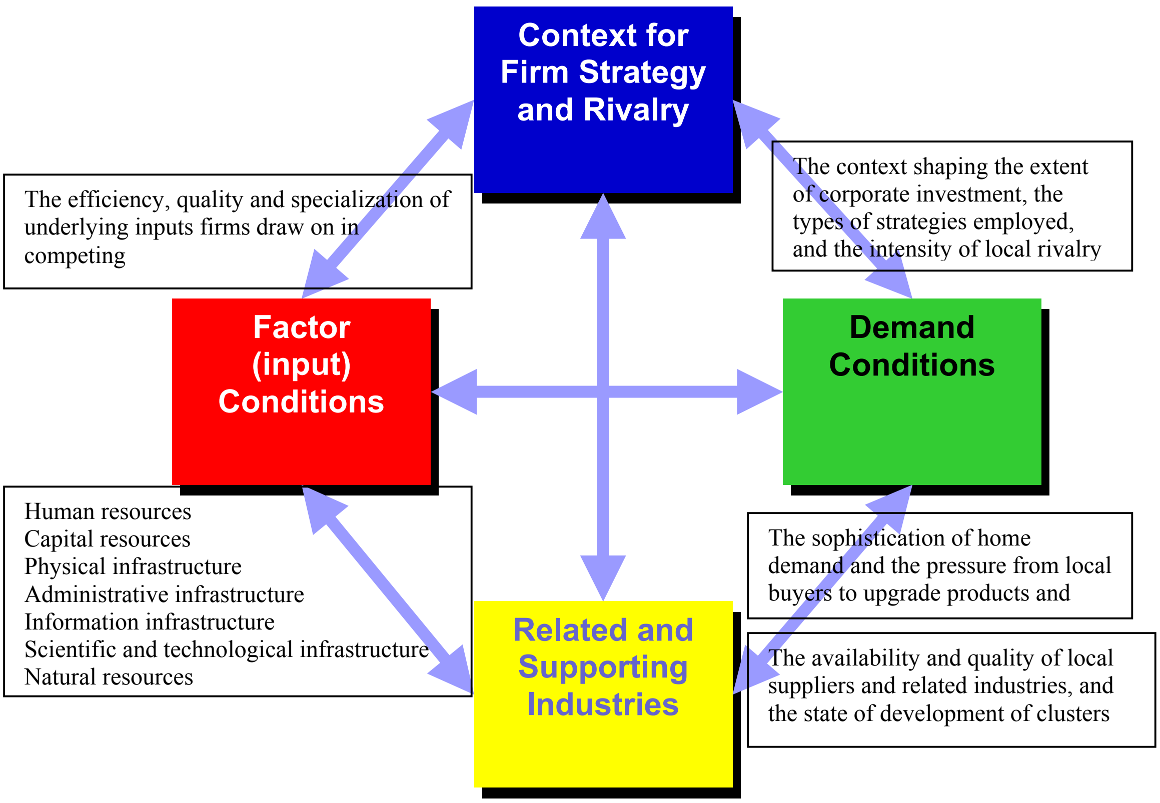
[67] Ohmae (1990) argues that globalization of economic activity is increasingly making national frontiers (and therefore the nation state as a unit of economic analysis, not to mention region) irrelevant.

[68] Cooke (1992) is one of the first works to discuss the concept of regional innovation systems (RIS). Cooke (1998, 2001) further elaborates this concept.

and best practice."[69] Innovation is an increasingly significant source of competitive advantage for firms, regions and nations. Porter (1998) argues that the enduring competitive advantage in a global economy is often heavily local, arising from a concentration of highly specialized regional factors. Figure 2.1 illustrates the importance of regional factors in the diamond model of Porter.

Figure 2.1 Diamond model of Porter



The efficiency, quality and specialization of underlying inputs firms draw on in competing

The context shaping the extent of corporate investment, the types of strategies employed, and the intensity of local rivalry

Human resources
Capital resources
Physical infrastructure
Administrative infrastructure
Information infrastructure
Scientific and technological infrastructure
Natural resources

The sophistication of home demand and the pressure from local buyers to upgrade products and

The availability and quality of local suppliers and related industries, and the state of development of clusters

Source: Porter (1990)

In particular, using the diamond model, Porter (1990, 1998) shows that the United States' global lead in the competition of innovation was predicated on the existence of regional innovation systems. Innovation is crucial in our understanding regional prosperity (Malecki, 1990; Feldman and Florida, 1994). There are many reasons that compel scholars to focus on the regional level to study innovation: Spatial proximity facilitates the sharing of tacit knowledge and capacity for localized learning; firms clustered in a region share a common regional culture that facilitates learning; and localized learning is facilitated by a common set of regional institutions.

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[69] See Nauwelaers and Reid (1995) for elaborations of this definition.

Regions surely play an important role in innovation.[70] After all, as any other social and economic activities, innovation is place-based. It occurs in an institutional, political and social context. Regions are the sites of economic interaction. And regions are the loci of innovation.[71] Successful clusters of innovative firms and industries have emerged in many regions around the world. And most studies on innovation in regions focus on only the successors, namely those places that qualify as "industrial districts". Although these studies provide clues to understanding regional development, one must take into account that these studies are by no means conclusive and are largely based on a few successful regions.[72] Yet not all regions are equally successful in generating innovation. Why are some regions highly innovative while other regions are bad innovators? Studying regional innovation system will help us answer this big question in the real world as well as in academia. We can compare innovative regions with non-innovative regions provided that they are comparable. Consequently, solid recommendations for innovation policy and regional policy can be proposed based on the analysis of regional innovation systems as some regional factors can well be changed by government policy.

Although it is almost undeniable that regions are important for innovation, there is no consensus about what regional factors affect innovation significantly. The following regional factors are said to play some roles in creating innovation: regional areas of specialization, research infrastructure (higher education sector), specialized training institutions, industrial attraction and retention, government policy/support, physical infrastructure (transportation and communications), primary and secondary educational system, civic governance, culture (such as lifestyle assets).

Despite the sheer size of literature on innovation, surprisingly, most studies on the geography of innovation so far are static in nature in that they do not sufficiently examine the evolution of spatial patterns of innovation and do not perform long-run inter-temporal comparisons.[73] Today's technology leaders could risk falling into laggards in future. During the 1970s, Route 128 in Boston was the undisputed center for electronic industry.

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[70] Storper (1995) emphasizes the important role that regions play in national technology policy.

[71] See Storper (1997) for elaborations of this argument.

[72] Cooke and Morgan (1998) is a typical study. It focuses on Baden-Wuerttemberg, the most innovation region in Germany. And it proposes that a strict reading of the literature would suggest that only three regions are true regional innovation systems: Silicon Valley in the USA, Emilia-Romagna in Italy and Baden-Wuerttemberg in Germany.

[73] Sokoloff (1988) is one of the earliest works to trace the temporal and spatial patterns of patents in US regions. He finds evidence of catching up in inventions. Using US data, Varga (1999) also finds out that patent laggards catch up with patent leaders. One recent study Powell et al. (1999) tracks the patents granted to 388 biotechnology firms and find out that firms with initially low patents tend to register more patents in succeeding periods.

By the late 1980s, Boston already lost its early lead. The center shifted to Silicon Valley in California. In this chapter, we are interested in the spatial distribution of patents and, furthermore, how the pattern evolves over time. Then we strive to measure the extent that these various factors affect innovation in Prussian regions. The rest of the chapter is organized as follows. Section 2 discusses units of analysis and measurement issues. Section 3 investigates how the geography of innovation evolves in Prussia and tries to identify whether there is catch-up of technologically backward regions. Section 4 describes the data and explanatory variables. Section 5 presents the estimation results of our benchmark model. Section 6 modifies the model and presents the new estimation results. Section 7 concludes the chapter.

2.2 UNIT OF ANALYSIS

Although there is still no general understanding of how to define a region (Cooke et al., 2000), any study on regional innovation system should start by defining regions.[74] The diversity of the units of analysis employed in studies of innovative systems presents a major problem in constructing a conceptual framework of research. Some researchers suggest using cities as units of analysis.[75] Meanwhile, some scholars favor using metropolitan regions.[76] At a more aggregate level, administrative regions (such as states, provinces) are used as scale. Lundvall and Borras (1997) claim that the region is increasingly the level at which innovation is produced through regional networks of innovators, local clusters and the cross-fertilizing effects of research institutions. For instance, this is the case in the research on Belgian province of Wallonia (Capron and Cincera, 1999). The main concern of this kind of studies is on the understanding of the role institutions and policies in sustaining innovativeness and competitiveness. The rationale for adopting this unit of analysis is that regional units are constituted by specific institutional structures and cultural traditions that facilitate and regulate economic behavior and social activity (Wolfe and Gertler, 1998). Audretsch and Feldman (1996) argue that regions are the most relevant policy-making units in the promotion of innovation generating activities. Therefore, the innovative efforts of this geographic unit can display some of the features of a regional innovation system. This study uses regional

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[74] See Niosi (2000) for elaborations of this argument.

[75] See Crevoisier and Camagni (2001) and Simmie (2001).

units (Regierungsbezirk) as units of analysis as they fit our research purpose, namely which regional factors are associated with high innovative performance. We choose Prussia over German Empire for several reasons. Firstly, it is easier for data aggregation and compilation. Some regions in the German empire, such as Thuringen, are extremely fragmented and cause considerable troubles in data work. Secondly, the statistical yearbooks of Prussia normally provide more detailed information at regional level than the yearbooks of the German Empire. One example is the number of pupils in vocational schools. Thirdly, many non-Prussian states had quite different social and administrative contexts than their Prussian counterparts. For example, before the patent law was introduced in the whole German Empire in 1877, the patent system already existed in some parts of Prussia, although it was new to non-Prussian regions.[77] People in Prussian regions were likely quite experienced with patenting activities. Thus, comparisons of Prussian regions and non-Prussian regions in the unified German empire are prone to mistakes. There are not many drawbacks for focusing on Prussian regions. We do lose some observations. Nevertheless, Prussia had 37 Regierungsbezirks[78], sufficient for our search purpose. As a matter of fact, Prussian residents thoroughly garnered the majority of high-value patents granted by the patent office as figure 2.2 tells us. The share had been rather stable over time: about 60 %.

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[76] Audretsch and Feldmann (1999) argue that metropolitan areas are the most important sites of innovation. Browner et al (1999) argues that metropolitan areas have high potential for innovation.

[77] See “Patentgesetz vom 25. Mai 1877”, Reichsgesetzblatt 1877, 501-510. For the genesis of the German patent law see Heggen, Alfred, 1977, Zur Vorgeschichte des Reichspatentgesetzes von 1877, Gewerblicher Rechtsschutz und Urheberrecht, 322-327.

[78] In the statistical yearbook, data on Allenstein did not become available until 1905. Both Gumbinnen and Koenigsberg gave out some territories to form Allenstein.

Figure 2.2 Share of high value patents issued to Prussian residents from 1878 to 1914

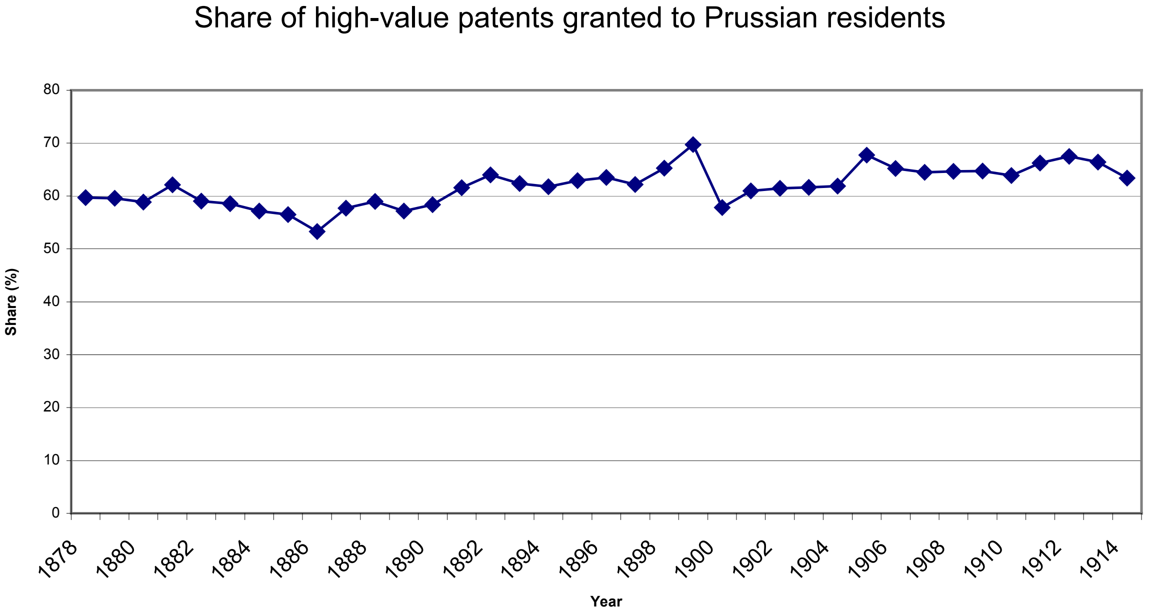
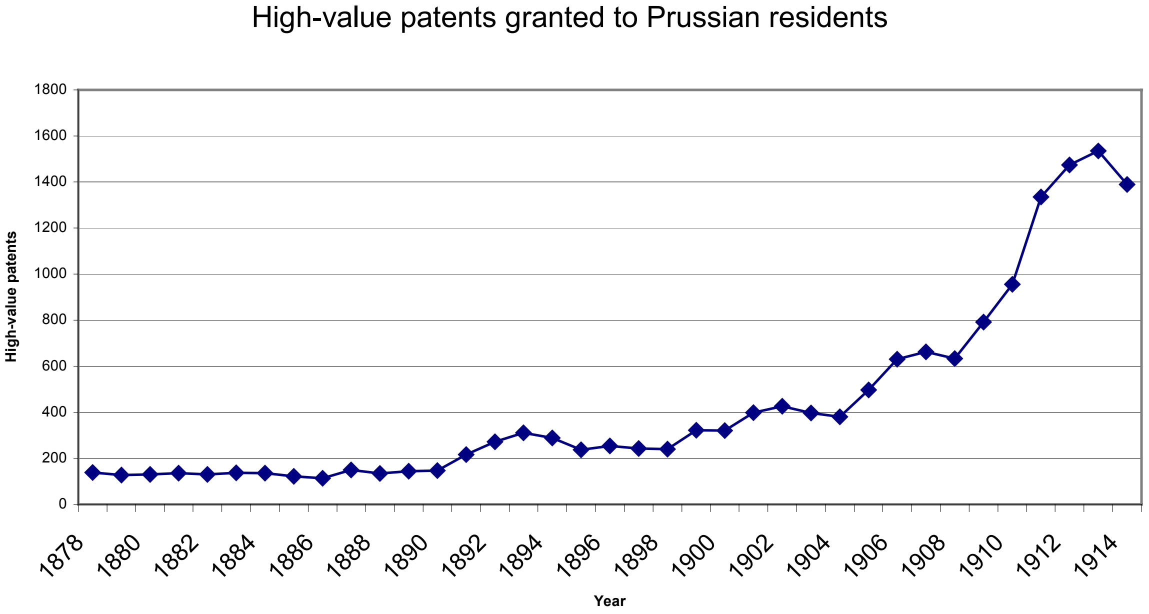
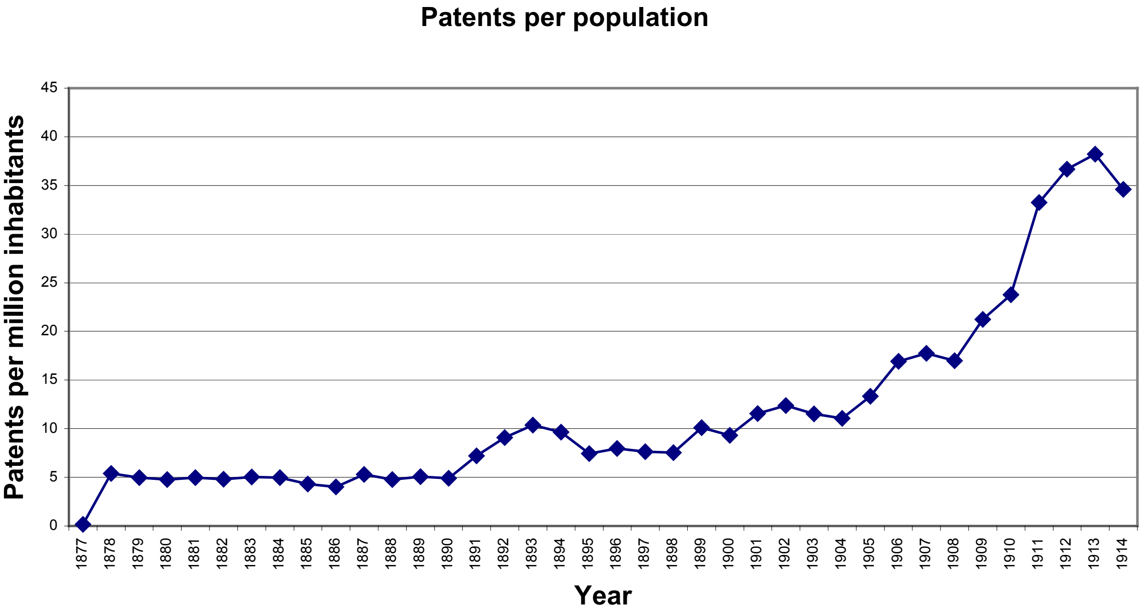


Figure 2.3 Number of high-value patents issued to Prussian residents from 1878 to 1914



In figure 2.3, we observe that the high-value patents obtained by Prussian residents had been stagnant during the 1880s. The number increased relatively modestly during the 1900s. And then it rose drastically during the 1910s till the World War One. And it is not right to argue that this growth is largely due to the population growth. From 1880 to 1914, the Prussian population rose from 26 million to 40 million. The growth rate of high-value patents is much higher than the growth rate of population.

Figure 2.4 Number of high-value patents issued per million inhabitants in Prussian regions from 1878 to 1914



We divide high-value patents by Prussian population (million residents) and make figure 2.4. The pattern captured in figure 2.4 is not much different from that shown in figure 2.3.

2.3 EVOLUTION OF THE GEOGRAPHY OF INNOVATION

We put the geographical distributions of patents across Prussian regions in map 2.1. The map shows that the high-value patents were by no means uniformly distributed over various Prussian regions. Instead they were geographically clustered in a broad belt that ran from the districts close to the river Rhine in the West to Berlin in the center. This innovation belt corresponds to the industrial zones in Germany at that time well. Eastern

Prussia had scanty patents. The two extreme cases are Berlin (about 4,526 patents from 1877 to 1914) and Allenstein (virtually no patents).

Map 2.1 The geographical distribution of high-value patents 1878-1918

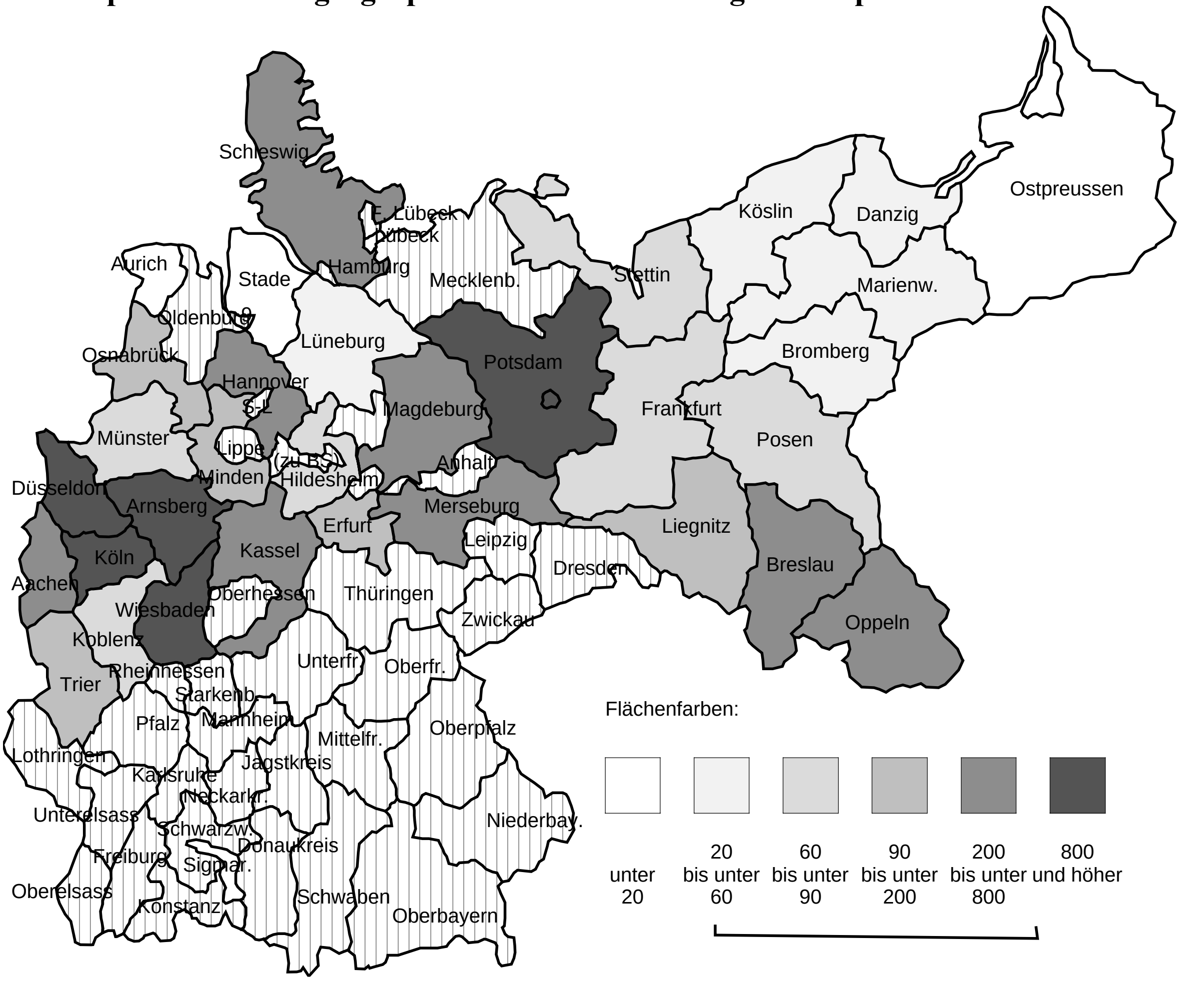


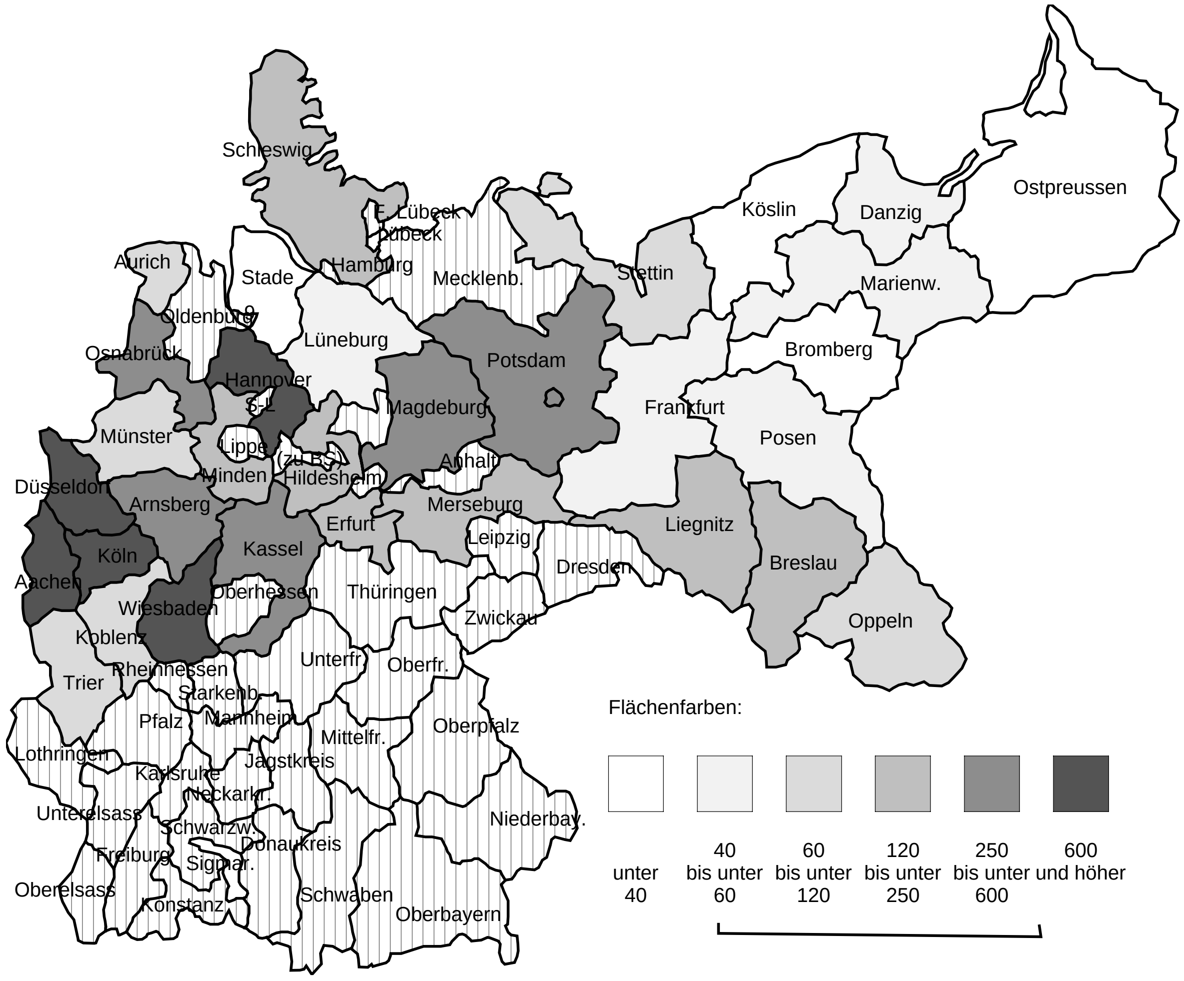
Table 2.1 The most innovative Prussian regions measured by patent counts (annual average in each sub-period)

1878-1885		**1886-1895**		**1896-1905**		**1906-1910**		**1911-1914**	
Region	Patent	Region	Patent	Region	Patent	Region	Patent	Region	Patent
Berlin	**32.3**	**Berlin**	**48.5**	**Berlin**	**96.0**	**Berlin**	**219.6**	**Berlin**	**425.3**
Duesseldorf	**17.3**	**Duesseldorf**	**46.7**	**Duesseldorf**	**72.5**	**Duesseldorf**	**114.2**	**Duesseldorf**	**253.5**
Wiesbaden	**10.3**	**Wiesbaden**	**27.8**	**Wiesbaden**	**41.7**	**Wiesbaden**	**88**	**Wiesbaden**	**166.5**
Arnsberg	8.9	Cologne	12.4	Potsdam	18.9	Potsdam	62	Potsdam	132.3
Cologne	8.4	Arnsberg	11.2	Arnsberg	17.9	Arnsberg	39	Cologne	65
Magdeburg	8.3	Magdeburg	6.8	Cologne	17.7	Cologne	36.8	Arnsberg	64
Merseburg	5.3	Potsdam	5.7	Hannover	12.4	Hannover	17.4	Hannover	40.8
Aachen	4.8	Merseburg	4.2	Aachen	8.8	Aachen	16	Aachen	37
Hannover	4.5	Aachen	4.0	Magdeburg	8.4	Kassel	13.8	Kassel	29.5
Osnabrueck	3.9	Hannover	3.8	Merseburg	6.6	Schleswig	11.4	Schleswig	25

The ranking of the most innovative Prussian regions, however, changed over time. Table 2.1 allows us to distinguish regions with continuous, decreasing and increasing relative innovativeness. We use annual average in each time period to render a comparison over sub-periods possible. Berlin, Duesseldorf, and Wiesbaden had always occupied the top three positions during the whole period under consideration. Yet it is interesting to note that Duesseldorf initially was able to catch up to Berlin with respect to the number of high-value patents, and then fell behind considerably. Potsdam initially did not enter the top ten rank. Yet later it developed its innovative capacity, perhaps due to the influx of mechanical engineering patents. Magdeburg made a strong debut. Yet it displayed relatively decreasing innovativeness later on, perhaps due to the fact that it did not fare well in electrical engineering, an industry that created increasingly large numbers of patents.

We divide patent counts by population (per million residents) and make map 2.1.

Map 2.1 The geographical distribution of high-value patents per million residents 1878-1918



In table 2.2, we rank Prussian regions in terms of patents per million inhabitants.

Table 2.2 The most innovative Prussian regions measured by patents per million residents (annual average in each sub-period)

1878-1885		**1886-1895**		**1896-1905**		**1906-1910**		**1911-1914**	
Region	Patent	Region	Patent	Region	Patent	Region	Patent	Region	Patent
Berlin	**33.8**	**Wiesbaden**	**34.6**	**Berlin**	**53.8**	**Berlin**	**108**	**Berlin**	**205**
Wiesbaden	**14.5**	**Berlin**	**33.5**	**Wiesbaden**	**43.5**	**Wiesbaden**	**79**	**Wiesbaden**	**137**
Osnabrueck	13.6	**Duesseldorf**	**25.0**	**Duesseldorf**	**30.3**	**Duesseldorf**	**48**	**Duesseldorf**	**74**
Cologne	12.4	Cologne	15.7	Hannover	20.1	Cologne	32	Hannvoer	55
Duesseldorf	11.3	Arnsberg	8.8	Cologne	18.4	Potsdam	27	Aachen	54
Hannover	10.1	Hannover	7.5	Aachen	14.6	Hannover	25	Cologne	52
Aachen	9.3	Aachen	7.2	Arnsberg	10.6	Aachen	24.6	Potsdam	46
Magdeburg	9.1	Magdeburg	6.6	Potsdam	10.5	Arnsberg	18.4	Kassel	29
Arnsberg	8.6	Erfurt	4.7	Erfurt	8.1	Kassel	14.4	Arnsberg	27
Merseberg	5.6	Potsdam	4.3	Magdeburg	7.4	Erfurt	9.6	Minden	25

Comparing table 2.1 with table 2.2, we observe that the ranking has not changed much after normalizing patents by population. Berlin region still stands out, even though it had around 1.8 million population. Berlin, Wiesbaden and Duesseldorf have constantly occupied the top three positions. A comparison of map 2.1 and map 2.2 confirms this observation.

Following Feldman (1994), we employ a Chi-squared test of independence between the technological classes and regional locations of patents.[79] There is evidence that geography affects inventive activity in all sub-periods. In table 2.3, the Chi-squared statistics are very high. As we have very high degree of freedom, the p-values of the χ^2 statistics are even less than 0.005. Thus, we reject the null hypothesis that the probability of patenting in the technological class and the probability of patenting in the state are independent. Thus, we firmly established the base for further exploration.

Table 2.3 Chi-square test of independence of region and technological class, using high-value patents per million inhabitants (1877-1914)

Period	**Chi-square statistic**	**P-value**
1877-1885	10414.2	0.000
1886-1895	10943.8	0.000
1896-1905	11554.3	0.000
1906-1910	11896.8	0.000
1911-1914	12434.5	0.000

Degree of freedom (df) = (89-1) * (38-1) = 3256

Table 2.4 ranks the top ten regions in terms of the growth rates for total patents. Table 2.5 takes population into consideration and ranks the top ten regions regarding the growth rates for patents per million residents.

Table 2.4 Top regions in growth rates of annual total high-value patents (%)

From 1878-1885 to 1886-1895		**From 1886-1895 to 1896-1905**		**From 1896-1905 to 1906-1910**		**From 1906-1910 to 1911-1914**	
Region	Growth rate	Region	Growth rate	Region	Growth rate	Region	Growth rate
Danzig	380	Gumbinnen	900	Stralsund	500	Trier	366
Munster	247	Aurich	400	Frankfurt a/o	275	Munster	332
Wiesbaden	171	Potsdam	232	Stettin	260	Hildesheim	275
Duesseldorf	170	Hannover	226	Potsdam	228	Osnabrueck	263

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[79] See chapter 1 for details of this test.

Marienwieder	140	Koeslin	200	Marienwieder	225	Minden	243
Koeslin	140	Lueneberg	200	Liegnitz	214	Oppeln	205
Minden	127	Posen	183	Lueneberg	200	Koenisberg	181
Frankfurt a/o	120	Kassel	176	Schleswig	200	Stettin	178
Schleswig	100	Aachen	120	Kassel	138	Posen	141
Erfurt	78	Koblenz	120	Berlin	129	Hannover	134

Some caution should be called for when we analyze this ranking in table 2.4. A low base for comparison may make some region's growth rate appear very high although the patents added are modest. This is especially true for the early periods, when patents were not abundant for most regions. In general, patent-intensive regions do not fare well on this ranking, suggestive of catch-up of technologically backward regions. Yet no region occupies a high position in this ranking constantly over time. Thus, it is not possible to identify a technologically backward region that raised its innovativeness persistently.

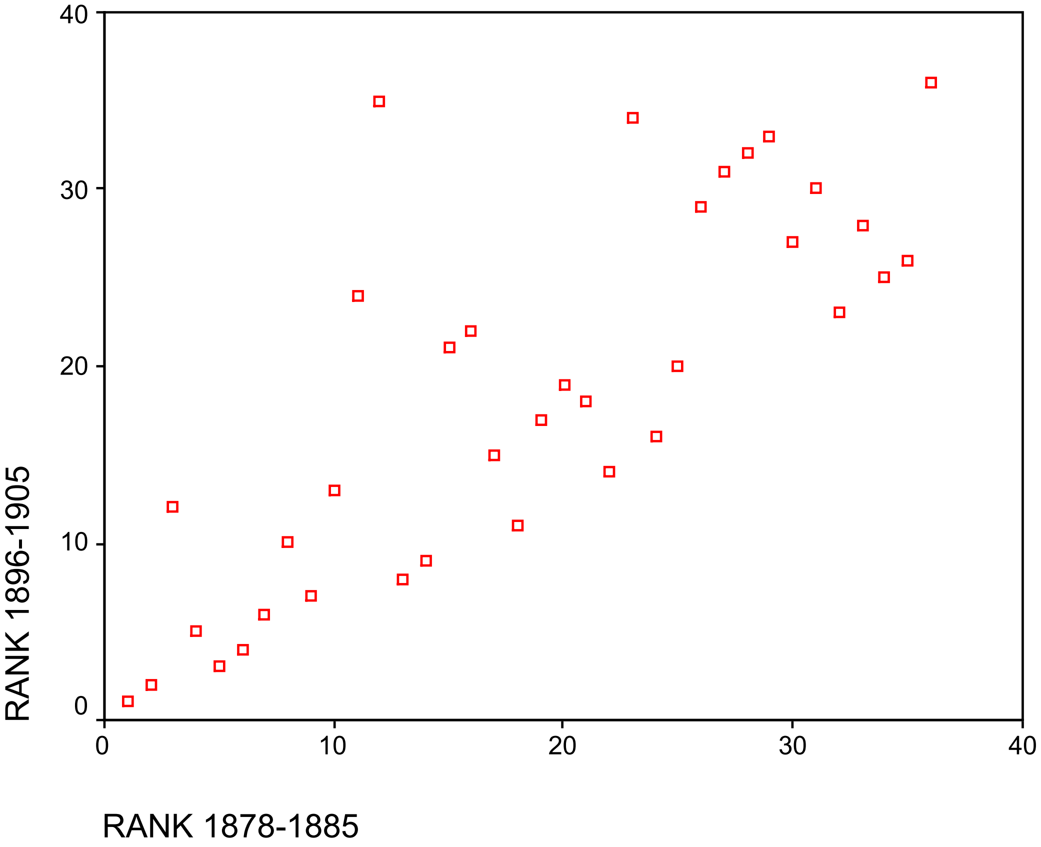
Table 2.5 Top regions in growth rates of annual total high-value patents per million residents (%)

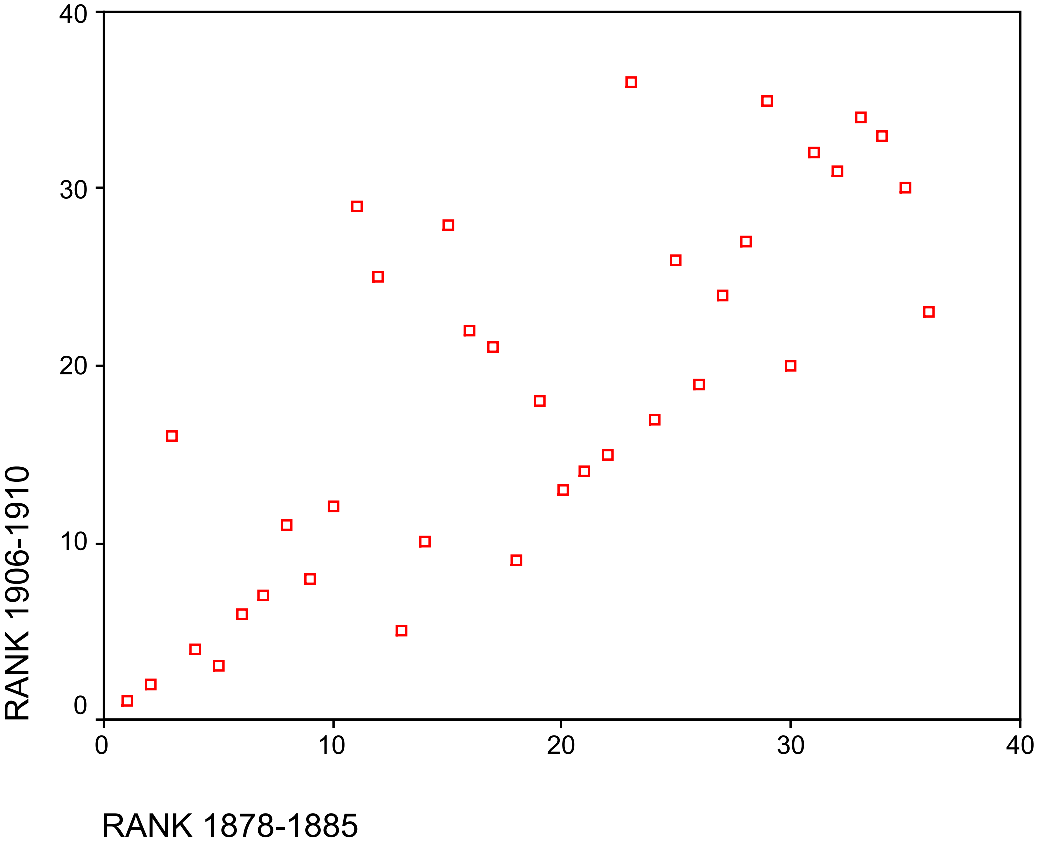
From 1878-1885 to 1886-1895		**From 1886-1895 to 1896-1905**		**From 1896-1905 to 1906-1910**		**From 1906-1910 to 1911-1914**	
Region	Growth rate	Region	Growth rate	Region	Growth rate	Region	Growth rate
Danzig	357	Gumbinnen	888	Stralsund	486	Trier	330
Munster	208	Aurich	359	Frankfurt a/o	266	Hildesheim	266
Koeslin	143	Koeslin	192	Stettin	239	Munster	257
Wiesbaden	138	Lueneberg	168	Marienwieder	209	Osnabrueck	236
Marienwieder	135	Hannover	167	Liegnitz	201	Minden	223
Duesseldorf	122	Posen	166	Lueneberg	172	Oppeln	181
Frankfurt a/o	114	Kassel	162	Schleswig	167	Koenigsberg	175
Minden	109	Potsdam	144	Potsdam	152	Stettin	173
Schleswig	86	Koblenz	106	Kassel	117	Posen	128
Erfurt	66	Aachen	103	Berlin	100	Danzig	122

The caution mentioned above for table 2.4 also applies to the ranking contained in table 2.5. The rankings in table 2.4 and table 2.5 are fairly similar.

We would like to study the evolution of region's innovative output over time. Figure 2.5 presents state's rankings in patents per capita for several periods. The first panel depicts a state's ranking in 1877-1885 against is ranking in 1886-1895; the second panel contains a state's ranking in 1877-1885 against its ranking in 1896-1905; and so on. In these panels, points along a 45-degree line from the bottom left to the top right suggest no change in ranking. Points above a 45-degree line indicate a drop in ranking. Points below a 45-degree line suggest a rise in ranking.

Figure 2.5 Evolution of Prussian regions' patent rank, 1877-1914


RANK 1896-1905
RANK 1878-1885
0
10
20
30
40
0
10
20
30
40


RANK 1906-1910
RANK 1878-1885
0
10
20
30
40
0
10
20
30
40

Note:

Rank 1878-1885: Ranking of high-values patents per million residents in 1878-1885,

Rank 1886-1895: Ranking of high-values patents per million residents in 1886-1895,

Rank 1896-1905: Ranking of high-values patents per million residents in 1896-1905,

Rank 1906-1910: Ranking of high-values patents per million residents in 1906-1910,

Rank 1911-1914: Ranking of high-values patents per million residents in 1911-1914.

Convergence and divergence are enduringly interesting topics in the study of economic and social activities[80]. The information contained in tables 2.4 and 2.5 and figure 2.5 does seem to indicate patent catch-up by some lagging states of innovation. In tables 2.4 and 2.5, we see that the regions lagging in patenting activities top the list of growth rates of patents. In figure 2.5, we observe that a significant amount of spots are dispersed off the 45-degree line.

To confirm this impression and to better understand the catch-up process, we construct a simple econometric model.

$$\text{Ln}\,[\text{Pat}_{(\text{later period})}/\text{Pat}_{(1877\text{-}1885)i}] = \alpha + \beta\,\text{Ln}\,[\text{Pat}_{(1877\text{-}1885)i}] + \delta\,\text{Ln}\,(\text{PatOther}_{(1877\text{-}1885)}] + \varepsilon_i \quad (1)$$

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[80] Gerschenkron (1962) argues for the advantage of backwardness, contending that backward states could use more updated technology to catch up leaders quickly.

where i indexes the region; $Pat_{(later\ period)i}$ is high-value patents per one million residents in state i in each of the four sub-periods following 1877-1885 (1886-1895, 1896-1905, 1906-1910, 1911-1914); $Pat_{(1877-1885)i}$ is the number of high-value patents per one million residents in 1877-1885; and ε_i is an assumedly well-behaved error term. Thus, our dependent variable measures the growth rate of patents compared with the initial period 1877-1885.

For independent variables, in addition to $Pat_{(1877-1885)i}$, following Smith (1999), we include a measure of knowledge spillover because of the quasi public good nature of knowledge. Variable PatOther captures spillovers from neighboring regions as spillovers are often spatially bound. The variable is constructed using all high-value patents per million residents registered in bordering Prussian regions in 1877-1885.

It is an interesting and open question about how long a patent can affect later patenting. Patent citations reflect knowledge transfers between generations of inventors. Caballero and Jaffe (1993) discover that citations fall off sharply a decade after the patent's grant date. Yet Nicholas (2004) finds that forty-two (that equals 31.8 percent) of great inventor Edison's 132 patents granted from 1910 to 1930 by the USPTO (United States Patent and Trademark Office) are cited in patents granted between 1976 and 2002. Of course this proportion might be inflated if patent examiners have a propensity to cite the classics without regard to true values. Nevertheless, according to Nicholas (2004), of the 19,948 patents granted to firms between 1920 and 1929 by the USPTO, 21 percent are cited in patents granted between 1976 and 2002. Of the 4,215 patents cited, 2,548 receive one citation while 1,667 receive two or more citations, with the maximum number of cites for a patent being 27. These numbers of citations over a long time period are really remarkable. We conclude that patents might have an influence that exceeds the ten-year limit suggested by Caballero and Jaffe (2003). Our regression might be able to give us additional hint about how long patents can impact later patenting activities. Table 2.6 presents the empirical results of our regression using OLS method.

Table 2.6 Regression results for patent growth equation

Dependent variable	**Ln [$Pat_{(1886-1895)i}/Pat_{(1877-1885)i}$]**	**Ln [$Pat_{(1896-1905)i}/Pat_{(1877-1885)i}$]**	**Ln [$Pat_{(1906-1910)i}/Pat_{(1877-1885)i}$]**	**Ln [$Pat_{(1911-1914)i}/Pat_{(1877-1885)i}$]**
Ln [$Pat_{(1877-1885)i}$]	-0.276*** (0.101)	-0.210*** (0.103)	-0.158* (0.093)	0.101 (0.083)
Ln ($PatOther_{(1877-1885)}$]	0.755*** (0.238)	0.575*** (0.241)	0.607*** (0.218)	9.290E-02 (0.637)

R square	0.243	0.153	0.192	0.127
number of observations	36	36	36	36

Note:
1. Standard errors are given in parenthesis
2. * means statistically significant at 10 % level, ** means statistically significant at 5 % level, and *** means statistically significant at 1 % level.

We have to admit that this model is not perfect. In particular, over a long time as we have in this chapter, technological regimes might have experienced substantial changes, which are hard for us to detect and track. Nevertheless, the model is illuminating. The regression results are pretty consistent for the first three regressions: patents at the initial stage have negative impact on patenting in later periods, suggesting catch-up and regional convergence in inventive activities. These outcomes confirm our impression gained from the tables four and five and figure three. In the last regression, none of the explanatory variables has statistically significant impact. And the R square is very low. The reason is perhaps that the patents at the initial stage have impact on later sub-periods, but this effect does not last long enough to the very last sub-period in our study, at least not as long as Nicholas (2004) suggests, although we do not have patent citation data to support our argument more forcefully.

2.4 EXPLANATORY VARIABLES AS DETERMINANTS OF REGIONAL INNOVATION

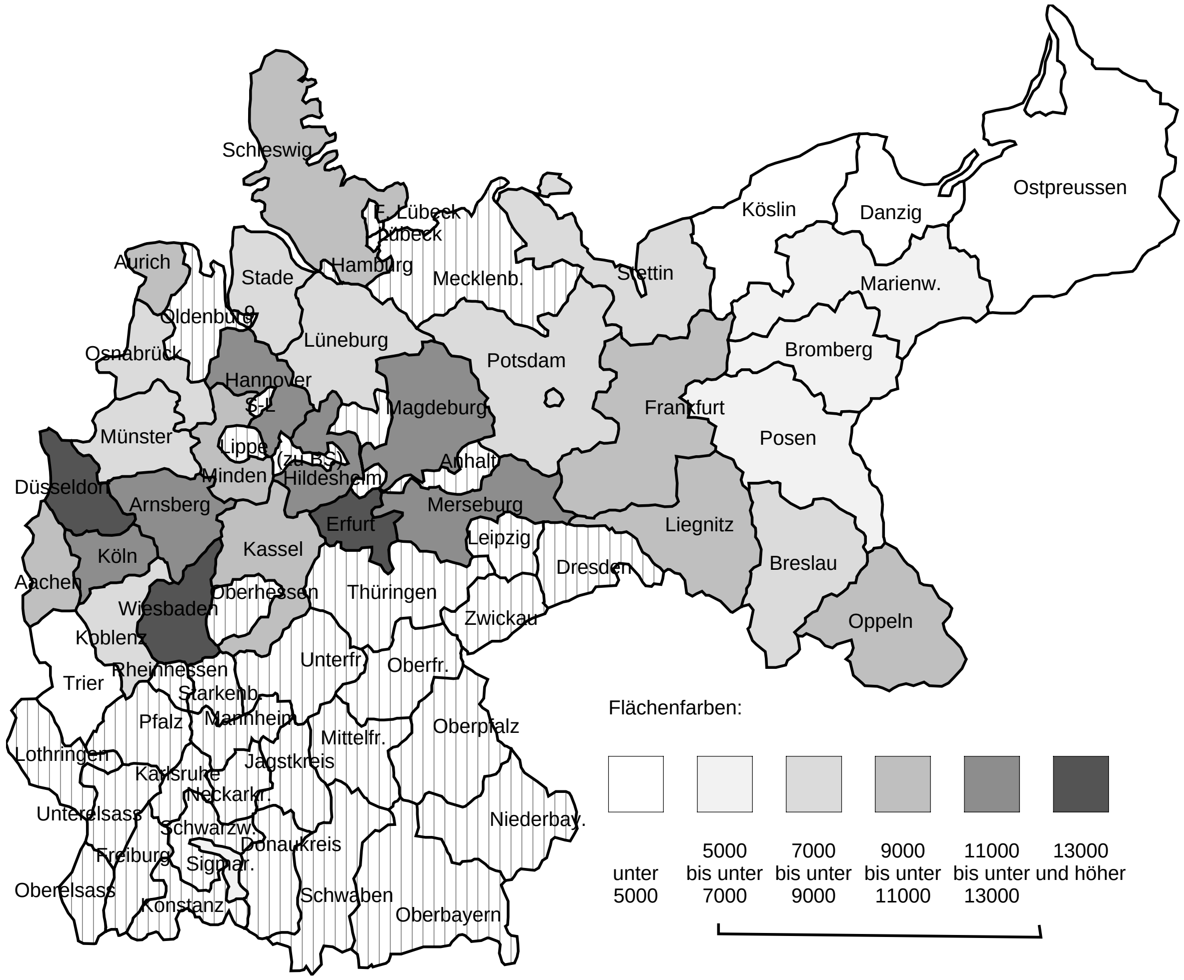
We go further to explore the determinants behind regional performance in patenting activities. Our dependent variable is innovation, measured by annual high-value patents of Prussian regions per million residents to normalize regional size. We use annual data to render a comparison over time convenient. The geographic distribution of patents is made according to the state residence of the first named register. Our explanatory variables are the factors that might have an impact on innovation at the regional level. We obtain these explanatory variables from statistical yearbooks of Prussia (*Statistisches Jahrbuch fuer den Preussischen Staat*). Actually these statistical yearbooks were not available every year before 1903. Between 1877 and 1903, only four yearbooks were published: 1883, 1888, 1893, and 1898. Facing this limitation and irregularity of data sources, we split our study period into five intervals: 1877-1885, 1886-1895, 1896-

1905, 1906-1910, and 1911-1914. Using the mean number of patents for each interval reduces inter-annual variances in patent numbers, which is especially troublesome in areas that often receive only few patents in a given year.

When we study regional variables, we need to control the regional size. A region with more people naturally tends to generate more patents. Thus, in this study wherever applicable, we use population (million residents) of various regions to divide various explanatory variables to control the size effect.

Human capital is one significant regional factor that might be associated with innovative performance. Lucas (1988) suggests that the ability to development and implement new technology depends on the average level of human capital in the local economy. Bartel and Lichtenberg (1987) demonstrate that more local skilled labor force produces greater innovation. We have data for the number of students in various Prussian regions. However, we have to be selective. Not all students are equally likely to conduct R&D (Research and Development) activities after their graduation. We have to choose the index that has systematic difference across regions. Prussia had a very good public school system. Almost all Prussian districts enjoyed high enrolment rates of primary schools. It does not make much sense to use overall number of students. Moreover, students from school of arts and music are very unlikely to engage in technologically innovative activities. With discretion, we use students of technical and commercial schools. After graduation, students from these two kinds of schools are most likely to generate new knowledge that could be patented. Furthermore, the numbers of students of these two kinds of schools demonstrate systematic difference across regions. Berlin and Duesseldorf are clearly leaders. We gather the numbers of students at technical and commercial schools. Map 2.3 demonstrates the regional distribution of human capital.

Map 2.3 The geographic distribution of number of pupils in technical and commercial schools per million residents (1877-1914 annual average)



Technological discoveries are more likely to occur to those who are involved in an industry than to outsiders as insiders might be expected to be more knowledgeable about problems and opportunities in the industry and also better positioned to gain from their knowledge. This principle would lead one to expect that geographic distribution of innovations would correspond generally to the distribution of the industrial labor force.[81] We try to test this hypothesis. We use industrial labor force per million residents in each region as one explanatory variable. Duesseldorf leads this index, partially because it is where the industrial Ruhr area is located.

After considering human capital, labor, we take physical capital formation into account. We use horsepower (both steam engine and electrical) per million residents as proxy for physical investment.[82]

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[81] A more sophisticated version of this argument is the theory of "learning by doing" associated with scholars such as Kenneth Arrow and Armen Alchian. See Arrow (1962b) and Alchian (1963).

[82] See Broadberry (1997) for using horsepower as a proxy for physical capital formation. In particular, it is reasonable to regress on horsepower when we also control for industrial employment and capital stock. The capital stock of joint stock firms is a proxy of large firm and capital of banks and other financial

Innovation is associated with finance. Arrow (1964) shows how well functioning financial markets can encourage risky undertakings by allowing that risk be spread across many investors. Lack of funding can constitute a serious hindrance for firm's innovative efforts. And there might be regional home bias because it was much easier to monitor a firm nearby. Although it is not clear how efficiently capital allocated towards firms that have innovative opportunities, it is hardly to deny that availability of capital facilities firm's innovative endeavors. We use the capital of joint stock firms (Deutsche Mark) per million residents as a measure of capital intensity. Berlin is the undisputed leader in this measure, followed by Duesseldorf and Cologne. This might be also interpreted as the complementariness between financial capital and innovation.

The possible association between firm size and innovation is an interesting and controversial one. Schumpeter (1912) argues that small firms are best at innovating. Schumpeter (1942) reverses this opinion and argues that large monopolistic firms are the best innovators because they are able to fund research into innovations.[83] Anselin, Varga, and Acs (1997) argue that small firms generate more inventions per dollar of research expenditure. Morck and Yeung (1999) find that measures of firm size, like total sales and the number of industries in which the firm operates, magnify the extra value each dollar of R&D adds to the firm's share price. As we do not have data for market size, we cannot investigate the association between market structure and innovation. Yet we do have data to measure firm size. We use employee per firm as a proxy of firm size. Not surprisingly, Arnsberg, Aachen and Berlin rank high in this index as big firms made strong presence in these regions.

Infrastructure is expected to affect innovation. Good infrastructure reduces transport and transaction costs. Infrastructure is very special in that government is often involved in the construction and maintenance of infrastructure as infrastructure often needs huge amounts of investment and often has the feature of public goods. Transportation and communications are both typical examples of infrastructure. Sokoloff (1988) examines the significant influence of transportation on patenting in the U.S. Railway was the most important means of transportation in Germany. We use railway density (kilometer per thousand square kilometers of territory) as one explanatory

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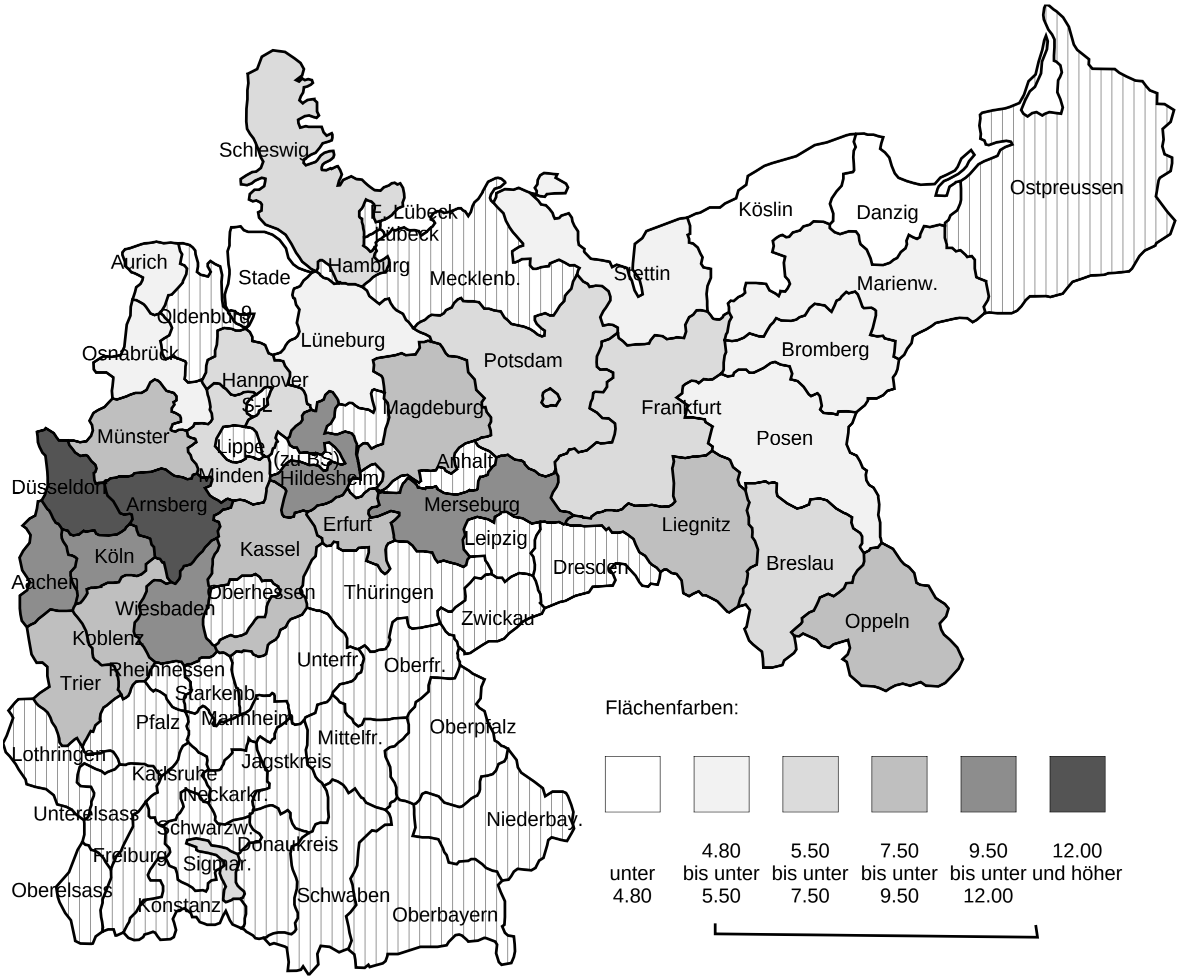
institutions, because joint stock firms were typically larger and financial institutions accounted for a large share, whereas horsepower is really a proxy for capital of all firms (including the smaller ones).

[83] A really interesting and comprehensive exposition of Schumpeterian thought is Scherer (1992). Cayseele (1998) performs a more recent review of contributions on the relationship between market structure and

variable. This variable varies over regions. Cologne, Duesseldorf and Wiesbaden rank high in this variable. Map 2.4 helps us visualize this regional distribution of railway density.

Map 2.4 The railway density of Prussian regions 1878-1918 (kilometre per thousand square kilometre) (annual average)



It is interesting to observe that the regional distributions of patents, human capital, and railway density are quite similar. Our subsequent regression outcomes would confirm this impression.

There are certainly some other factors that might affect innovation. Some of these factors are social capital and culture.[84] Yet some of these factors are hard to measure and

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innovation. For reasons to expect that large firms to have advantages in carrying out R&D, see Henderson and Cockburn (1996).

[84] It is possible that some cultures are more supportive of innovation than others. Chandler (1977, 1990) contends that the U.S. economy became more purposeful between 1870 and 1910, and that this greatly enhanced the success rate of innovations. Saxenian (1994) argues quite convincingly that the open, informal, flexible commercial culture enabled Silicon Valley to replace Boston as the global center for high technology.

difficult to quantify while for other factors we do not have data available. We have to leave these factors in the residual.

2.5 REGRESSION RESULTS OF THE BASIC MODEL

Above we have explained our data and variable. We use OLS method to estimate the following equation[85]

Ln (patents per million residents) = β_0+ β_1 Ln (number of industrial labor per million residents) + β_2 Ln (firm size) + β_3 Ln (horsepower per million residents) + β_4 Ln (railway density) + β_5 Ln (professional school students per million residents) + β_6 Ln (incorporated capital per million residents) + ε (2)

Table 2.7 Estimation results: Determinants of annual high-value patents per million residents (in natural log form)

	1878-1885	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
constant	-14.825** (5.446)	-4.808 (4.679)	-11.378*** (3.934)	-8.078* (4.365)	-7.610* (4.486)
share of industrial labor	1.185** (0.549)	0.201 (0.456)	0.744 (0.515)	0.675 (0.464)	0.268 (0.442)
firm size	1.169 (0.803)	1.181 (0.721)	-0.678 (0.659)	-0.362 (0.550)	0.250 (0.648)
horsepower per population	-2.972E-02 (0.250)	-4.691E-02 (0.245)	7.545E-02 (0.236)	-0.430* (0.221)	-0.345 (0.212)
railway density	**0.212** **(0.372)**	**1.068***** **(0.302)**	**0.749**** **(0.345)**	**0.754**** **(0.348)**	**0.787**** **(0.360)**
number of school pupils per population	**0.176**** **(0.079)**	**0.209***** **(0.069)**	**0.486*** **(0.243)**	**0.661**** **(0.308)**	**0.720*** **(0.383)**
incorporate	data not	data not	0.106	0.356*	0.611***

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[85] We express our variables in natural logarithms in order to reduce the influence of outliers and overdispersion.

capital	available	available	(0.179)	(0.184)	(0.206)
R square	0.698	0.754	0.702	0.774	0.791
Number of observations	36	36	36	37	37

Our regressions for various periods have fairly good fitness (Table 2.7). Our independent variables explain our dependent variable pretty well.

Human capital (measured by pupils in vocational schools per million residents) stands out in the estimation. They always have positive impact on innovation. And its impact has been statistically significant through the whole period under our consideration. Infrastructure (measured by railway density) also calls for our attention. It has a positive effect on innovation. And its impact has been statistically significant most of the time.

The effect of capital intensity is not very conclusive, partially because we do not have data for the whole period, although they have positive effect during the whole period when data are available. And from 1906 to 1914, for two sub-periods consecutively, the positive effect is statistically significant. One possible implication is that as time goes on, capital availability and intensity becomes more and more significant for innovative activities as inventive efforts demand more capital input.

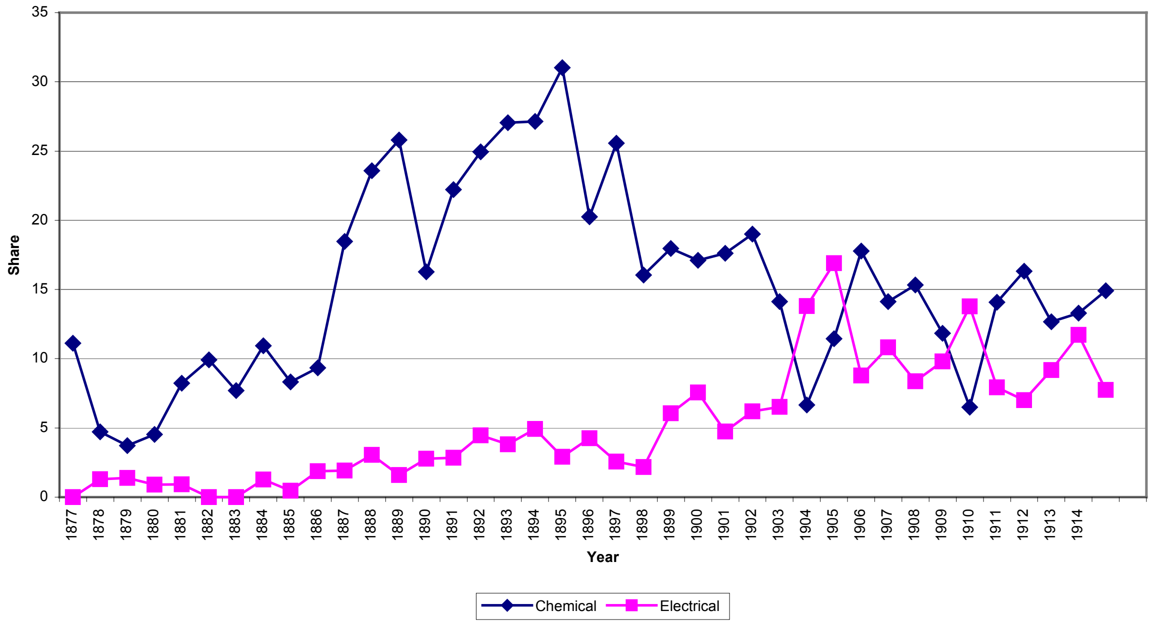
The impact of industrial employees has been positive through the whole period under our consideration. Yet the positive impact is statistically significant only for the first time period (1878-1885). A possible explanation is that as firms establish research labs using the trial and error method to conduct R&D more effectively, the benefit from general worker's production on innovation becomes no longer significant.

The association between firm size and innovation is not confirmed. The impact has never been statistically significant. This outcome indicates that the Schumpeterian hypothesis (which is drawn primarily from the American observation) that firm size is a necessary pre-condition for outstanding innovativeness wasn't necessarily true during German industrialization.

2.6 MODIFICATIONS

The research results listed above are pretty encouraging and promising as well. Yet we can go further. Patents from chemical (technological class 12 and technological class 22) and electrical engineering (technological class 21) occupy a big share in our high-value patent pool. In total, 23% of high-value patents (1877 to 1914) fall into these two industries. Figure 2.6 captures the change of this share over time.

Figure 2.6 Share of chemical and electrical patents in German domestic patents (1877-1914)



We would like to exclude the chemical and electrical engineering from our regression. These industries have several special features. Firstly, they are highly concentrated geographically. The two most important electrical engineering firms, AEG and Siemens, were located in Berlin.[86] In the period between 1901 and 1916, for instance, Siemens and AEG got as much as 19 % of 2,607 high-value patents in the technological class of electrical engineering. Chemical industry is very sensitive to geographic location. The industry had to be located near rivers to release wastes nearby during the production process and to use the transport advantage. Secondly, these industries have highly concentrated market structure. A handful of firms (such as BASF) produced most of the patents in these technological classes. Thirdly, big firms in these industries have research labs and hire technicians from anywhere. Regional factors do not tend to affect the innovativeness of these big firms as much as they influence the patenting activities of other industries that often had smaller firms. Given all the reasons listed above, including patents from chemical and electrical industries could distort the real picture.

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[86] Details are described in Hughes (1983).

Table 2.8 Numbers of patents in chemical and electrical industries and their relative shares in total patents by region (1877-1914 all years pooled)

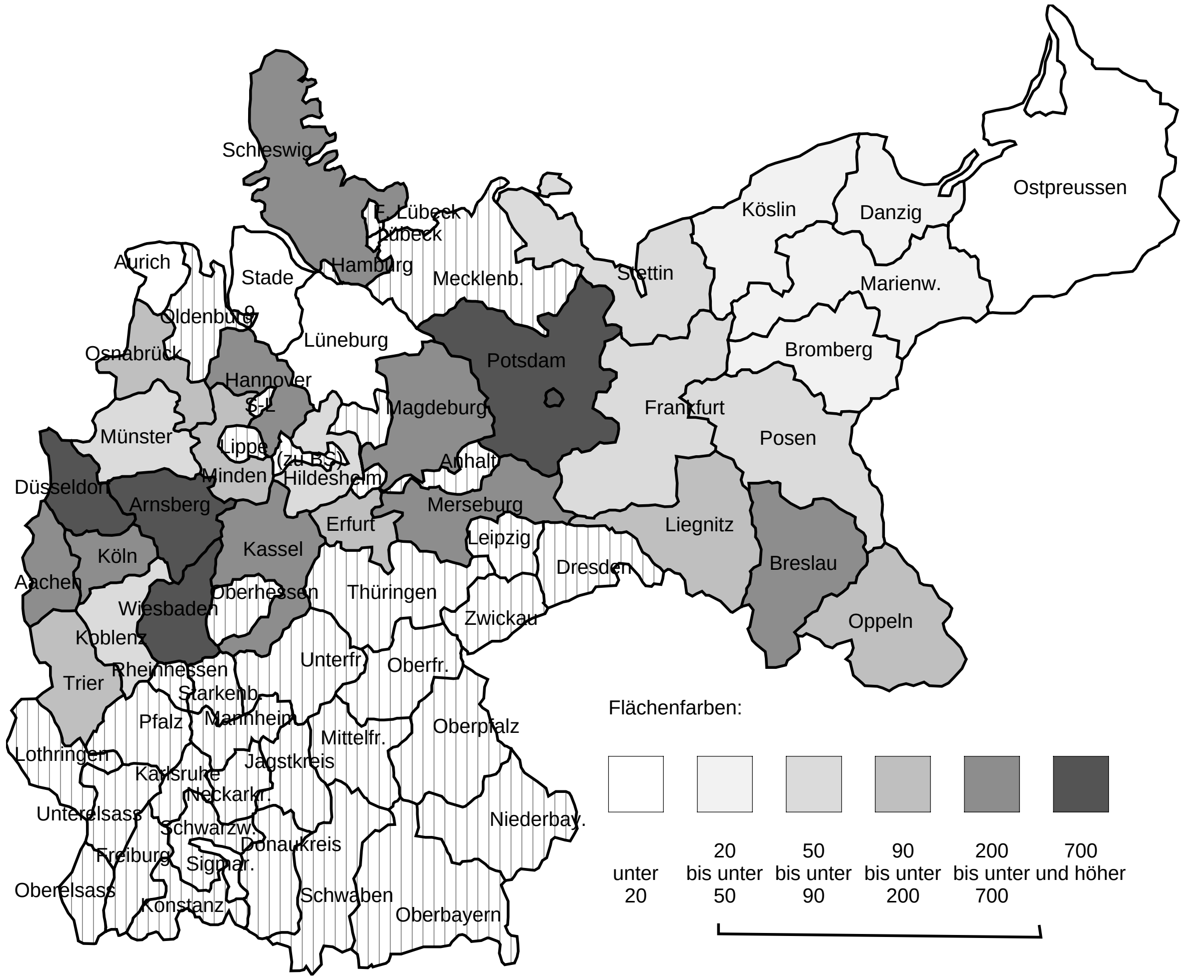
region	**chemical**	**share (%)**	**electrical**	**share (%)**
Aachen	26	6.60	2	0.51
Allenstein	0	0	0	0
Arnsberg	31	3.81	28	3.44
Aurich	0	0	1	6.25
Breslau	12	5.45	0	0
Bromberg	0	0	0	0
Danzig	2	5.88	0	0
Duesseldorf	**855**	27.91	32	1.04
Erfurt	2	1.67	0	0
Frankfurt O	6	9.84	0	0
Gumbinnen	4	21.05	0	0
Hannover	21	4.69	25	5.58
Hildesheim	12	17.14	5	7.14
Kassel	11	3.90	8	2.84
Koblenz	11	12.94	0	0
Cologne	70	8.63	47	5.80
Koenigsberg	0	0	4	13.79
Koeslin	0	0	0	0
Liegnitz	4	2.44	1	0.61
Lueneburg	6	27.27	0	0
Magdeburg	21	5.74	0	0
Mariewerder	6	12.50	0	0
Merseburg	23	8.27	1	0.36
Minden	7	4.49	2	1.28
Muenster	15	18.07	0	0
Oppeln	10	4.90	11	5.39
Osnabrueck	0	0	0	0
Posen	1	1.59	0	0
Potsdam	100	8.85	137	12.12
Schleswig	2	0.82	15	6.17
Sigmaringen	0	0	0	0
Stade	0	0	0	0

Berlin	346	7.67	**1019**	22.58
Stettin	4	4.94	0	0
Stralsund	0	0	0	0
Trier	1	1.06	1	1.06
Wiesbaden	**983**	52.18	142	7.54
In total	**2592**	**16.23**	**1481**	**9.28**

Table 2.8 shows the absolute numbers and relative shares of patents in chemical and electrical industries by region (1877-1914 all years pooled). Chemical patents stand out in the patent pools of Duesseldorf and Wiesbaden. Electrical patents are eminent in the patent pool of Berlin. To visualize the effect of chemical and electrical patents, we made a map of the geographical distribution of high-values patents after excluding chemical and electrical patents.

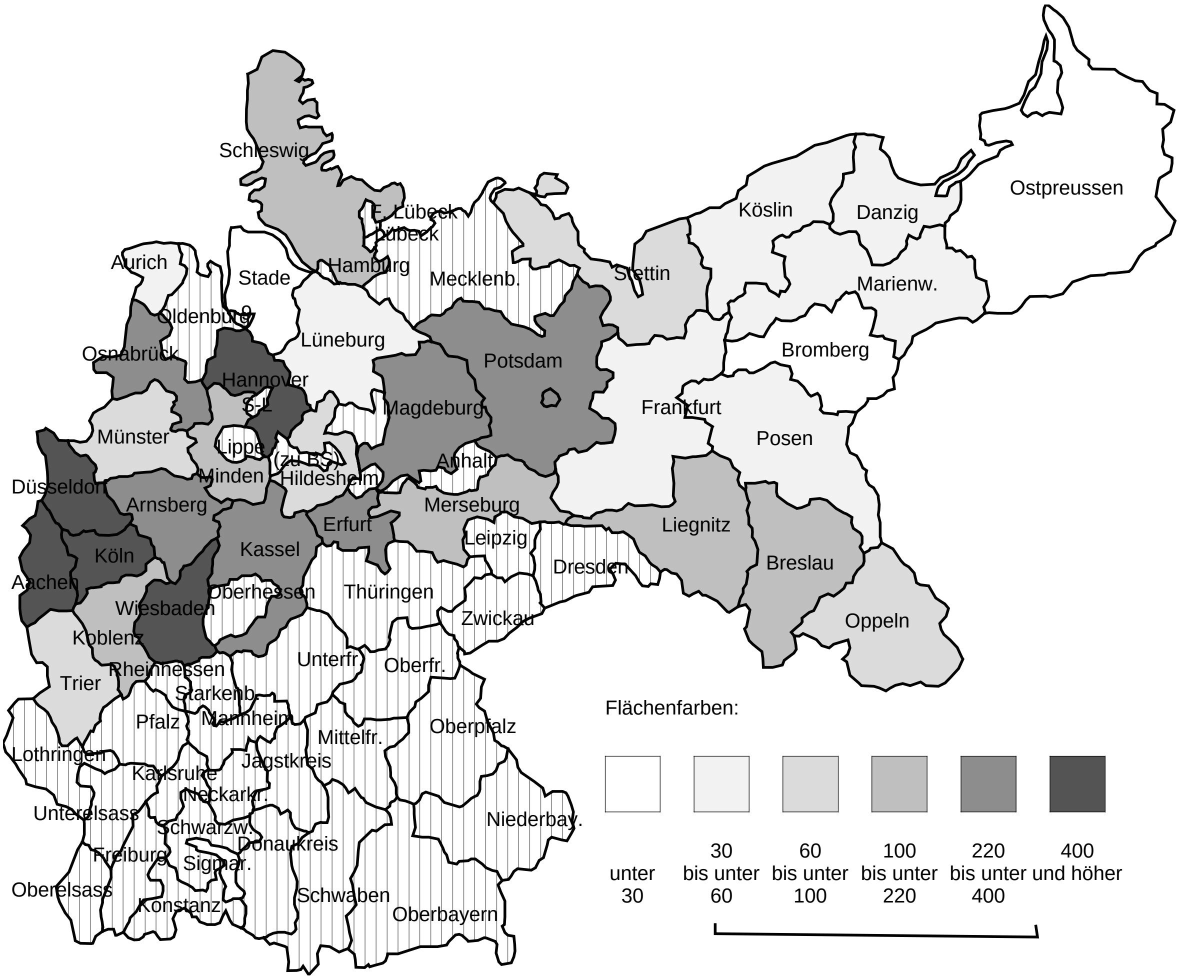
We plot the geographical distributions of patents (excluding chemical and electrical patents) in map 2.5.

Map 2.5 The geographical distribution of high-value patents 1878-1918 (excluding chemical and electrical patents)



Map 2.6 gives us information about the geographical distributions of patents (excluding chemical and electrical patents) per million residents.

Map 2.6 The geographical distribution of high-value patents per million residents 1878-1918 (excluding chemical and electrical patents)



It is interesting to compare map 2.1 and map 2.5. There are similarities and differences between these two maps. The Rhein region is no longer so outstanding in patents, partially because the chemical industries are highly concentrated along the Rhein River. Berlin, Potsdam, and Duesseldorf remain salient in both maps. Compared with other regions, eastern Prussia still had little patents.

We rank the regions by high-value patent counts after excluding patents from chemical and electrical industries. We use annual average in each sub-period to make inter-period comparison possible.

Table 2.9 The most innovative regions in Prussia (excluding chemical and electrical patents) (annual average in each sub-period)

1878-1885		**1886-1895**		**1896-1905**		**1906-1910**		**1911-1914**	
Region	Patent	Region	Patent	Region	Patent	Region	Patent	Region	Patent
Berlin	**31.25**	**Berlin**	**36.6**	**Berlin**	**68.2**	**Berlin**	**143**	**Berlin**	**284**

Duesseldorf	**16.1**	**Duesseldorf**	**21.8**	**Duesseldorf**	**47.5**	**Duesseldorf**	**110.2**	**Duesseldorf**	**201**
Arnsberg	9	Cologne	10.9	Potsdam	16.3	Potsdam	49	Potsdam	100.5
Cologne	8.4	Arnsberg	10.1	Arnsberg	16.2	Arnsberg	36	Wiesbaden	74
Magdeburg	8.1	Wiesbaden	7.8	Cologne	15.3	Wiesbaden	34.4	Arnsberg	59.8
Wiesbaden	5.9	Magdeburg	6.7	Wiesbaden	14.0	Cologne	32.6	Cologne	55.5
Merseburg	5.0	Potsdam	5.6	Hannover	11.5	Hannover	16.2	Aachen	34.5
Aachen	4.8	Merseburg	4.0	Magdeburg	8.2	Aachen	15	Hannover	33.25
Hannover	4.5	Hannover	3.7	Aachen	7.9	Kassel	12.6	Kassel	28.2
Osnabrueck	3.9	Aachen	3.6	Merseburg	6.1	Schleswig	10.8	Schleswig	23

Table 2.1 (which ranks all high-value patents) and table 2.9 (which ranks only high-value patents excluding chemical and electrical industries) are quite similar. Yet the importance of Wiesbaden declines in table 2.9, partially because the exclusion of chemical industries. Table 2.10 ranks the most innovative regions in Prussia in terms of high-value patents (excluding chemical and electrical patents) per million residents.

Table 2.10 The most innovative regions in Prussia in terms of patents per million residents (excluding chemical and electrical patents) (annual average in each sub-period)

1878-1885		**1886-1895**		**1896-1905**		**1906-1910**		**1911-1914**	
Region	Patent	Region	Patent	Region	Patent	Region	Patent	Region	Patent
Berlin	**30**	**Berlin**	**25**	**Berlin**	**38**	**Berlin**	**70**	**Berlin**	**137**
Osnabrueck	14	Cologne	14	Duesseldorf	20	Duesseldorf	37	Wiesbaden	61
Cologne	12	Duesseldorf	12	Hannover	19	Wiesbaden	31	Duesseldorf	59
Duesseldorf	11	Wiesbaden	10	Wiesbaden	17	Cologne	29	Aachen	50
Hannover	10	Arnberg	8	Cologne	16	Hannover	23.3	Hannover	44
Aachen	9.3	Hannover	7.3	Aachen	13	Aachen	23.1	Cologne	40
Magdeburg	8.9	Magdeburg	6.5	Arnsberg	10	Potsdam	21	Potsdam	35
Arnsberg	8.8	Aachen	6.49	Potsdam	9	Arnsberg	17	Kassel	28
Wiesbaden	8.3	Erfurt	4.5	Erfurt	8	Kassel	13	Arnsberg	25
Merseburg	5.3	Potsdam	4.3	Magdeburg	7	Erfurt	10	Minden	23

After controlling population, the importance of Potsdam in terms of patent count decreases, partly because of the large population (around two million) of Potsdam region. This case also applies to Schleswig, which had around 1.5 million residents.

The similarity of table 2.1 and table 2.9 and the similarity between table 2.2 and table 2.10 to a certain degree dismiss the concern that chemical and electrical industries distort the picture greatly due to the special features of these two industries. Nevertheless, we run regression after excluding patents from chemical and electrical industries.

Table 2.11 Estimation results: Determinants of annual high-value patents excluding chemical and electrical industries per million residents

	1878-1885	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
constant	-15.298*** (5.459)	-6.057 (4.197)	-10.810*** (3.592)	-8.627* (4.163)	-9.118** (4.247)
share of industrial labor	1.243** (0.551)	0.372 (0.409)	0.795 (0.470)	0.722 (0.443)	0.307 (0.419)
firm size	1.136 (0.805)	1.142* (0.646)	-0.515 (0.602)	-0.355 (0.524)	0.315 (0.513)
horsepower per population	-6.403E-03 (0.251)	-4.048E-03 (0.220)	-1.907E-02 (0.215)	-0.340 (0.211)	-0.271 (0.201)
railway density	**9.818E-02** **(0.373)**	**0.738**** **(0.271)**	**0.550*** **(0.315)**	**0.734**** **(0.332)**	**0.652*** **(0.341)**
number of school pupils per population	**0.147*** **(0.079)**	**0.122*** **(0.062)**	**0.411**** **(0.222)**	**0.576**** **(0.293)**	**0.783**** **(0.363)**
incorporated capital	Data not available	Data not available	0.124 (0.163)	0.252 (0.176)	0.500** (0.195)
R square	0.678	0.728	0.698	0.757	0.785
Number of observations	36	36	36	37	37

Our modified estimation still enjoys high degree of fitness. The results of this modified estimation are roughly the same as the results of the previous estimation.

After this modification (excluding patents from chemical and electrical industries), we go even further. We would like to omit Berlin, Duesseldorf and Wiesbaden from our regression. These three regions had been occupying the top three positions that we consider. And these three regions are very special for various reasons. Berlin was the capital of the unified German empire. Duesseldorf region, as a major administrative center, is close to the industrial Ruhr area. Wiesbaden is a county where many chemical firms clustered. These three regions can be regarded as outliers due to their special situations and their predominance in claiming patents.

We estimate the original benchmark model again after excluding these three special regions.

Table 2.12 Estimation results: Determinants of high-value patents excluding Berlin, Duesseldorf and Wiesbaden

	1878-1885	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
constant	-10.782 (5.056)	-5.126 (3.985)	-8.905** (3.520)	-7.191* (4.004)	-11.837** (4.332)
share of industrial labor	0.765 (0.511)	0.192 (0.388)	0.513 (0.456)	0.829* (0.418)	0.170 (0.404)
firm size	0.682 (0.862)	0.628 (0.632)	-0.310 (0.610)	-0.499 (0.543)	-0.247 (0.521)
horsepower per population	0.162 (0.292)	0.206 (0.244)	-2.102E-02 (0.205)	-0.447* (0.239)	-0.295 (0.239)
railway density	**0.310** **(0.481)**	**0.815**** **(0.361)**	**0.896**** **(0.356)**	**0.846*** **(0.414)**	**0.817*** **(0.410)**
number of school pupils per population	**0.139*** **(0.081)**	**0.109*** **(0.060)**	**0.420*** **(0.215)**	**0.424*** **(0.176)**	**1.306***** **(0.382)**
incorporated	Data not	Data not	7.223E-02	0.334*	0.411*

capital	available	available	(0.156)	(0.187)	(0.208)
R square	0.624	0.695	0.649	0.717	0.778
Number of observations	33	33	33	34	34

Our modified estimation still enjoys high degree of fitness. The original regression results are quite robust. They do not experience dramatic changes after modifications. Human capital and infrastructure have positive and statistically significant effects throughout the whole period. The effects of firm size are mixed: sometimes positive while sometimes negative. Yet this point is not conclusive from the regressions as these effects are never statistically significant.

2.7 CONCLUSION

Innovations are place-based. Regions play a key role in innovative activities. Consequently, studying regional innovation systems help us answer the big question "why are some regions innovative while other regions are bad innovators?" Using data on Prussian regions from 1877 to 1914, this empirical study investigates the extent that various regional factors affect innovation. We find that both human capital and infrastructure have economically and statistically significant impact on innovation in Prussian regions. Furthermore, these results are pretty robust. They remain true after we exclude patents from special industries such as chemical and electrical industries and after we omit patents from very special regions such as Berlin, Duesseldorf and Wiesbaden. Thus, the concern that patents from special industries and special regions should not be exaggerated, at least for the research purpose of this paper. Our analysis of regional innovation systems certainly has implications for innovation policy and regional policy. To facilitate innovation, it seems advisable that government should be committed to infrastructure and education, both of which are closely related to innovativeness in this research.

Chapter 3

Innovation in German Cities

1890-1914

Abstract

Urban residents obtained most of the patents awarded in Germany from 1890 to 1914. We investigate the question what kind of conditions fostered innovation in German cities. We gather data on urban conditions in 44 cities in Germany from 1890 to 1914. Using rank-size relationship equation, we find that big cities dominated patent awards, signifying that urbanization externalities facilitate invention. Then we take variables for human capital, employment, and diversity of industries (measured by Herfindahl index). We investigate these variables' impact on innovation. We find out that besides population, both human capital and employment have an impact on patenting in German cities. Location in the traditional manufacturing belt also plays a role. Urban residents in the manufacturing belt were the most active inventors. Moreover, we find that industrial diversity is conducive to innovation.

3.1 INTRODUCTION

Innovation and cities are closely related. Most of innovative activities concentrate in cities. Conversely the formation and development of cities are closely dependent on innovative activities. And innovation is key to the success of cities. It facilitates city formation (Jacobs, 1969; Marshall, 1890; Arrow, 1962; and Romer, 1986) and regional industrial performance (Saxenian, 1994). Therefore, many researchers focus on the city as the key site of innovation processes. Crevoisier and Camagni (2001) and Simmie (2001), for example, argue that cities generate innovation because they act as arenas for the confluence of innovative factors. In particular, using city as unit of analysis has some additional advantages for our research. Firstly, it allows us to study the "geography of innovation"[87] in Germany as a whole while many data were not available at regional level

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[87] This term is taken from Feldman's work (*Geography of innovation*) published in 1994, which stands as one of the main reference in this field.

in Germany at this time period (1890-1914). Secondly, innovative activities are not evenly distributed in a region. For instance, the modestly high patenting in Bavaria was largely boosted by patents in Munich and Nuremberg rather than somewhere else (such as Wuerzburg) in the region.

German cities differ sharply in their innovative abilities. Some cities are highly innovative while some cities are bad innovators. Our primary goal is to identify the factors that foster innovation in German cities and to estimate the impact of these factors.

To be specific, the central questions of this chapter are the following. Firstly, what are the conditions that account for the uneven distribution of inventions in various cities? Secondly, do the conditions of big cities differ from those of small cities? Thirdly, do the conditions vary when we compare cities in the manufacturing belt with those in other regions in Germany?

The rest of this chapter is divided into several parts. Section 2 explains the data used in this paper. Section 3 provides some descriptive statistics and employs the rank-size equation to study the effect of city size on innovation. Section 4 describes the regression equations that relate patent counts to urban conditions. Section 5 presents the results of regressional analysis. Section 6 concludes the chapter.

3.2 DATA

We use patent data as proxy of innovation. A patent is located to a specific city depending on the residence of the first inventor in the list of inventors. We get data of cities from the German statistical yearbook of cities (*Statistisches Jahrbuch deutscher Städte*) for the years from 1890 to 1914. The yearbook lists information of 44 German cities[88]. Eighteen of these cities had over 200,000 residents. They were Berlin, Bremen, Breslau, Chemnitz, Dortmund, Dresden, Duesseldorf, Essen, Frankfurt a/m, Hamburg, Hannover, Leipzig, Magdeburg, Mannheim, Munich, Nuremberg, Stettin, Stuttgart. These cities are classified as big cities in this chapter as we want to study the impact of urban size on innovation. The main manufacturing zone in Germany stretches from the districts neighboring the Rhine River in the West to Greater Berlin and Saxony in the center. The following cities were located in the manufacturing belt: Aachen, Barmen, Berlin,

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[88] As time went on, the yearbook had information for more cities. Yet to keep the research scope consistent, we focus on these 44 cities whose information had always been available in the yearbook.

Braunschweig, Cassel, Chemnitz, Dortmund, Dresden, Duesseldorf, Elberfeld, Erfurt, Essen, Frankfurt a/m, Halle, Hanover, Karlsruhe, Cologne, Krefeld, Leipzig, Magdeburg, Mainz, Mannheim, Stuttgart, Wiesbaden.

As we intend to study the continuity and changes of the impact of urban conditions on innovation, we split the whole time period into five intervals: 1890-1894, 1895-1899, 1900-1904, 1905-1909, and 1910-1914.[89] As each interval contains five years, this division renders inter-temporal comparison convenient in our study.

3.3 PATENTS IN URBAN HIERARCHY

Patents were highly concentrated in German cities. Table 3.1 shows the absolute number of patents registered by patentees in the 44 German cities. It also lists the relative share of these patents among the total patents registered by Germans. From 1890 to 1914, more than half of domestic patents were claimed by patentees living in the 44 German cities, although these cities accounted for only about 15-20% of German population.

Table 3.1 Population and high-value patents of the 44 cities and their respective shares in whole Germany

	1890-1894	**1895-1899**	**1900-1904**	**1905-1909**	**1910-1914**
population in 44 cities	7790106	8678520	10640003	11830849	13275365
share of national total	15.8%	16.6%	18.9%	20.0%	20.4%
high-value patent counts in 44 cities	1140	1202	1922	2864	5541
share of national total	57%	60%	61%	58%	54%

The population share had risen continuously. The share of patents rose initially, and then declined slightly. This concentration is a clear evidence of the relationship between invention and population that was established in the nineteenth century (Pred, 1966; Feller, 1971; Higgs, 1971; Sokoloff, 1988).[90]

Even among the 44 German cities, patents were by no means evenly distributed. Table 3.2 ranks the top ten most innovative cities at various time periods.

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[89] Some variables are averaged over shorter intervals due to the unavailability of the whole series.

[90] This relationship was substantiated by Ullman (1958) and Thompson (1962) for the 1950s.

Table 3.2 The top ten most innovative cities by high-value patent counts

1890-1894		**1895-1899**		**1900-1904**		**1905-1909**		**1910-1914**	
city	patent	city	patent	city	patent	city	patent	city	patent
Berlin	271	Berlin	339	Berlin	517	Berlin	842	Berlin	1744
Elberfeld	171	Elberfeld	128	Frankfurt a/m	131	Frankfurt a/m	220	Frankfurt a/m	438
Frankfurt a/m	107	Frankfurt a/m	88	Elberfeld	121	Elberfeld	169	Elberfeld	277
Chemnitz	55	Leipzig	52	Dresden	110	Dresden	153	Duesseldorf	247
Dresden	50	Hamburg	50	Hamburg	97	Essen	141	Leipzig	236
Leipzig	41	Dresden	44	Leipzig	90	Hamburg	109	Hamburg	220
Hamburg	39	Duesseldof	42	Hannover	71	Cologne	101	Dresden	195
Cologne	35	Hannover	34	Nuremberg	67	Stuttgart	98	Stuttgart	188
Munich	28	Magdeburg	32	Cologne	62	Duesseldorf	94	Munich	168
Duesseldorf	28	Chemnitz	31	Essen	58	Leipzig	90	Cologne	167

In table 3.2, Berlin, Frankfurt a/m and Elberfeld had always occupied the top three position. Chemnitz made a strong debut. Yet it fell out of top ten as time went on. However, using patent data from all industries can be misleading. Chemical (including dyes) and electrical industries are very special as patenting is concerned. One such example is Elberfeld, whose patents were predominantly from the chemical industry (including dyes). So we tabulate this table again after excluding patents from chemical (including dyes) and electrical industries.

Table 3.3 Most innovative cities by high-value patent counts (excluding patents from chemical, dyes and electrical industries)

1890-1894		**1895-1899**		**1900-1904**		**1905-1909**		**1910-1914**	
city	patent	city	patent	city	patent	city	patent	city	patent
Berlin	202	Berlin	241	Berlin	331	Berlin	523	Berlin	1127
Chemnitz	49	Dresden	47	Dresden	105	Essen	138	Duesseldorf	237
Dresden	45	Hamburg	46	Hamburg	87	Dresden	125	Frankfurt a/m	235
Frankfurt	42	Leipzig	46	Leipzig	82	Frankfurt a/m	108	Leipzig	203
Hamburg	36	Duesseldorf	40	Frankfurt a/m	68	Hamburg	94	Hamburg	183
Cologne	34	Frankfurt a/m	30	Cologne	58	Duesseldorf	87	Cologne	172
Leipzig	31	Braunschweig	29	Hannover	57	Leipzig	86	Dresden	171
Brauschweig	28	Hannover	28	Essen	56	Stuttgart	84	Stuttgart	171

Magdenburg	26	Magdeburg	28	Stuttgart	50	Koeln	81	Essen	142
Duesseldorf	25	Chemnitz	27	Duesseldorf	48	Munich	75	Nuremberg	132

Some cities are affected by the exclusion of chemical and electrical patents seriously. On this list, Elberfeld loses its eminent position. The importance of Frankfurt a/m also declines as its patents are heavily dominated by chemical industry. The patents held by Berlin residents also drops quite sharply, partly because a high share of Berlin patents come from electrical industries. Nevertheless, Berlin solidly holds the first position thoroughly. In contrast, Metz, Wuerzburg, Frankfurt a/o had been laggards persistently.

Table 3.4 ranks the top ten cities by population in each time period. The order had not changed much over time. Berlin, Hamburg and Munich had constantly occupied the top three positions.

Table 3.4 Top ten cities ranked by population

1890-1894	**1895-1899**	**1900-1904**	**1905-1909**	**1910-1914**
Berlin	Berlin	Berlin	Berlin	Berlin
Hamburg	Hamburg	Hamburg	Hamburg	Hamburg
Leipzig	Munich	Munich	Munich	Munich
Munich	Leipzig	Dresden	Dresden	Leipzig
Breslau	Breslau	Leipzig	Leipzig	Dresden
Cologne	Dresden	Breslau	Breslau	Cologne
Dresden	Cologne	Cologne	Cologne	Breslau
Magdeburg	Frankfurt a/m	Frankfurt a/m	Frankfurt a/m	Frankfurt a/m
Frankfurt a/m	Hannover	Nuremberg	Nuremberg	Duesseldorf
Hannover	Magdeburg	Hannover	Hannover	Nuremberg

To control the factor of urban size, we divide patent counts by population (one million residents) and tabulate the high-value patent ranking table again.

Table 3.5 Most innovative cities by high-value patent counts per one million residents (excluding patents from chemical, dyes and electrical industries)

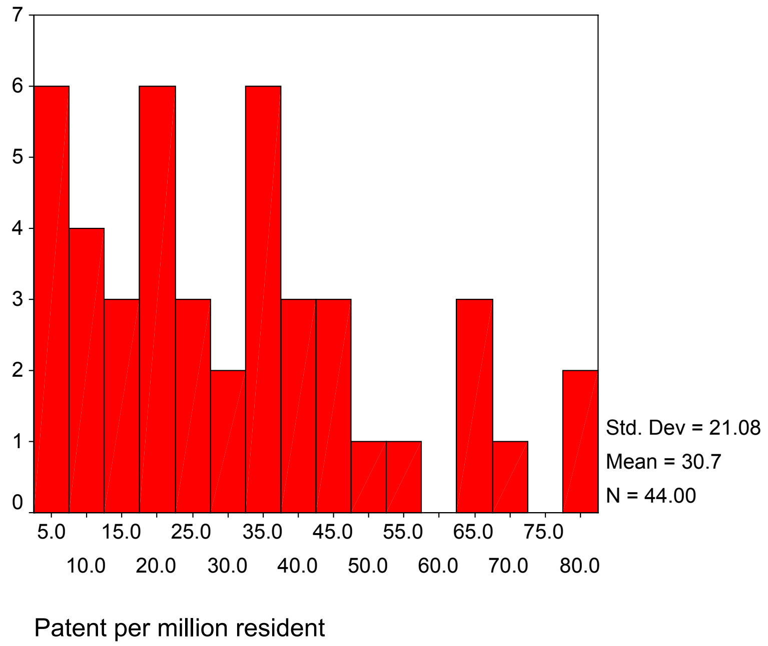
1890-1894		**1895-1899**		**1900-1904**		**1905-1909**		**1910-1914**	
city	patent	city	patent	city	patent	city	patent	city	patent
Chemnitz	350	Essen	266	Essen	302	Essen	557	Aachen	707

Braunschweig	266	Braunschweig	244	Braunschweig	274	Braunschweig	400	Braunschweig	698
Frankfurt a/m	227	Duesseldorf	217	Stuttgart	258	Duesseldorf	325	Duesseldorf	585
Dortmund	194	Erfurt	177	Hannover	228	Stuttgart	317	Stuttgart	558
Duesseldorf	172	Aachen	169	Frankfurt a/m	218	Frankfurt a/m	305	Berlin	544
Dresden	158	Chemnitz	161	Dresden	212	Aachen	302	Frankfurt a/m	532
Erfurt	154	Erbelfeld	154	Duesseldorf	205	Mannheim	296	Mannheim	485
Luebeck	152	Berlin	140	Aachen	190	Luebeck	252	Essen	447
Stuttgart	140	Dresden	135	Mannheim	179	Berlin	248	Elbelfeld	429
Essen	138	Magdeburg	129	Chemnitz	174	Dresden	233	Luebeck	423

The ranking becomes quite different after we control for population. For instance, Berlin is no longer number one in terms of patents per million residents. Hamburg disappears from the list. Braunschweig (whose population was about 130,000) had occupied the second position in all time periods.

The finding that patent awards concentrate in big cities is a commonplace feature of urban systems. Most urban-size distributions (of population and of patenting) are sharply positively skewed to the right. That is, there are few large cities but many small cities so that the number of cities in each size class increases as city size decreases. The following histograms assure us that the German urban system confirms this rule. We use histogram as it is a powerful tool to graphically summarize and display the distribution of data.

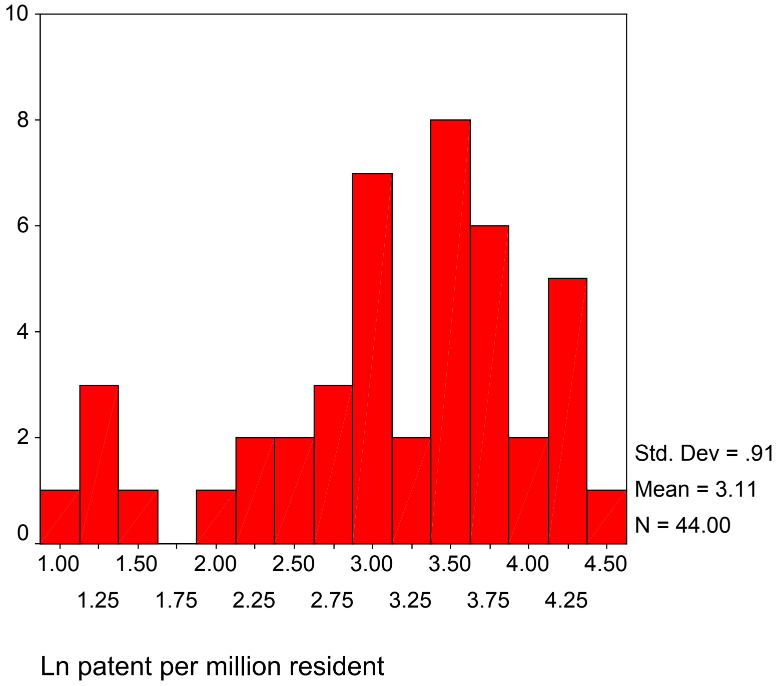
Figure 3.1 Histogram of patents per million residents in 44 German cities (1890-1914 yearly average)



We construct a histogram by segmenting the range of the data (in our case patents per million residents) into equal sized bins. In this histogram, the vertical Y-axis is labeled with the number of counts for each bin, and the horizontal X-axis of the histogram is labeled with the range of our variable (patents per million residents).

The distribution is skewed to the right. We take natural log of patents per million residents and draw the histogram again.

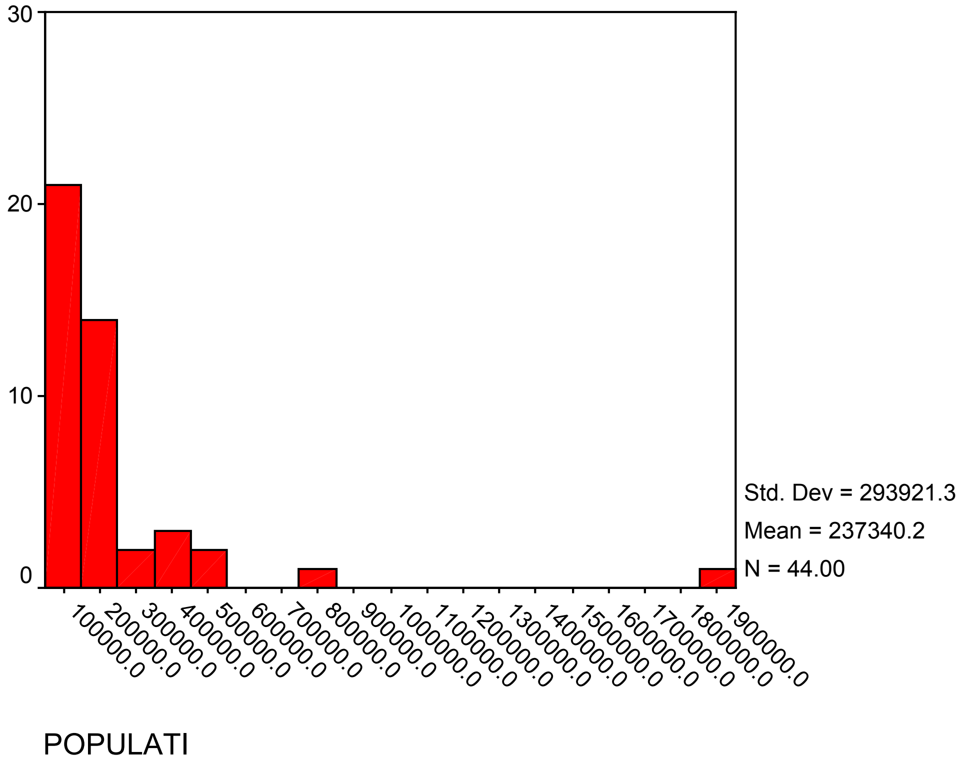
Figure 3.2 Histogram of patents per million residents in 44 German cities in natural log form (1890-1914 yearly average)



After taking natural logs, the distribution of patents per million residents is closer to normal distribution.

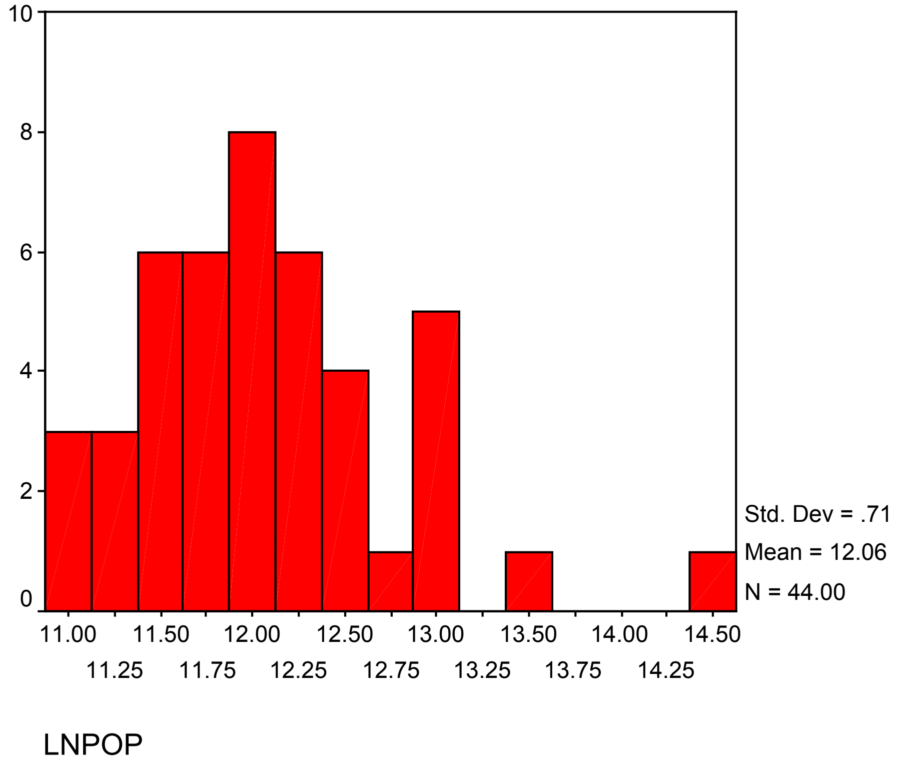
The distribution of population follows a similar pattern.

Figure 3.3 Histogram of population of 44 German cities (1890-1914 average)



Located at the right end of the chart, Berlin and Hamburg stand out with their large populations. We take natural log of population.

Figure 3.4 Histogram of population in 44 German cities in natural log form (1890-1914 yearly average)



Now, the distribution of population is more or less close to normal distribution. As German cities have highly unevenly distributed population and patents, we use natural log form of population and patents in our regressions.

Rank-size rule is a powerful tool to study urban distribution. The theory was originally developed by Zipf (1949).[91] It can be employed to investigate the relationship between the ranks of cities and their populations. A standard formula is

$$Pop_r=Pop_1/PopRank^q \quad (1)$$

We take natural log on both sides of the equation to get the linear form

$$Ln\ Pop_r=Ln\ Pop_1 + (-q)\ LnPopRank \quad (2)$$

In these two equations, Pop_r is the population size of a given city, Pop_1 is a constant approximately equal to the population size of the biggest city, PopRank is the rank of population in a given city, and $(-q)$ is a parameter to be estimated. The rank-size theory suggests a linear sloping relationship between cities in a geographical area. According to this theory, there is one largest city and the rest cities will be strictly proportionally smaller than the largest city. If $q = 1$, the rank-size rule stands valid and the size of some city equals the division of the largest city by the rank of the city in question. For instance, if the largest city has a population of 100,000 people, the second largest city will have a population of 50,000 (100,000/2) people, the third largest city will have a population of 33,333 (100,000/3) people and so on.

Berry (1961, 1964) theoretically interpreted the rank-size distribution as the outcome of a stochastic process in which multiple forces cause an urban system to reach an equilibrium set of city sizes. It is also the most probable distribution representing maximum entropy in steady-state equilibrium in theory. It is ideal because it shows the highest level of economic development, an equal distribution of wealth, and is important for implicating planning. However, in the real world, q is unlikely to be equal to unity as the most probable distribution may be neither observed nor optimal (Richardson, 1972). If $q > 1$, the largest cities dominate the system. That is, large cities are larger than they should be designated by rank-size relationship and they usurp much of the population of the following cities. Dynamic increasing returns that are external both to firms and industries concentrate invention, high-technology industries, and well-educated labor in the largest urban centers. Although the fundamental causes for their initial advantage are often small and difficult to identify and measure, they create enduring conditions favoring

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[91] For a good survey on this rank-size rule, see Carroll (1982).

agglomeration and large-city dominance (David and Rosenblum, 1990). The United States urban system (dominated by mega cities, especially in the manufacturing belt) falls into this category. Values of $q < 1$ are urban distributions that contain many substantial intermediate cities, as the case of Germany. The great number of smaller towns, very often competing with each other economically, is one of the major characteristics of Germany's urban landscape.

Substituting the number of high-value patents Pat awarded to residents of a city for population in Equation (2) gives us the rank-size relationship for patents

$$\text{Ln Pat}_r = \text{Ln Pat}_1 + (-q)\ \text{LnPatRank} \qquad (3)$$

In this equation (3), Pat_r is the high-value patent counts of a given city, Pat_1 is a constant approximately equal to the patent count of the most innovative city, PatRank is the rank of high-value patent counts in a given city, and $(-q)$ is a parameter to be estimated.

Thus, we can use equation (2) and equation (3) to compare the distributions of population and patents. Figure 3.5 and 3.6, two scattergrams, show the rank-size distributions of 44 German cities using population and patents as measures of urban size respectively.

Figure 3.5 Urban-size distribution of all German cities by population in natural log form (1890-1914 annual average)

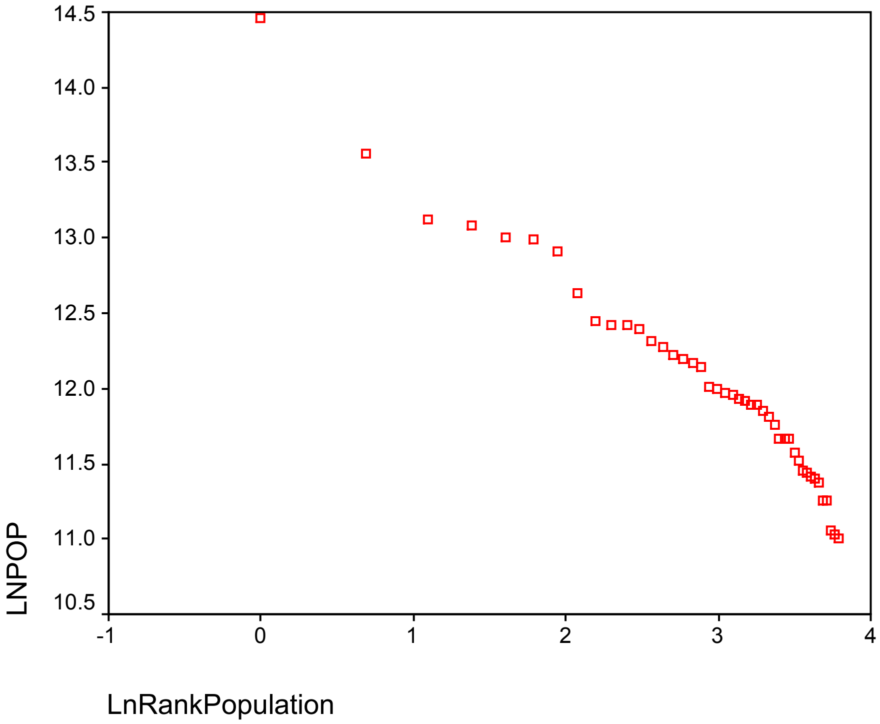
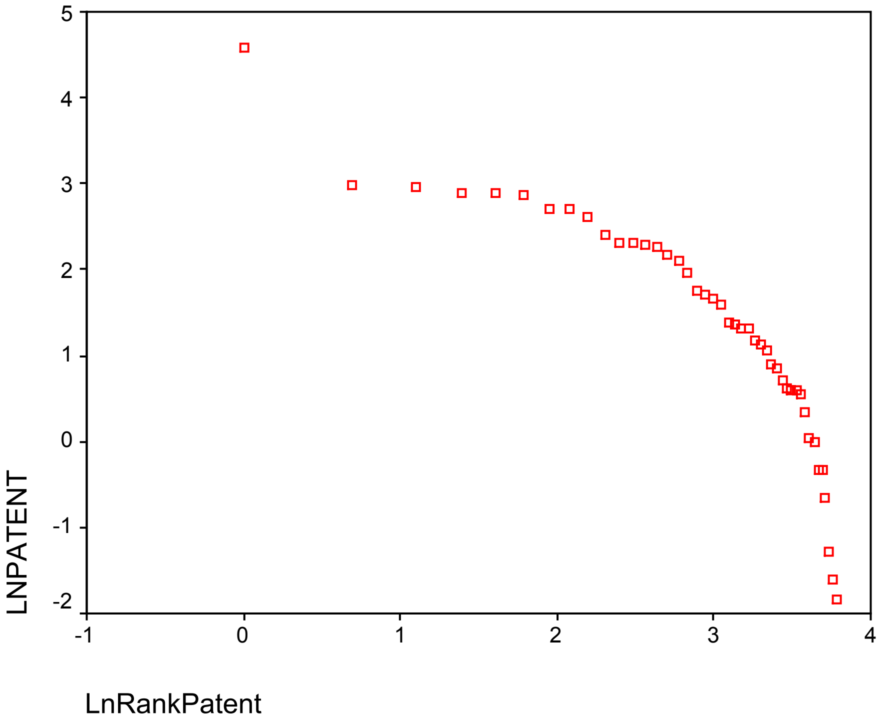


Figure 3.6 Urban-size distribution of all German cities by high-value patent counts (excluding chemical and electrical) in natural log form (1890-1914 annual average)



A notable feature of the patent distribution is that many cities obtained very few patents. In contrast, all 44 cities in our study had population greater than 50,000 residents. Moreover, when we compare figure 3.5 with figure 3.6, we find that the gradient of the patent distribution is generally steeper than that of population. This is especially true among the small cities located at the right end of the charts. And this implies that patents were more concentrated than population in the urban hierarchy.

Tables 3.6-3.10 show our estimates of q for various types of cities—all cities, 18 big cities (over 20,000 residents), 26 small cities, 24 cities in the manufacturing belt, and 20 cities outside the manufacturing belt in each time period under our study. Separate rankings were calculated for population and high-value patents of each category.

Table 3.6 Regression results for urban size and rank relationships (using patent (excluding chemical and electrical) and population) (1890-1894)

	Dependent variable	**Independent variable**	**Intercept**	**Regression coefficient**	**Standard error**	**R square**	**Number of observations**
all cities	LnPat	LnPatRank	0.383	-1.199***	0.08	0.832	44
	LnPop	LnPopRank	-0.337	-0.779***	0.02	0.981	44

large cities	LnPat	LnPatRank	-0.214	-0.968***	0.08	0.899	18
	LnPop	LnPopRank	-0.194	-0.929***	0.04	0.975	18
small cities	LnPat	LnPatRank	0.618	-1.059***	0.09	0.841	26
	LnPop	LnPopRank	-8.979E-02	-0.459***	0.02	0.965	26
cities in manufacturing zone	LnPat	LnPatRank	-4.983E-02	-1.072***	0.07	0.911	24
	LnPop	LnPopRank	-0.570	-0.828***	0.04	0.950	24
cities in non-manufacturing zone	LnPat	LnPatRank	0.673	-1.252***	0.11	0.875	20
	LnPop	LnPopRank	7.659E-02	-0.820***	0.03	0.970	20

Note: * means statistically significant at 10 % level, ** means statistically significant at 5 % level, and *** means statistically significant at 1 % level.

Table 3.7 Regression results for urban size and rank relationships (using patent and population) (1895-1899)

	Dependent variable	Independent variable	Intercept	Regression coefficient	Standard error	R square	Number of observations
all cities	LnPat	LnPatRank	0.348	-1.223***	0.10	0.793	44
	LnPop	LnPopRank	-0.257	-0.788***	0.02	0.982	44
large cities	LnPat	LnPatRank	-0.288	-0.974***	0.13	0.778	18
	LnPop	LnPopRank	-0.183	-0.888***	0.04	0.971	18
small cities	LnPat	LnPatRank	0.906	-1.089***	0.11	0.802	26
	LnPop	LnPopRank	-0.137	-0.458***	0.02	0.957	26
cities in manufacturing zone	LnPat	LnPatRank	-0.328	-0.940***	0.08	0.858	24
	LnPop	LnPopRank	-0.489	-0.833***	0.04	0.959	24
cities in non-manufacturing zone	LnPat	LnPatRank	0.460	-1.300***	0.10	0.904	20
	LnPop	LnPopRank	0.107	-0.830***	0.04	0.967	20

Table 3.8 Regression results for urban size and rank relationships (using patent and population) (1900-1904)

	Dependent variable	Independent variable	Intercept	Regression coefficient	Standard error	R square	Number of observations
all cities	LnPat	LnPatRank	0.493	-1.187***	0.07	0.867	44
	LnPop	LnPopRank	-0.143	-0.798***	0.02	0.962	44
large cities	LnPat	LnPatRank	-3.680E-02	-0.971***	0.12	0.792	18
	LnPop	LnPopRank	-0.229	-0.792***	0.04	0.968	18

small cities	LnPat	LnPatRank	0.339	-0.907***	0.08	0.855	26
	LnPop	LnPopRank	-0.118	-0.481***	0.03	0.896	26
cities in manufacturing zone	LnPat	LnPatRank	1.909E-02	-1.208***	0.09	0.895	24
	LnPop	LnPopRank	-0.417	-0.823***	0.04	0.960	24
cities in non-manufacturing zone	LnPat	LnPatRank	0.282	-1.194***	0.07	0.947	20
	LnPop	LnPopRank	0.258	-0.882***	0.04	0.966	20

Table 3.9 Regression results for urban size and rank relationships (using patent and population) (1905-1909)

	Dependent variable	Independent variable	Intercept	Regression coefficient	Standard error	R square	Number of observations
all cities	LnPat	LnPatRank	0.660	-1.343***	0.11	0.783	44
	LnPop	LnPopRank	-0.117	-0.795***	0.03	0.939	44
large cities	LnPat	LnPatRank	-2.652E-02	-1.073***	0.12	0.839	18
	LnPop	LnPopRank	-0.266	-0.746***	0.04	0.961	18
small cities	LnPat	LnPatRank	0.796	-1.180***	0.14	0.739	26
	LnPop	LnPopRank	-0.120	-0.490***	0.04	0.868	26
cities in manufacturing zone	LnPat	LnPatRank	9.463E-02	-1.147***	0.10	0.861	24
	LnPop	LnPopRank	-0.410	-0.800***	0.04	0.954	24
cities in non-manufacturing zone	LnPat	LnPatRank	0.752	-1.410***	0.16	0.811	20
	LnPop	LnPopRank	0.261	-0.900***	0.05	0.954	20

Table 3.10 Regression results for urban size and rank relationships (using patent and population) (1910-1914)

	Dependent variable	Independent variable	Intercept	Regression coefficient	Standard error	R square	Number of observations
all cities	LnPat	LnPatRank	0.527	-1.320***	0.10	0.815	44
	LnPop	LnPopRank	8.204E-2	-0.817***	0.03	0.944	44
large cities	LnPat	LnPatRank	-0.221	-1.004***	0.11	0.845	18
	LnPop	LnPopRank	-0.178	-0.701***	0.03	0.978	18
small cities	LnPat	LnPatRank	0.763	-1.188***	0.10	0.857	26
	LnPop	LnPopRank	-0.155	-0.509***	0.04	0.863	26
	LnPat	LnPatRank	-3.295E-02	-1.124***	0.10	0.854	24

cities in manufacturing zone	LnPat	LnPatRank	-3.295E-02	-1.124***	0.10	0.854	24
cities in manufacturing zone	LnPat LnPop	LnPatRank LnPopRank	-0.723 0.236	-1.177*** -0.871***	0.04 0.01	0.890 0.904	24 20
	LnPop	LnPopRank	0.245	-0.930***	0.05	0.953	20

For various sub-periods from 1890 to 1914, the patent gradient of all cities was roughly between –1.2 and –1.3. And the population gradient of all cities was about –0.8. Compared with gradients of all cities, the patent and population gradients of small cities were notably gentler. The patent gradient of small cities was about from –0.9 to –1.1. The population gradient of small cities was very low in absolute value, roughly between –0.45 to –0.5. The population gradient of big cities was about between –0.7 and –0.9. These gradients confirm the more uneven concentration of population in big cities compared with small cities. Moreover, the patent gradient of small cities is steeper than the patent gradient in big cities. This means that the sharp dwindling of inventive activity in small cities leading to a dearth of patents awarded to residents of most minor cities. Furthermore, rank-size relationships also vary by region. The manufacturing belt had a somewhat shallower patent gradient (largely between –1.0 to –1.1) compared with the non-manufacturing belt (roughly from –1.2 to –1.4), showing greater patent concentration in cities beyond the traditional German manufacturing belt.

3.4 MODEL FOR LOCATIONAL DETERMINANTS OF URBAN INNOVATION

The above revealing investigation informs us about patenting in German urban hierarchy. It also tells us that location in manufacturing zone have impact on innovation in German cities. What other factors affect innovation in cities? In this section, we try to identify some key factors and estimate their effects on innovation in cities.

Kuznets (1960) and Pred (1966) underline the role of urban externalities in innovation. They argue that abundant supplies of inventors, more interaction among inventors (and ordinary people as potential inventors), larger numbers of corporations focusing on invention, and flexible social structures allowing unconventional thinking precipitate the increasing returns of large urban centers in knowledge generation. Malecki (1980) notes that big cities are also important during new firm formation because spin-offs more easily grow from dependence on parent corporations to become technological innovators. These diverse forces are cumulative. They enable technological progress to build on past advance. Following this approach, we first estimate the relationship between population and innovation

$$LnPat_i = \alpha + \beta\, LnPop_i + \varepsilon_i \qquad (4)$$

where

$LnPat_i$ = The natural logarithm of the total number of high-value patents granted to residents of city i in each period from 1890 to 1914

$LnPop_i$ = The natural logarithm of the mean population of city i in each period from 1890–1914

α and β = scalar regression coefficients to be estimated

ε_i = an error term for city i

Using the total number of patents for each of the five periods from 1890 to 1914 reduces inter-annual variances in patent numbers, which is especially troublesome in cities that often receive few patents in a given year.[92] Underlying the functional form of Equation (4) is the following logic. The sizes of the coefficients on $LnPop_i$ are elasticities of patent awards with respect to population. If $\beta \geq 1$, then the locations of patents distribute in increasing or constant proportions as urban population increases. If $0 < \beta < 1$, the proportion of patents in city i decreases as population increases. Negative values of β would mean an inverse relationship between patents and population.[93]

Although helpful, Equation (4) is too simplistic. It suffers from omitted variable bias. We should construct a second regression equation that would identify additional determinants of patent distribution and study the influence of their inclusion on the size of regression coefficients.

We should use our discretion to choose additional variables carefully. Almost no serious economists would doubt that human capital (an important component of R&D input) has great impact on innovation. We use data for school enrollment as proxy for human capital. Not all schools are equally important in stimulating technological innovation. We choose technical schools and commercial schools. Students from these two kinds of students are more likely to engage in technological innovation. As we should

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[92] Kelley (1972) estimates a similar model in his temporal analysis of the American interstate distribution of patents in the period 1870–1920.

[93] Kelley (1972) speculates that the benefits of population, while positive in the past, have probably diminished over time and are possibly insignificant today.

control population, we use the share of pupils from these schools in the total population of a city as an explanatory variable.[94]

Number of industrial workers should also have impact on innovation. Technological discoveries are more likely to occur to those who are involved in an industry than to outsiders as insiders are normally more knowledgeable about problems and opportunities in the industry and have a better position to gain from their knowledge. We try to test the hypothesis whether geographic distribution of innovations would correspond generally to the distribution of the labor force. We use the share of industrial labor force among the total population in each city as one explanatory variable.

There is a large literature on the tendency of innovative firms to spontaneously form geographical clusters. If so, concentrated pools of skilled labor would seem to underlie cluster formation. Jacob (1969) argues that the most important spillovers occur across industries, not between firms in a single industry. This theory appears strongly supported by empirical studies. Rosenberg (1963) discusses how the use of machine tools spread from industry to industry, and Scherer (1982) finds that 70 percent of inventions in a given industry are applied in other industries. This theory stresses the importance of the cross-industry transfer of ideas, and implies that one-industry clusters like Silicon Valley and Detroit are less stable than more diversified clusters, like Chicago, New York, or London. This suggests that highly focused centers of excellence might produce only limited innovation while cities with diverse industries are more stable in generating innovation.

We strive to shed some light on the debate about one industry cluster (like Detroit) vs. diversified cluster (like London). Our proxy is Herfindahl index, which is an indicator of clustering and agglomeration. It is defined as the sum of the squares of the employment shares of each individual industry. As such, it can range from 0 to 10000, moving from a very large amount of industries to a single dominant industry. Decreases in the Herfindahl index generally indicate decrease in concentration, whereas increases imply the opposite.

Finally, we include whether a city is located in the manufacturing belt as a dummy variable as we learnt from the previous section that this location factor is significantly related to innovation.

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[94] See chapter 2 of this dissertation for justifications of using number of students of these two kinds of schools as proxy for human capital. Germany enjoyed high literacy rate and had quite good system of

Ultimately, we construct the equation

$$\text{InPat}_i = \alpha + \beta_1\text{LnPop}_i + \beta_2\text{HC}_i + \beta_3\text{Employ}_i + \beta_4\text{Herfindahl}_i + \beta_5\text{M}_i + \varepsilon_i \qquad (5)$$

where

InPat_i, LnPop_i, α, ε_i are defined as previously.

Employ_i = The proportion of city i's industrial employment in the city's total population in each time period

HC_i = The proportion of city i's population that was in technical and commercial schools in each time period

Herfindahl_i = The Herfindahl index of all industries in a city in each time period

M_i = A dummy variable with unity values for cities located in the manufacturing belt

β_1, β_2, β_3, β_4, β_5 = The coefficients to be estimated in regression.

3.5 RESULTS OF REGRESSION

The regression results of Equation (4) for all, big, small cities and for cities in manufacturing areas and non-manufacturing areas using OLS estimation method for each time period are shown in tables 3.11-3.15.

Table 3.11 Regression results for patent and city size relationship
Dependent variable: LnPat
1890-1894

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-12.348*** (2.02)	-6.683*** (2.91)	-13.741*** (4.82)	-10.228*** (1.85)	-12.228*** (2.96)
LnPop	1.245*** (0.17)	0.803*** (0.18)	1.351*** (0.42)	1.101*** (0.16)	1.192*** (0.25)
R square	0.556	0.548	0.299	0.695	0.550
Number of observations	44	18	26	24	20

Note: Standard errors are shown in parenthesis

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primary education at this time period. Thus, we will not see systematic difference in primary education across cities.

Table 3.12 Regression results for patent and city size relationship 1895-1899

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-12.909*** (2.11)	-7.733*** (2.63)	-13.913*** (5.19)	-9.596*** (1.36)	-13.031*** (2.87)
LnPop	1.287*** (0.18)	0.886*** (0.21)	1.362*** (0.45)	1.053*** (0.12)	1.245*** (0.24)
R square	0.556	0.522	0.275	0.780	0.591
Number of observations	44	18	26	24	20

Table 3.13 Regression results for patent and city size relationship 1900-1904

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-11.961*** (1.80)	-7.329*** (3.26)	-10.674*** (3.76)	-10.815*** (1.43)	-10.146*** (2.50)
LnPop	1.233*** (0.15)	0.880*** (0.26)	1.112*** (0.32)	1.172*** (0.02)	1.039*** (0.21)
R square	0.620	0.422	0.332	0.821	0.578
Number of observations	44	18	26	24	20

Table 3.14 Regression results for patent and city size relationship 1905-1909

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-14.096*** (2.13)	-8.757*** (3.74)	-15.368*** (5.11)	-12.141*** (2.07)	-12.285*** (3.36)
LnPop	1.411*** (0.18)	1.003*** (0.29)	1.513*** (0.43)	1.288*** (0.17)	1.217*** (0.23)
R square	0.582	0.424	0.336	0.728	0.514
Number of	44	18	26	24	20

observations					

Table 3.15 Regression results for patent and city size relationship 1910-1914

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-13.640*** (1.92)	-9.802*** (3.41)	-14.538*** (4.37)	-11.592*** (1.89)	-12.042*** (2.02)
LnPop	1.417*** (0.16)	1.126*** (0.26)	1.490*** (0.37)	1.286*** (0.15)	1.245*** (0.21)
R square	0.664	0.533	0.405	0.766	0.663
Number of observations	44	18	26	24	20

The regression fitness and the significance of the models are consistently high. The R-square values approximately ranged from 0.5 to 0.8 except for small cities. The low R square values for small cities show substantial variation unexplained by population, perhaps partially because compared with big cities, small cities suffer more from omitted variable bias in this simplified regression. Other urban conditions are at work in small cities beyond population size. The estimates of the regression coefficients of LnPop for all cities ranged from 1.2 to 1.4. The estimates of the regression coefficients for small cities were larger in general, roughly ranging from 1.3 to 1.5.

Table 3.16 to table 3.20 show the regression results for Equation (5) using OLS estimation methods for each time period from 1890 to 1904.

Table 3.16 Regression results for patents and urban conditions relationships Dependent variable: LnPat (1890-1894)

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-9.828*** (1.521)	-10.712*** (1.814)	-13.799*** (3.792)	-8.940*** (2.092)	-9.624*** (2.325)
LnPop	0.958*** (0.124)	0.980*** (0.124)	1.264*** (0.321)	1.012*** (0.167)	0.858*** (0.194)
School pupil %	0.310*** (0.100)	0.141 (0.097)	0.677*** (0.193)	0.185 (0.174)	0.387*** (0.125)

Employment %	2.395E-02* (0.014)	5.861E-02** (0.023)	2.405E-02 (0.022)	9.020E-03 (0.019)	4.662E-02** (0.021)
Herfindahl index	-5.757E-04* (0.000)	-1.582E-04 (0.001)	-4.185E-04 (0.000)	-7.304E-02 (0.001)	-3.483E-04 (0.000)
Manufacturing dummy	0.804*** (0.167)	0.779*** (0.192)	0.769*** (0.224)		
R square	0.829	0.864	0.761	0.749	0.822
Number of observations	44	18	26	24	20

Table 3.17 Regression results for patents and urban conditions relationships

Dependent variable: LnPat (1895-1899)

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-7.554*** (2.160)	-6.207*** (1.811)	-8.503* (4.609)	-4.653** (1.964)	-8.600** (4.415)
LnPop	0.740*** (0.150)	0.758*** (0.113)	0.736* (0.355)	0.678*** (0.140)	0.675** (0.320)
School pupil %	7.669E-02* (0.043)	4.677E-02 (0.029)	0.258* (0.150)	6.186E-02* (0.036)	0.222* (0.121)
Employment %	3.990E-02*** (0.015)	1.536E-02 (0.014)	5.124E-02** (0.021)	1.211E-02 (0.015)	6.693E-02** (0.025)
Herfindahl index	-5.202E-04* (0.000)	-1.193E-03** (0.000)	-1.331E-04 (0.000)	-1.054E-03 (0.000)	9.475E-05 (0.000)
Manufacturing dummy	0.752*** (0.168)	0.658*** (0.155)	0.705*** (0.244)		
R square	0.884	0.940	0.828	0.884	0.836
Number of observations	44	18	26	24	20

Table 3.18 Regression results for patents and urban conditions relationships

Dependent variable: LnPat (1900-1904)

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-8.409*** (1.597)	-7.540** (2.497)	-3.725 (2.685)	-8.312*** (1.747)	-5.477* (0.065)

LnPop	0.813*** (0.128)	0.843*** (0.168)	0.405* (0.227)	0.904*** (0.148)	0.535** (0.218)
School pupil %	5.291E-02* (0.027)	2.690E-02 (0.027)	0.185* (0.095)	4.409E-02* (0.024)	0.201** (0.085)
Employment %	5.241E-02*** (0.013)	2.886E-02 (0.025)	4.655E-02*** (0.016)	3.308E-02* (0.019)	5.924E-02*** (0.017)
Herfindahl index	-2.371E-04* (0.000)	-9.273E-04* (0.000)	-1.876E-04 (0.016)	-2.522E-04 (0.000)	-2.368E-04 (0.000)
Manufacturing dummy	0.685*** (0.142)	0.827*** (0.208)	0.585*** (0.193)		
R square	0.872	0.872	0.770	0.870	0.843
Number of observations	44	18	26	24	20

Table 3.19 Regression results for patents and urban conditions relationships

Dependent variable: LnPat (1905-1909)

	all cities	**big cities**	**small cities**	**cities in manufacturing areas**	**cities in non-manufacturing areas**
Intercept	-7.563*** (2.510)	-4.558 (3.305)	-5.053 (3.276)	-7.475** (3.050)	-7.949** (3.205)
LnPop	0.751*** (0.199)	0.680*** (0.223)	0.538*** (0.272)	0.811*** (0.261)	0.755*** (0.249)
School pupil %	0.126** (0.062)	4.186E-02 (0.054)	0.310** (0.142)	0.118* (0.065)	0.289** (0.131)
Employment %	6.770E-02*** (0.018)	5.179E-03 (0.033)	5.912E-02** (0.023)	4.981E-02* (0.026)	6.103E-02** (0.025)
Herfindahl index	-2.863E-04* (0.000)	-9.632E-04* (0.000)	-2.682E-04 (0.000)	-2.129E-04 (0.000)	-1.561E-04 (0.000)
Manufacturing dummy	0.519** (0.212)	0.723** (0.241)	0.172 (0.315)		
R square	0.832	0.878	0.768	0.798	0.849
Number of observations	44	18	26	24	20

Table 3.20 Regression results for patents and urban conditions relationships

Dependent variable: LnPat (1910-1914)

	all cities	**big cities**	**small cities**	**cities in**	**cities in non-**

				manufacturing areas	**manufacturing areas**
Intercept	-7.427*** (2.258)	-7.347** (3.359)	-2.279 (4.514)	-5.832* (2.964)	-4.287 (2.915)
LnPop	0.841*** (0.188)	0.865*** (0.264)	0.646* (0.352)	0.755*** (0.258)	0.543** (0.243)
School pupil %	0.120* (0.080)	8.452E-02 (0.062)	0.409* (0.237)	0.150** (0.066)	0.187* (0.093)
Employment %	3.219E-02* (0.016)	2.747E-02 (0.028)	1.131E-02 (0.027)	3.297E-02 (0.025)	6.595E-02* (0.034)
Herfindahl index	-2.190E-04** (0.000)	-4.372E-04* (0.000)	-2.183E-04 (0.000)	-1.405E-04 (0.000)	-2.197E-04* (0.000)
Manufacturing dummy	0.778*** (0.177)	0.758*** (0.223)	0.582* (0.325)		
R square	0.847	0.865	0.720	0.823	0.839
Number of observations	44	18	26	24	20

For the regression including all cities, following the inclusion of three additional independent variables (share of school pupil, employment share and Herfindahl index), the goodness-of-fit rose from about 0.6 to 0.8. The size of the regression coefficients of LnPop of all categories in Equation (5) declined when compared with the results of Equation (4). This decline shows that the combined influence of human capital, labor force, and industrial diversity account for a sizable portion of the high concentration of patenting activities. The variables measuring population, human capital, employment, Herfindahl index of diversity, and location in manufacturing zone are significant, mostly at 5 % probability level. The effects are all positive, with Herfindahl index as the only exception, signifying that diversified industry structure is conducive to innovation.

The coefficient of InPop for big cities is larger than for small cities (except the first sub-period). And the coefficient of LnPop for cities in the manufacturing zone is larger than for cities in the non-manufacturing zone.

We find that the impact of human capital has been always statistically significant for small cities, while it is not always the case with big cities. The reason might be that big cities attracted a lot of brainpower and did not have to rely totally on local schooling. The coefficients of human capital are always larger for cities located in the non-manufacturing zone than the cities in the manufacturing zone.

In terms of Herfindahl index, their role has been always statistically significant for big cities while it is not the case with small cities.

3.6 CONCLUSION

Innovation and cities are closely related. Using the patent data, we analyze the patterns of innovation in German cities from 1890 to 1914. Urban residents obtained most of the patents granted in Germany from 1890 to 1914. In this chapter, we stress the increasing returns to city size in technological innovation. Big cities hosted abundant interacting inventors, firms focused on innovation, social norms and structures that favor creative thinking, and industrial systems that encourage formation of dynamic firms. Examining the sources of increasing returns to urban size is key to our understanding the geographical conditions of invention.

Although the existence of many small towns is a major feature of German urban landscape, regression results confirm that big cities dominated technological innovation from 1890 to 1914. Innovation in Germany was characterized by polarized developments to the advantage of big cities such as Berlin, Duesseldorf, and Dresden. The gradient of the size distribution of cities is substantially steeper when we use high-value patents to measure city size compared with we use population to measure city size. Moreover, that difference is more pronounced in small cities than in big cities. The patent gradient is steepest outside the traditional manufacturing belt. Abundant human capital and industrial labor partly explains the inventiveness of urban residents. Regional location also plays a role. Urban residents in the manufacturing belt were the most industrious inventors. Residents of cities beyond the manufacturing belt obtained few patents.

After taking human capital, employment, and industrial diversity into account, we use regressions to explain the distribution of patents in German cities quite successfully. Human capital and industrial labor had significant, positive effects on innovation. Using Herfindahl index as a measure of diversity, we learn that cities with diverse industries are more conducive to innovation.

Chapter 4

Clusters, externalities and innovation: new evidence from firms in Baden, Germany

1878 to 1913[95]

Abstract

Do firms in clusters tend to innovate more? An important tradition of work has given a positive answer to this question and attributed the reason to knowledge spillovers (intra-industry and inter-industry) enjoyed by firms within clusters as a factor promoting innovation. This chapter revisits these issues through an original database including information on patents and firms in the German state of Baden. Using negative binomial regressions, the analysis shows that both intra-industry and inter-industry externalities have a positive effect on the innovative activity of small and large firms. In contrast, regional human capital formation is important only for small firms, a result consistent with Winter's theory of "technological regimes" and rich in policy implications.

4.1 INTRODUCTION

Innovation is a broad concept, embracing three main areas: products, production processes and organizational set-ups (Dosi, 1988).[96] This chapter focuses on firms' innovative activity concerning the first two areas and follows the definition of innovation as research, development, imitation and adoption of new products and new production processes (Dosi, 1988).[97] This approach is consistent with an important stream of historical and theoretical works that regard innovation, in the form of technological

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[95] See also Baten, Spadavecchia, Yin, and Streb (2004) on these issues.

[96] The similarity between the various types of innovation identified by Dosi and those that had been previously identified by Schumpeter is clear, see Schumpeter (1942), pp.65-66; on this point see also Nelson and Winter (1982), pp. 276-278.

[97] This choice is also dictated by the usage of patents as a proxy for innovation. New organizational set-ups would not be patented and therefore their determinants cannot be analyzed in this paper. However, it is acknowledged the importance of new organizations in promoting knowledge transfer across firms' boundaries, as showed in previous studies. See Streb (2003).

progress, as a fundamental determinant of economic growth.[98] Moreover, it is consistent with Schumpeter (1942), who focuses on the "introduction of new methods of production and new commodities" in his discussion of innovation, in turn as a part of monopolistic practices (Schumpeter, 1942, pp. 81-106).

This chapter assesses the impact of various determinants of innovation, with particular attention to the impact of clustering of firms and externalities generated in this pattern of business organization. An important tradition beginning with Marshall (1890) has stressed external economies arising from geographical concentrations of similar industries. This chapter tests whether such externalities played a positive role in promoting innovation, thus placing itself at the crossroad of two major historical and economic topics. Marshall had the economic situation around 1900 in mind when he wrote his famous work, which has high explanatory power for today's world, as many studies found. Augmenting our knowledge about the time-variance or time-invariance of the relationships is obviously a very important aim.

The analysis is performed using an original dataset including information on patents granted and firms located in the state of Baden between 1895 and 1913, which at the time occupied a middling economic position in Germany. The dataset was constructed using two main sources: German factory inspections lists and the *Annual Patent Directory* published by the German Patent Office in Berlin.

This chapter is organized in seven sections. The following section analyzes the theories behind the determinants of innovation, the impact of which is discussed in this chapter. Section 3 discusses some methodological issues. Section 4 presents the data used in the analysis, explains how various sources were combined and the methodology adopted to overcome the shortcomings related to using patents as a proxy for innovation. Section 5 discusses the model adopted in the econometric analysis, whereas section 6 presents and interprets the results of the econometric analysis. Section 7 concludes the chapter discussing the policy implications of the findings.

4.2 THEORETICAL BACKGROUND

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[98] Works on innovation, technological change in particular, and its impact on growth are numerous. Among theoretical works it seems important to mention seminal works in endogenous growth theory such as Lucas (1988) and Romer (1990). Among historical works, see Landes (1969) and Mokyr (1990).

The concept of innovation adopted in this chapter stresses the implementation of "new knowledge" either in the production process or in the form of new products, which in turn is very likely to imply changes in the production process. From this fundamental feature of innovation derive various theoretical approaches. This section addresses two in particular: knowledge externalities and technological regimes.

Knowledge externalities. If innovation entails the implementation of new knowledge, which according to Winter (1984) is the single most important input in the production of innovations, factors facilitating the generation and diffusion of such knowledge should have a positive effect on the rate of innovation. In this approach, externalities and knowledge spillovers in particular play an important role in fostering innovative activities, as maintained by a stream of research in economics of technology, *new growth* economics and economic geography (Audretsch and Feldman, 1996; Krugman, 1991; Porter, 1998). Most of these studies share the assumption that new technological knowledge is at least partly informal, uncodified and tacit, and thus can flow more easily over short rather than long distances (Pavitt, 1984).

Since the second half of the 19th century, Marshall had explained the advantages that similar firms enjoy by concentrating in the same neighborhood, and called them external economies. He claimed that external economies arise mainly from the development of subsidiary industries and the concentration of a specialized labor force. This brings about a rapid diffusion of innovations as ideas are readily discussed and developed. Porter (1998) pointed out that firms within clusters of different though technologically related industries, learn more quickly about evolving technology not only through frequent contacts with suppliers and other firms located in the cluster, but also through frequent contacts with customers, which provide an ever more sophisticated demand. All these factors provide conditions particularly appropriate to foster innovation and are strengthened by the competition among firms.

Contemporary works have brought forward the concept of Marshallian external economies. In contemporary economic geography, Krugman (1991) has pointed out that economic activities and production tend to concentrate within clusters. Externalities enjoyed in these clusters yield increasing returns to scale, which are geographically bound (Lucas, 1988; Romer, 1986 and 1990).

While it is widely agreed that clusters foster knowledge externalities, more controversial is the path of diffusion of such knowledge. Marshall, Arrow (1962) and Romer (1986) (hereinafter abbreviated as M-A-R) support that knowledge spillovers take place among firms in the same industry, thus fostering the growth of that industry and region. On the contrary, Jacobs (1970) believes that the most important knowledge spillovers take place across various industries. Therefore, according to the M-A-R approach, knowledge externalities should be more pronounced in specialized industrial areas, whereas according to Jacobs such dynamic externalities will take place particularly in highly diversified industrial regions (Glaeser et al., 1992). Jacobs's argument has received further support by studies confirming the significance of inter-industry technology flows and pointing out that technological solutions are often transposed from the sector where it was originally envisaged and applied in a variety of industries (Bairoch, 1988; Scherer, 1984).

While the stream of literature following from Marshall, Arrow, Romer and Jacobs concentrate on positive externalities, other works point out the limits to the positive feedback process generated within clusters. Such limits are related to congestion and competition effects that might overcome the benefits as clusters grow (Brezis and Krugman, 1993). Costs of labor, land and facilities, together with pressure on infrastructure might discourage employers and employees to concentrate within crowded clusters, as exemplified by contemporary developments in Silicon Valley (Morck and Yeung, 2001). Moreover, knowledge externalities might be perceived as a leakage of information, which would erode the appropriability of the innovation. Patent licensing contracts can ensure the patenting firm a significant share of competitors' profit. However, due to imperfect contracts and reverse engineering[99], this solution can be impractical (Caves, 1982). Therefore, the most innovative and best performing firms might be the most likely to move out of the cluster (Shaver and Flyer, 2000).

Recent works have set forth to test empirically whether firms within clusters are more innovative than firms located elsewhere. Baptista and Swann (1998) indicate on the basis of a dataset of 248 firms that cluster specialization has a moderate positive effect on innovative activity of firms within the same sector. On the contrary, employment in other industries has a negative although not significant effect. Therefore, such results suggest externalities of a M-A-R type, whereas the authors infer that employment in other industries could be a source of weak congestion effects. However, the authors admit that the use of aggregated two-digit industries might conceal important results, as inter-

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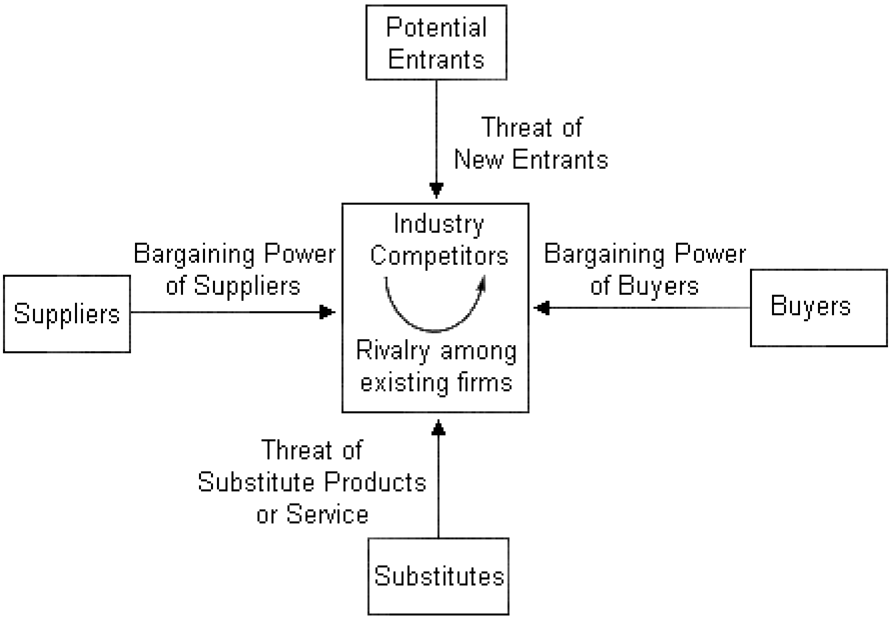
[99] Reverse engineering is the process of taking something (a device, an electrical component, a software program, etc.) apart and analyzing its workings in detail, usually with the intention to construct a new

industry externalities might take place among technologically close industries that would be combined in the two-digit industries.

This line of investigation is brought forward by Breaudry and Breschi (2003), using a very large dataset for 1990-98 from the UK and Italy. Their analysis shows that the concentration of innovative firms in the same industry fosters firms' innovative activity rather than the cluster itself. On the contrary, the presence in the region of innovative firms in other industries has a negative and significant coefficient in the case of the UK.

Technological regimes. Technology plays an important role in firm strategy. Porter (1980) provides a framework that models an industry as being influenced by five forces: the entry of competitors, the threat of substitutes, the bargaining power of buyers, the bargaining power of suppliers, and rivalry among the existing players.[100] A firm seeking to develop an edge over rival firms can use this model to better understand the industry context in which the firm operates and to develop competitive strategies accordingly. As shown in figure 4.1, the model is particularly powerful in thinking about firm's outside-in strategy. Technological innovation is behind every force in the five-force model.

Figure 4.1 Outside-in business strategy within the five-force framework



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device or program that does the same thing without actually copying anything from the original. Reverse engineering is commonly done to avoid patent law.

[100] Government could be added as a sixth factor.

The neo-schumpeterian model developed by Nelson and Winter (1982) puts innovation at the center stage of industry evolution. The model proposes that the competitive advantage of firms is based on their innovative capacity; the selection of firms is determined by their innovative capacity; and hence innovative behavior of firms determines the structure of the industry and its evolution.

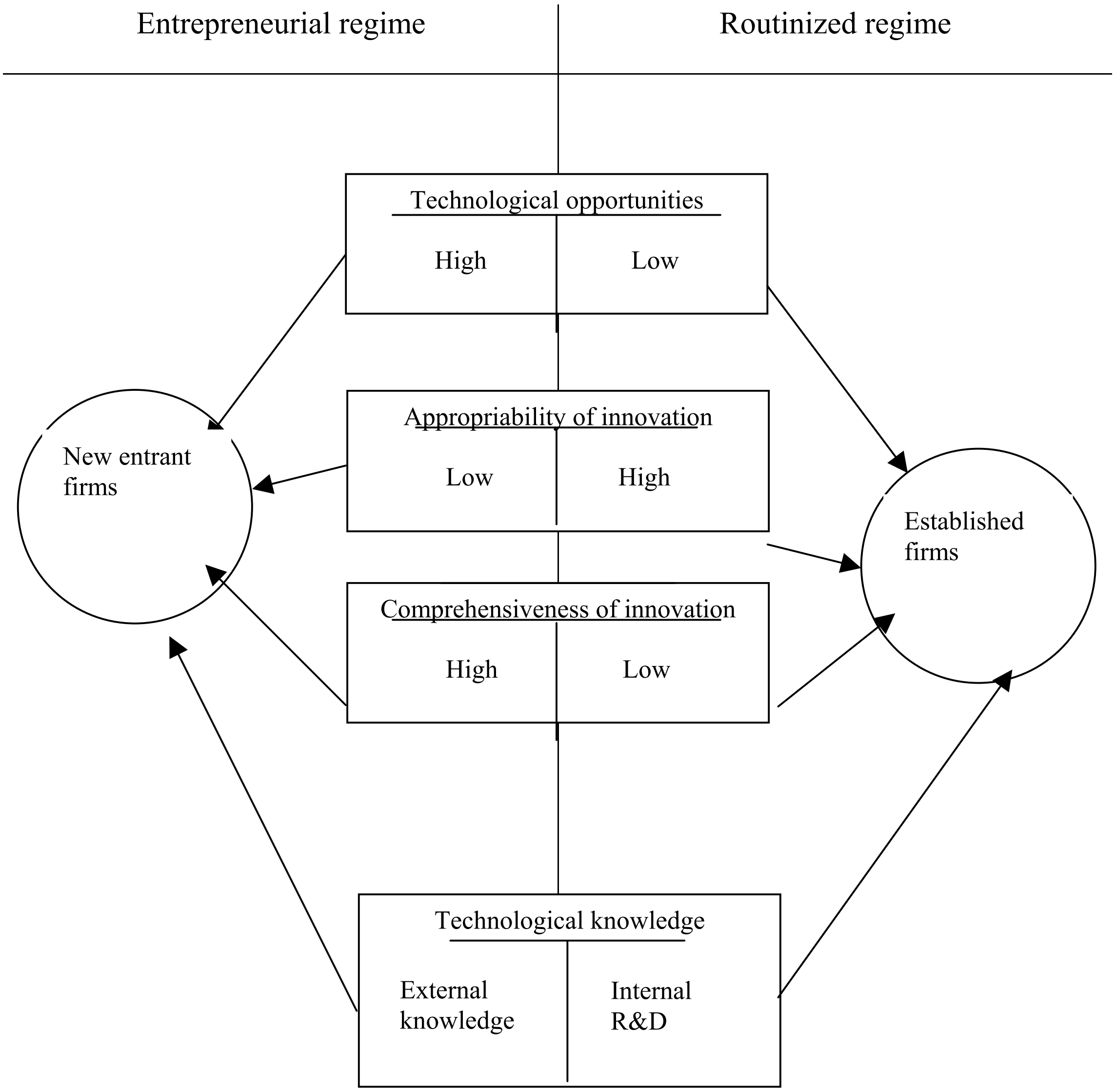
Christensen (1997) studies the big question “Why new technology causes great companies to fail.” Echoing Schumpeter, Christensen introduced the concept “disruptive innovation.” He argues that new disruptive technology brings new risks to established entities and lowers the barrier of market entry for new comers.

The argument of increasing returns to scale does place large, established firms in a better position to innovate as compared to small firms. However, a different line of reasoning confers a comparative advantage in innovation to small firms. Christensen (1997) suggests that established firms might become bureaucratic and resistant to change; familiarity with established products and processes might even make management slow to see the advantages to be gained from new products or processes. Winter (1984) argues that innovation in new entrants or established firms emanate from different economic and technological conditions or “technological regimes”. In particular “an entrepreneurial regime is one which is favorable to innovative entry and unfavorable to innovative activity by established firms; a routinized regime is one in which the conditions are the other way around” (Winter, 1984, p. 297).

The concept of “technological regimes” summarizes the main economic characteristics of technology and of the learning processes involved in the innovative activity. The characteristics are: technological opportunities or the likelihood of innovating for any given amount of money invested in research; appropriability of innovations or the extent to which it is possible to protect innovations from imitation; cumulativeness of technical advances, meaning the extent to which an innovation might generate a stream of subsequent innovations; the properties of the technological knowledge on which the firms’ innovative activity is based. These may differ considerably across technologies presenting various degrees of specificity, tacitness, complexity and independence (Breschi et al., 2000; Winter, 1987). Winter differentiates between two major types of technological knowledge: R&D, which is a type of knowledge available only to the firm that produces it; the second source of knowledge is represented by the firm’s external environment. In turn, this can be represented by other firms involved in similar activities or by the external environment apart from those, such as prior education and experience of firms' personnel (Winter, 1984, pp.292-293).

Figure 4.2 below displays the main features of an "entrepreneurial regime" as compared to a "routinized regime".

Figure 4.2 Factors favoring innovation in new entrant and established firms



An entrepreneurial regime is characterized by high technological opportunities, which makes it easier for new firms to come up with innovations that established firms have not yet implemented (Breschi et al.). Especially important for our study is the difference between the sources of technological knowledge in the two regimes. In particular, Winter (1984) claims the small-firm innovative advantage is roughly correlated to the wide base of the external knowledge environment, from which innovative ideas might derive. This understanding is confirmed by studies showing that university R&D plays a more decisive role in the innovation activity of small firms, whereas corporate R&D plays a relatively more important role in large firms' innovative output (Acs et al., 1994; Acs and Audretsch, 1988). Moreover, the routinized regime is characterized by a high degree of appropriability and low degree of comprehensiveness of innovation. In the routinized regime, the "key innovation" ought to be complemented by other elements to constitute a functioning routine. This is not the case in an "entrepreneurial" regime, in which the innovation is itself the new technique; the founding of a new industry is often the result of an entrepreneurial innovation. As the industry matures, the founder might reach a position that new entrants cannot challenge. In this case, the industry will be dominated by a small number of large and old firms. The opposite occurs if early entrants find it difficult to push forward their initial innovative achievements. The new possibilities will then be captured by new entrants. Established firms hold a position of advantage in those industries where conditions are such that innovators can appropriate substantial returns, due to a mix of secrecy, patent protection and difficulty of imitation. However, even in a "routinized regime" a new entrepreneur could enter the industry for a component that could be isolated (Winter, 1984, pp. 296 and 306-317).

In conclusion, large and small firms respond to different economic and technological conditions. This implies for our analysis in the following that we will separate out the large firms and test potential influences on their patenting behavior separately.

4.3 METHODOLOGICAL ISSUES

This chapter revisits theoretical issues concerning clusters and innovation on the basis of an original dataset including information on patents and firms trading in the German state of Baden between 1878 and 1913. Therefore, this dataset is very close chronologically to the initial formulation of such theories by Marshall and Schumpeter. The previous section showed these theories have been brought forward by contemporary work, and their application to historical cases has proven most fruitful. Broadberry and Marrison (2002), expanding upon the distinction between M-A-R and Jacobs externalities, as explained by Glaeser et al. and Henderson et al. (1995), shed new light on the decline of the Lancashire cotton industry in the first half of the 20th century. Murmann (2003) developed a coevolutionary approach, a further development of evolutionary economics, to explain how the German dye industry was able to gain market dominance in the second half of the 19th century and retain it until the First World War. Moreover, focusing on a dataset of firms trading in the period of the German industrial take-off, this study might shed new lights on the Glaeser et al.'s approach and findings. Their study pointed out that Jacobs' externalities were more important to industry growth than M-A-R externalities. However, the authors suggest that the latter might matter more when industries grow, a point that admittedly they could not test.

The results of the analysis of our data set are compared with the behavior of innovating firms at the end of the 20th century. This comparison is established on grounds that the differences between the two systems of innovation, separated by roughly one century, are not as large as they may seem. R&D and patenting activities had nearly the same meaning for the innovating firms in the late 19th century as for their counterparts hundred years later. This is proven by developments in industry following the approval of the first German patent law in 1877. German firms not only invented industrial R&D departments, in which for the first time in economic history scientists tried to discover profitable inventions systematically and based on the division of labor between researchers, but also consciously deployed patents as a means to appropriate the profits from their product and process innovations (Homburg, 1992; Liebenau 1988; Meyer-Thurow 1982). The industrial leaders already well understood that they could use a patent also to prevent sales of competitors' innovations. In 1911, for example, Siemens' existing patent stock enabled the German firm to hinder General Electric from competitively entering the German market with an innovative light bulb containing a wolfram filament that was superior to Siemens' standard tantalum light bulb. Siemens forced the American firm into a cartel agreement about exchanging patents and allocating sales territories (Erker, 1990). When such a peaceful compromise was not possible firms were suing each other in patent courts. The obviously modern attitude towards innovating and patenting activities is revealed by a statement by Carl Duisberg, a former chief executive of Bayer corporation: "On March 17, 1885, we filed a patent for all dyestuffs based on tetrazo-bonds of the isomers of tolidine ... Given the prevailing patent laws, it was necessary to be the first one to file. We could not waste any time. It was possible that AGFA had also found these reactions in the meantime and filed for a patent. For this reason it was standard procedure when one discovered a new reaction to write it down with all its theoretical possibilities in the form of a patent application and mail it the same day for submission to the patent office in Berlin." (cited after Murmann, 2003, p. 134).

Mainly large firms in the chemical and electrical engineering industries of the German Empire heavily invested in the "industrialization" of their innovation processes. In 1889, for example, the already mentioned Carl Duisberg, convinced the top management of Bayer to spend half a million marks to build a new research laboratory (Murmann, p. 151). However, the new knowledge often spilled-over to the small and medium-sized firms of the downstream industries thereby enabling the latter to make economically useful discoveries on their own.[101] That is one of the reasons why large company size was neither a necessary nor a sufficient pre-condition for innovativeness in the German empire. The following table 4.1 shows that the sample of the 100 largest German firms of the year 1907 contains only 26 firms that were also among the 100 most innovative ones in the German Empire.

Table 4.1 The largest 100 firms and their presentation among the 100 most innovative firms in Germany, 1877-1914.

Industry	**Largest 100 firms (1907)**[a]	**Also 100 most innovative firms** [b]
Mining	23	0 (0%)
Stone and related mineral products	3	0 (0%)
Metals	31	8 (26%)
Machines	13	9 (69%)
Electrical Engineering	4	4 (100%)
Chemicals	17	5 (29%)
Textiles	3	0 (0%)
Paper	2	0 (0%)
Foodstuffs	4	0 (0%)
TOTAL	100	26 (26%)

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[101] For knowledge transfer in the German Empire, see, for example, Beer (1959).

Source: [a] Kocka and Siegrist (1979), pp. 55-122. [b] based on our patent data set for the whole German Empire, 1878-1914.
Key: figure in brackets refer to the number of firms in column 3 as a percentage of the number in column 2 for each industry.

Especially the many large, but technologically matured firms of the mining and metals sector were not or under-represented in the latter group. Firm size played some role when the complexity of a new technological wave required the building up of R&D departments. We find, for example, the four largest firms in the field of electrical engineering in both rankings. However, the fact that the list of the most innovative firms additionally includes twelve other firms that were engaged in electrical engineering supports the view that during the early stage of this technological wave smaller firms were able to contribute considerably to the production of new knowledge. Firm size only mattered when the growing technological complexity of an industry's innovation process required the building up of large R&D departments that could only be financed by large firms. As already discussed above this was especially true for the industries of the so-called second Industrial Revolution, namely chemicals and electrical engineering. Table 4.1 also suggests that the innovativeness of machinery firms, that dominated patenting activities in Baden, was positively influenced by size too.

4.4 DATA

In the following, we will address those theoretical issues using a dataset of 2407 firms from the southwestern German state of Baden, a separate arch-dukedom within the German Empire. Baden has often served as a sample region for Germany, starting with Hoffmann (1965), who used Baden's trade tax statistics to estimate German physical capital formation, due to the availability of accurate statistics. The state was formed in the early 19th century from a variety of territories. Two-thirds of the population were Catholic, while the ruling family was Protestant, thus the government was particularly interested in monitoring this state. Moreover, Baden provides a particularly good sample for the whole of Germany as it occupies a middle position among German states in terms of GDP per capita. In the period under consideration, Baden was in between the fastest industrializing states (such as Saxony, Berlin or Rhineland-Westfalia), and the agricultural states in the South East and East. However, Baden displayed an upper middle position in nominal and real wages, and a leading position in human capital formation (Baten, 2004). Today, Baden's economy is characterized by a concentration in capital goods production well above the national average - particularly in the regions (*Bezirke*) of Karlsruhe and Mannheim. On the contrary, in the period of our analysis the industrial structure of our Baden sample is similar to a random sample of German firms (table 4.2). The main difference is that Baden had many more firms in metal processing (especially jewellery, concentrated in the city of Pforzheim), and more firms in the food and tobacco sector (an especially large number of cigar-makers in Baden). On the contrary, there were fewer firms in textiles, apparel, and stone (especially brick) processing, whereas all other industries were similarly represented in Baden and Germany.

Table 4.2 Firms in Baden and Germany (industry percentage)

Industry	Baden	Germany
Stone	10.4	15.5
Metal processing	22.5	11.1
Machinery/Instruments	9.6	11.6
Chemicals	1.4	1.9
Textiles	6.6	11.8
Paper	4.5	3.7
Leather	2.0	2.3
Wood	10.8	11.9
Food processing	21.8	13.6
Apparel	5.1	8.5
Printing	4.4	4.5
Other	3.6	3.7

Baden: Firms with 10+ workers in 1906, Germany: firms with 11+ workers in 1907. Source: *Verzeichnis* (1906); Source: *Statistik des Deutschen Reichs*, volume 213-1, pp. 42-43.

The main dataset is a census of firms with 10 or more employees that was taken in the state of Baden in 1906. The source is one of the few that lists all individual firms, and excludes only the smallest artisan firms. Our "industrial" size segment of firms employing 10 or more workers contains 2407 manufacturing firms, after excluding branches and subsidiaries. From our patent data set, the patents that were registered by residents in Baden were singled out and matched with the patenting company or entrepreneur. Our procedure resulted in 378 important patents that could be matched with the population of 2,407 relevant firms located in the same state Baden.

After matching firms and patents, as expected some companies displayed a large number of patents, whereas most of the firms had no patents at all (henceforth these are described as non-innovative firms). Table 4.3 below displays the top 25 firms in terms of number of patents. Among the firms with many patents, machinery and chemical firms are clearly well represented. This is not surprising considering that these industries were historically and still are the so-called “net donors” of innovations that are often applied in other industries. The skewed distribution of patents among firms and industries and the large number of non-innovative firms means that any regression model that attempts to explain patent numbers per firm should be a count data model (such as the negative binomial model).[102] Moreover, it is obvious that we will need to control industry effects when analyzing the propensity to patent across firms.

Table 4.3 Top 25 patenting firms in Baden

Pat.[a]	**Firm name**	**Year**[b]	**Place**	**Workers**[c]	**Industry**
43	Lanz, Heinr.	1859	Mannheim	1924	Agricultural machinery
27	Schnabel & Henning	1869	Bruchsal	737	Machinery
18	Bopp & Reuther	1872	Mannheim	815	Machinery, metal foundry
16	Geiger'sche Fabrik	1891	Karlsruhe	80	Bureau equipment
14	Bad. Maschinenfabrik AG, vorm. Sebold, H	1854	Durlach	480	Machinery
13	Kromer, Theodor	1868	Freiburg	93	Locks
12	Verein Chem. Fabriken	1854	Mannheim	802	Chemicals
9	Metallschlauchfabrik Pforzheim	1899	Pforzheim	90	Iron and steel

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[102] For detailed technical discussion about using the negative binomial model, see Hausman et al. (1984); Crepon and Duguet (1997); and Greene (1997).

8	Eisenwerke Gaggenau	n.a.	Gaggenau	1044	Iron and steel
8	Boehringer, C.F. & Söhne	1859	Mannheim	452	Chemicals
7	Severische Patenteverwertungsges.	n.a.	Achern	0	Glass
7	Junker, Karl & Ruh, August	1868	Karlsruhe	615	Sewing machines and ovens
7	Dt. Woernerwerke Gmbh	n.a.	Mannheim	0	Machinery
7	Mohr & Federhoff	1820	Mannheim	435	Elevators and other Machinery
6	Fahr, J. G.	1870	Gottmadingen	150	Machinery
6	Ungerer, Karl Friedr.	1895	Pforzheim	17	Machinery
6	Schiesser, Jacques	1876	Radolfzell	545	Apparel
6	Spinnerei & Weberei Steinen	1836	Steinen	519	Cotton spinning & weaving
5	Maschfabrik vorm. Gritzner AG	1872	Durlach	2880	Machinery
5	Eirich, G.	1863	Hardheim	18	Machinery
5	Deutsche Metallpatronenfabrik	1873	Karlsruhe	1696	Munition
5	Stotz & Cie, Elektrizitaetsges. mbh	1891	Mannheim	93	Installation of electrical light & power
5	Strebelwerk Gmbh	1899	Mannheim	576	Iron foundry

					and machinery
5	Unionwerke AG	1891	Mannheim	304	Machinery

Keys: a= number of patents; b= year of establishment; c= total number of workers in 1906.

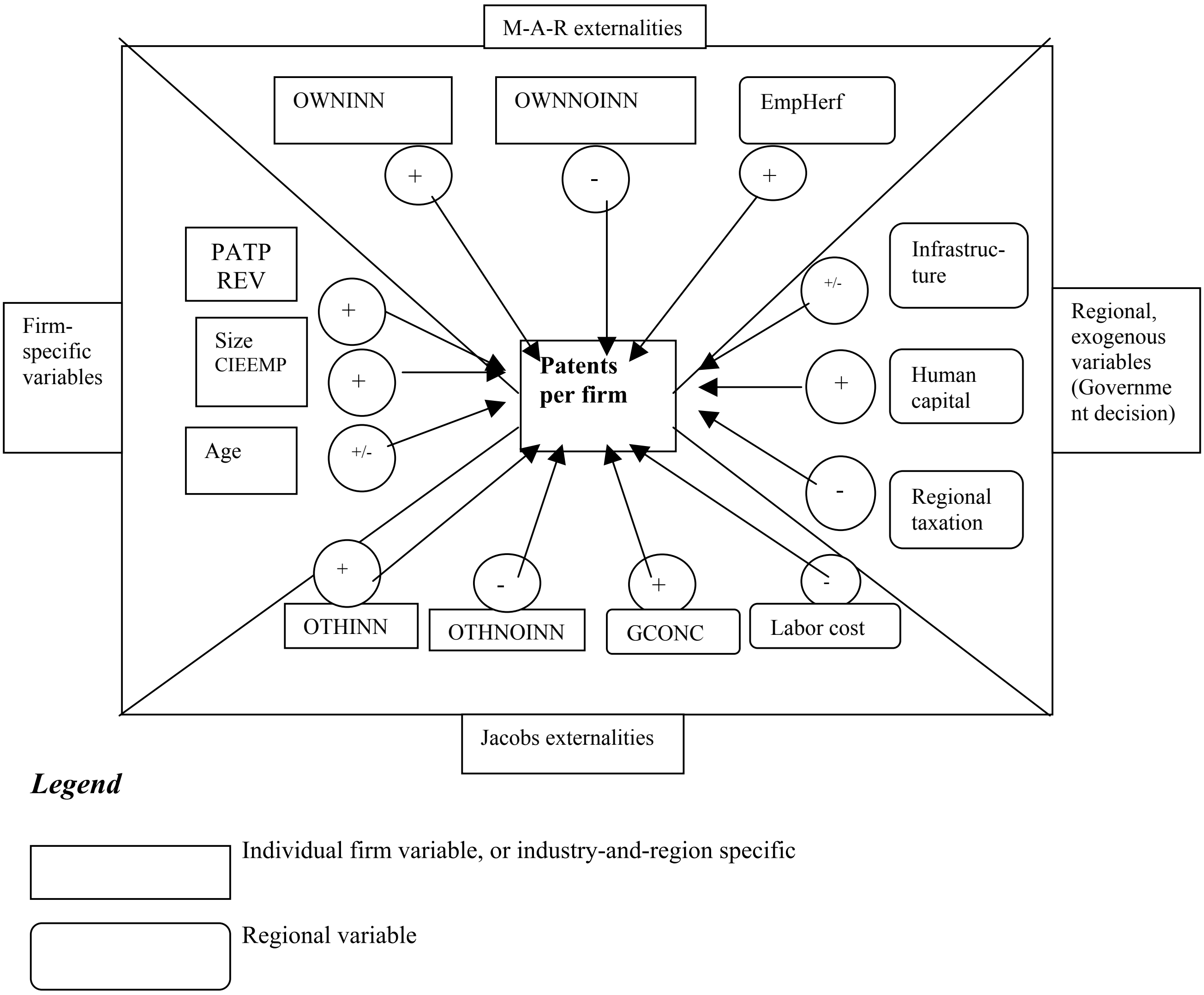
4.5 MODEL

Our model specification is

$$INNOV = \beta_0 + \beta_1 CIEEMP + \beta_2 OWNINN + \beta_3 OWNNOINN + \beta_4 OTHINN + \beta_5 OTHNOINN + \beta_6 PATPREV + \beta_7 EMPHEF + \beta_8 GCNOC + \beta_9 Tech\_SCHOOL + \beta_{10} Railway + \beta_{11} Tax + \beta_{12} Wage + \beta_{13} Age + IndustryDummy \quad (1)$$

Now we discuss the variables in this model one by one. Baptista and Swann found a positive effect of own industry employment in the same region (which they use as variable OWNEMP). Firms with higher values of this variable had a higher propensity to patent. However, Beaudry and Breschi rejected this result recently with a sample of British and Italian firms. The total number of workers in the own industry (and cluster) did not increase patent numbers. In contrast, the number of workers in innovative firms only within the same industry and cluster (OWNINN) did have a positive effect, while the employment in non-innovative firms (OWNNOINN) led only to negative congestion externalities. In the empirical analysis, we will focus on the number of patents per firm in 1907-13 as the dependent variable to be explained. The variables OWNINN and OWNNOINN will also be included as explanatory variables. They are constant for the firms of the same industry in the same region. We list those M-A-R-type externalities in the upper quarter of figure 4.2. The plus and minus signs indicate which influence we expect on patenting propensity. A third M-A-R variable, EmpHerf, is the Herfindahl index of industry employment within a region. M-A-R theory leads to a positive expectation from this variable. The rounded corners in figure 4.3 indicate that this variable is measured at the regional level.

Figure 4.3 Potential influences on patenting of firms in our model



The lower quarter of the figure lists Jacobs-type external effects that will be tested in the econometric analysis. Jacobs' inter-industry externalities are expressed through the following variables. OTHINN is the number of workers in innovative firms of other industries, but in the same region (positive expectation). OTHNOINN in contrast is the number of workers in non-innovative firms; those should create only negative congestion externalities. Those negative externalities might also be caused by high labor costs in agglomerated regions (especially considering that the share of labor cost was particularly high in this period). We would expect a positive influence from urbanization of the region (GCONC), because urbanized areas might transmit Jacobs-type externalities more easily. Closely related to these, we add a number of regional variables that are listed in the right quarter of figure 4.3: (1) infrastructure (proxied with a dummy variable RAILWAY in table 4.5, assuming the value of 1 for those districts with access to a major railway line);[103] (2) regional human capital formation (tech_ SCHOOL in table 4.5) expressed as number of pupils in technical and commercial schools per population; and (3) regional taxation. Taxes reduce the expected returns of successful patents and hence decrease a firm's propensity to apply for and to renew a patent, given the costs of patenting. Regional taxation has been proxied with a dummy variable (TAXHIGH in table 4.5) assuming the value of one if the average regional taxation was above the national average. Those important regional variables have not been considered by earlier studies. We decided not to model the other direction of causality, for example, the influence of patenting of individual firms on regional labor costs, because the influence of one individual firm is reasonably small. Finally, on the left side we list three firm-specific variables: firstly the dummy variable PATPREV that indicates whether a firm had a patent already in the period 1878-1906 (that is, before 1907-13, see also Beaudry and Breschi, 2003). The age (in logarithms) of the firm might proxy the experience of the firms, or the routine that might even act as a disincentive for new patents.

Finally, we will test the effect of firm size on patenting, given that we expect different behavior from small and large firms based on Winter's theories. We measure firm size (CIEEMP) by the average number of employees in our Baden sample. Concerning this point, it seems important to clarify how the size of firms in the Baden sample compares with that of contemporary Britain and Italy, used in Beaudry and Breschi (2003), in order to establish whether our results can be biased by a smaller weight of large firms.

Table 4.4 Number of enterprises by employment size, manufacturing industries and construction, Baden 1906, the UK and Italy 1996.

SIC	Industry	Country	10 - 19	20 - 49	50 - 199	200-999	1000+	Total
DA	Food, beverages, etc.[a]	Baden	22.1	40.9	35.2	1.7	0.0	804
		UK [j]	35.0	28.2	22.6	11.9	2.3	3,317
		Italy	59.1	28.4	9.9	2.3	0.3	6,645
DB	Textile	Baden	34.0	21.1	26.9	17.3	0.7	294

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[103] On the influence of means of transportation on patenting in the U.S. see Sokoloff (1988). Sokoloff focused in particular on navigable inland waterways. We could not control for access to the river Rhine as the RHINE variable would have a very strong collinearity with the RAILWAY variable. The main railway lines were built parallel to the Rhine, through the same districts, only a short distance away.

		UK	43.4	31.1	19.2	5.9	0.5	4,634
		Italy	60.4	29.4	8.8	1.4	0.1	17,273
DC	Leather	Baden	33.9	37.1	22.6	4.8	1.6	62
		UK	40.6	30.3	22.9	6.2	0.0	498
		Italy	61.2	30.8	7.4	0.6	0.0	6,688
DD	Wood and wood products	Baden	42.9	34.1	21.8	1.2	0.0	170
		UK	57.4	29.3	11.9	1.4	0.0	1,830
		Italy	68.8	24.9	5.9	0.4	0.0	3,285
DE	Pulp, paper, etc.[b]	Baden	25.3	37.4	29.7	6.6	1.1	91
		UK	47.8	30.6	16.2	5.0	0.4	6,708
		Italy	60.3	28.1	9.5	1.9	0.2	5,193
DF	Coke, etc.[c]	Baden[k]	------	------	------	------	------	------
		UK	0.0	22.5	43.7	28.2	5.6	71
		Italy	46.4	30.9	13.5	6.8	2.4	207
DG	Chemicals, etc. [d]	Baden	32.6	26.1	19.6	21.7	0.0	46
		UK	29.4	28.3	25.7	13.8	2.8	1,597
		Italy	38.3	31.1	21.1	7.9	1.6	2,009
DH	Rubber and plastic prod.	Baden[k]	------	------	------	------	------	------
		UK	37.6	32.3	22.5	7.1	0.6	3,042
		Italy	52.9	33.5	11.9	1.6	0.2	4,533
DI	Other non-metallic etc. [e]	Baden	39.9	36.7	20.6	2.8	0.0	316
		UK	40.8	28.6	22.5	6.7	1.4	1,545
		Italy	56.8	29.7	11.0	2.2	0.2	4,943
DJ	Basic metals, etc. [f]	Baden	39.3	26.8	28.0	4.8	1.2	168
		UK	48.3	32.4	15.8	3.2	0.3	9,177

		Italy	63.6	27.3	7.9	1.1	0.1	18,115
DK	Machinery etc.[g]	Baden	30.9	23.7	32.0	11.3	2.1	194
		UK	39.3	33.4	19.9	6.6	0.8	5,251
		Italy	50.3	32.2	14.3	2.9	0.3	9,752
DL	Electrical and optical [h]	Baden [k]	------	------	------	------	------	------
		UK	36.3	30.7	23.2	8.6	1.1	4,336
		Italy	54.2	30.6	11.8	2.9	0.5	6,732
DM	Transport equipment	Baden [k]	------	------	------	------	------	------
		UK	31.9	26.9	24.5	13.6	3.2	1,754
		Italy	40.2	32.4	20.1	5.8	1.5	1,872
DN	Others [I]	Baden	35.3	42.6	19.5	2.6	0.0	620
		UK	48.6	29.5	17.3	4.7	0.0	3,151
		Italy	62.7	27.9	8.5	0.9	0.0	7,188
F	Construction	Baden	49.1	33.0	12.5	5.4	0.0	112
		UK	97.2	1.9	0.8	0.2	0.0	180,470
		Italy	72.2	22.8	4.4	0.6	0.0	21,198

Keys: a= Food, beverages and tobacco; b= Pulp, paper and paper products; publishing and printing; c= Coke, refined petroleum products and nuclear fuel; d= chemicals, chemical products and man-made fibers; e= Other non-metallic mineral products; f= Basic metals and fabricated metal products; g= Machinery and equipment not elsewhere classified; h= Electrical and optical equipment; i = Manufacture not elsewhere classified.

Notes: j= Food and beverages only. Data on the size distribution of firms in the tobacco industry was not available; k = information has not been reported, as only few firms in the Baden sample belong to this industry.

Sources: Unpublished Factory Inspection Lists, Baden, 1906 – see text; Office for National Statistics (ONS), *Production and Construction Inquiries - Summary Volume*, Newport, 1998; Istituto Nazionale di Statistica (Istat), *Censimento dell'Industria e Commercio*, Rome, 1996.

The distribution of firms by size, in terms of employment, shows that the Baden dataset includes a large percentage of firms in the three largest size classes (above 50 employees), which represent the large firm sub-sample in the following econometric analysis. The higher percentage of firms employing more than 50 workers is particularly evident in the cases of textiles, engineering and construction. Moreover, the percentage of Baden firms belonging to the smallest size class is consistently lower than in its counterparts. This does not mean that Baden around 1900 had larger firms than Italy and the UK in the 1990s on average. The lower average of Baden is caused by the very many craftsmen-type "firms" with less than 10 employees. But in the size segment that we consider here, Baden's firms were certainly not smaller.

We sum up the differences between our analysis and previous studies. First and foremost, we focus on human capital formation, as it is reasonable to expect that this factor plays an important role. In particular, technological and commercial knowledge should increase the propensity to innovate, holding all other factors constant. We measure this factor with the number of pupils in advanced technical and commercial schools in Baden divided by population.[104] Second, applying for a patent and renewing it for ten years normally means that the actor has a substantial profit expectation, after deducting all costs of the production process and the economic environment. We expect that high regional taxation, for example, would discourage an entrepreneur or a firm from applying for a patent.

Analyzing the influence of railway infrastructure is also interesting. On the one hand, good marketing possibilities and easy shipment of raw materials increase profit expectations. On the other hand, after urbanization and all the other related variables are controlled for, it might be that firms close to the main railway lines have comparative advantage in bulky, perhaps simple products, whereas remote firms, such as in the Black Forest, are specialized in light and technology intensive products.

4.6 RESULTS

This section discusses the results of our econometric analysis. It is structured in two sub-sections. The first examines the major explanatory variables in a descriptive and visual way. The second section presents and interprets the results of our multiple negative binomial regression.

4.6.1 Descriptive results

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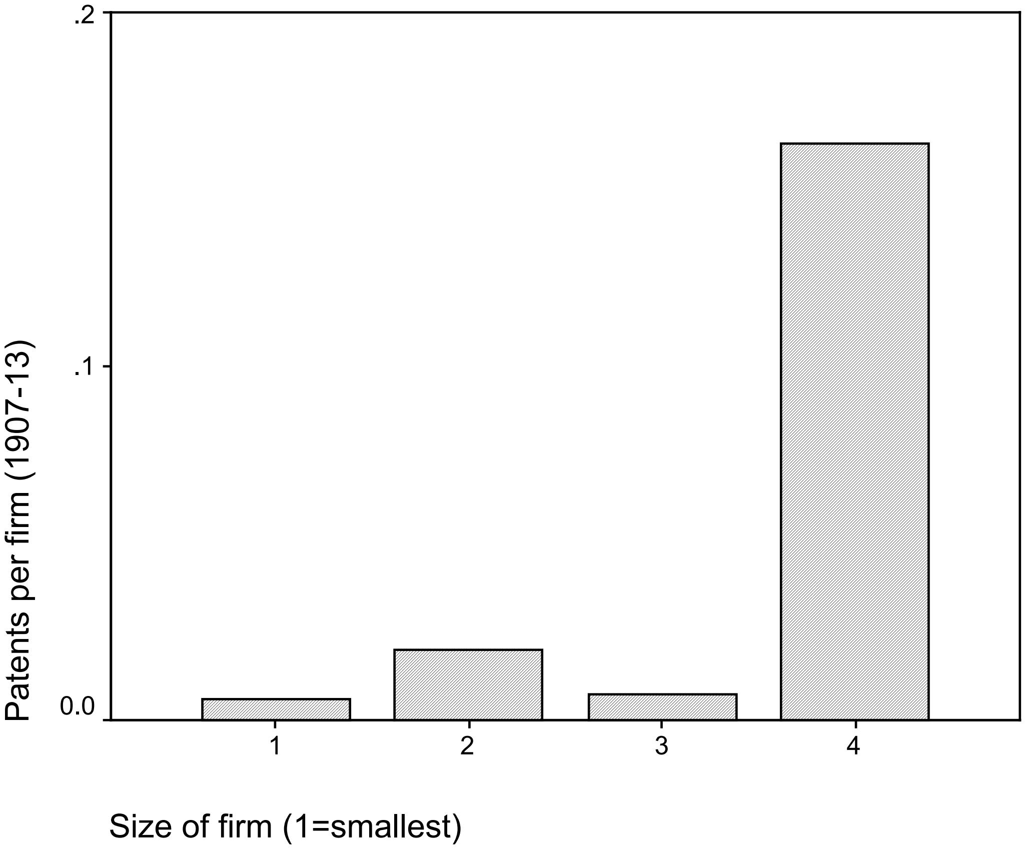
[104] See chapter 2 for the reasons behind selecting technological and commercial schools.

This sub-section examines graphically five of the major explanatory variables: firm size (CIEEMP), urbanization rate (GCONC), own-industry/cluster employment in innovative firms (OWNINN), own-industry/cluster employment in non-innovative firms (OWNNOINN), and regional human capital formation (tech_ SCHOOL).[105] In order to assess the effect of firm size on patenting activity, we divided the whole sample into four groups ranked by firm size (figure 4.4). Each quartile represents some 700 firms. Clearly, in those descriptive statistics we are not controlling for industry composition and the other variables. We find that especially the largest segment had a much higher propensity to patent. Among the largest firms, 0.2 patents per firm were observable.

Figure 4.4 Patents per firm: lowest to highest quarter of firm size (unadjusted)



The descriptive plot for the effect of urbanization looks similar (GCONC, figure 4.5). The 575 firms in districts with the highest urbanization ratio had clearly a higher propensity to patent, whereas the three lower quarters had low numbers of patents per

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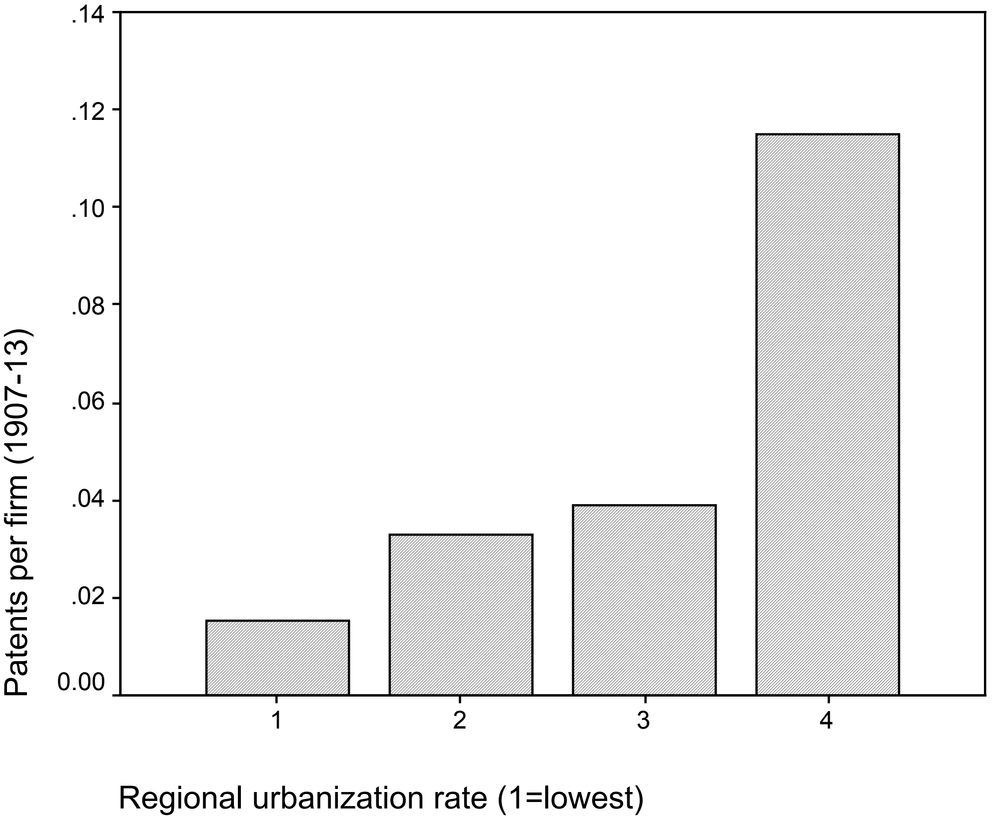
[105] In order to remove industry fixed effect, we also experimented with using the residuals (after regressing patents per firm on industry dummies), but the results were very similar.

firm. Again, this result will hold unless we find, in the subsequent multiple regressions, any other variables in the background that might make this relationship spurious.

Figure 4.5 Patents per firm: lowest to highest quarter of urbanization (unadjusted)



The number of workers in innovative firms of the same 2-digit industry and the same region might have a positive influence on patenting propensities (figure 4.6). The highest segment of this explanatory variable had a higher number of patents per firm, whereas the lowest segment clearly had a lower patent number (the middle parts might not be significantly different).

Figure 4.6 Patents per firm: lowest to highest quarter of own-industry/cluster employment in innovative firms

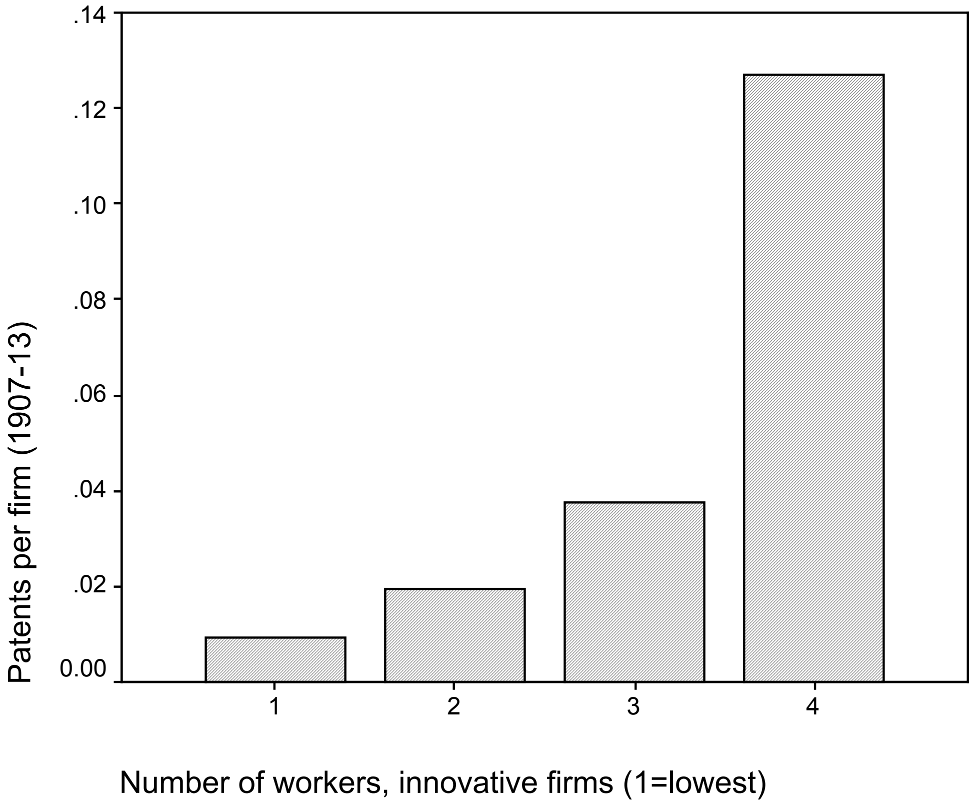
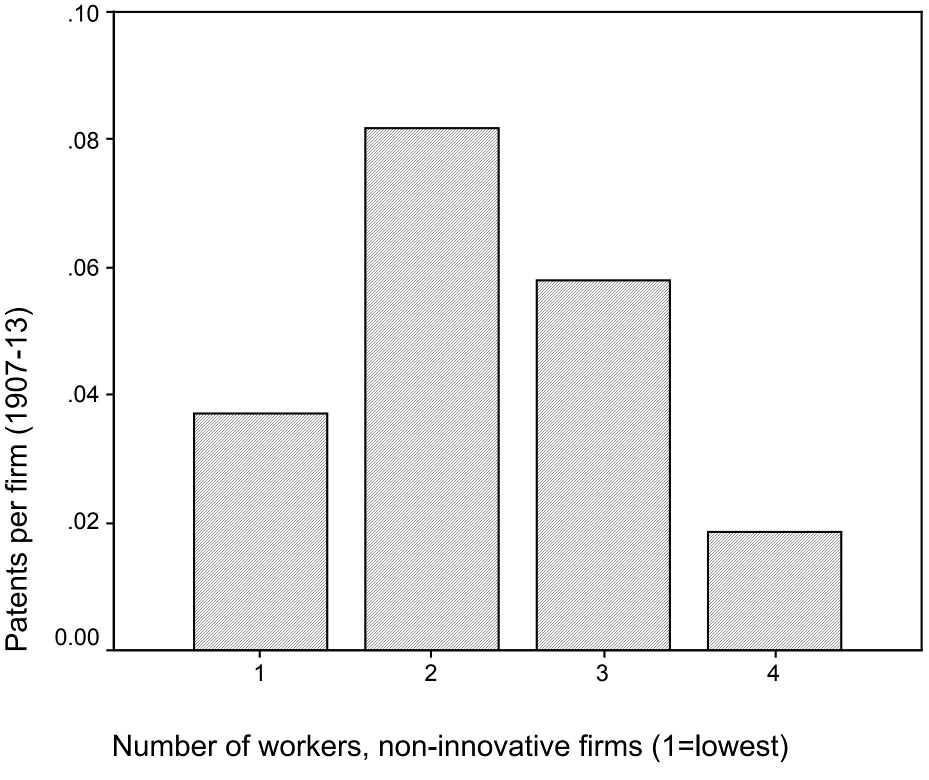


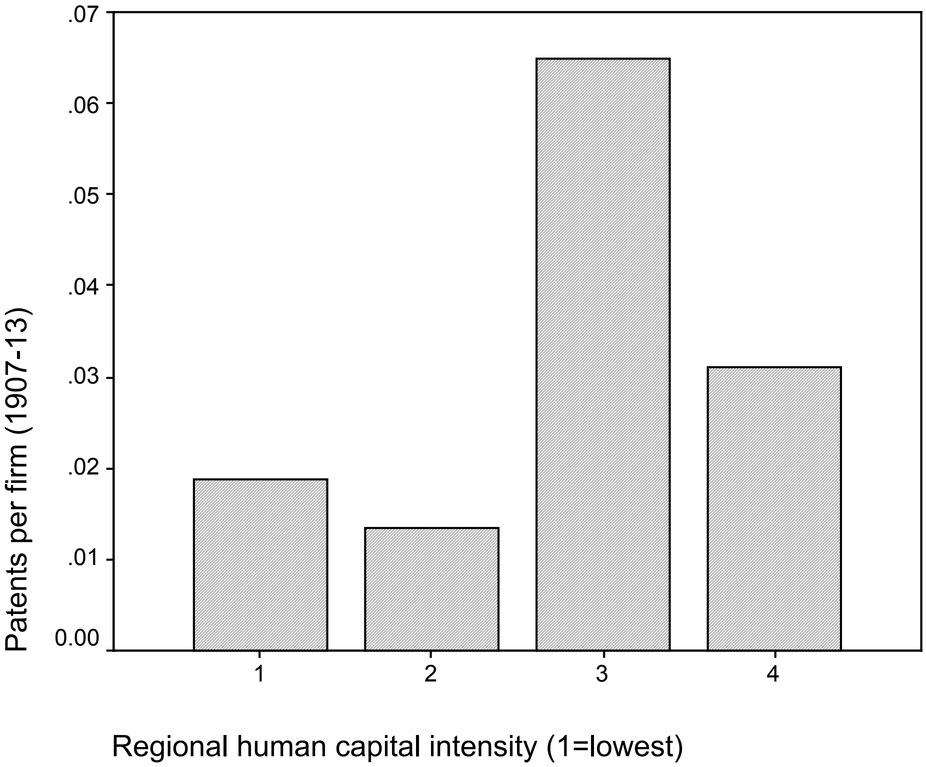
Figure 4.7 **Patents per firm: lowest to highest quarters of own-industry/cluster employment, non-innovative firms**



The distribution of patents per firm over the four quarters of employment in non-innovative firms, of the same industry and same region, is also very interesting (figure 4.7). The highest quarter had clearly a lower patent rate per firm than the middle quarters, as Beaudry and Breschi would have expected. However, the lowest quarter had again quite low rates.

Finally, the number of students in technical and commercial schools displayed a higher number of patents per firm particularly in segment 3, not in the highest quarter (figure 4.8). The two lower quarters were less patent intensive.

Figure 4.8 Patents per firm: lowest to highest quarters of regional number of students (technical schools)



Summing up, the descriptive statistics (using error bar plots of confidence intervals) of five of the most important explanatory variables confirm in general our expectations about their influence on patenting activity.

4.6.2 Multiple Negative Binomial Regression

This sub-section discusses the results of the econometric analysis. Table 4.5 below compares the results of our "historical" Baden sample with a similar analysis performed by Beaudry and Breschi for the 1990s, the results of which are reported in columns 2 and 3. Columns 4 and 5 display the results of our regressions including industry dummies to control for differences in the propensity to patent between various industries, whereas the results in column 6 do not control for such differences.

Table 4.5 Multiple negative binomial regression

Dependent variable: firms' patenting activity

Country/sample	**United Kingdom**	**Italy**	**Baden (all firms)**	**Baden (large firms only)**	**Baden (all firms)**
Time	1990s	1990s	1907-13	1907-13	1907-13
CIEEMP	0.53* (0.02)	0.82* (0.02)	1.15* (0.19)	1.22* (0.36)	1.13* (0.19)
OWNINN	0.21* (0.02)	0.24* (0.02)	0.01 (0.17)	-0.14 (0.24)	0.35* (0.11)
OWNNOINN	-0.25* (0.04)	-0.31* (0.04)	-0.03 (0.22)	0.13 (0.31)	-0.45* (0.17)
OTHINN	0.07 (0.04)	0.01 (0.03)	-0.14 (0.17)	-0.05 (0.23)	-0.19** (0.10)
OTHNOINN	-0.30** (0.07)	-0.02 (0.06)	0.44 (0.35)	0.78 (0.51)	0.65** (0.31)
PATPREV	-0.09 (0.32)	-1.34* (0.34)	2.24* (0.76)	2.57* (0.89)	2.37* (0.86)
KSTOCKFIRM	0.37* (0.04)	0.47* (0.05)			
EMPHERF	-0.31 (2.14)	0.34 (0.99)	6.07** (2.39)	9.65* (3.43)	3.17 (2.08)
GCONC	0.10 (0.29)	-0.05 (0.18)	0.05* (0.02)	0.09* (0.03)	0.04** (0.02)
Tech_SCHOOL			0.24** (0.10)	0.08 (0.14)	0.22* (0.08)
RAILWAY			-2.10** (0.95)	-2.09 (1.42)	-2.13** (0.88)
TAXHIGH			0.67 (0.70)	1.26 (0.98)	-0.44 (0.61)
WAGE			-11.29* (3.83)	-15.46* (5.65)	-8.73** (3.63)
AGE			-0.00 (0.01)	-0.00 (0.01)	-0.01 (0.01)
Industry dummies	YES	YES	YES	YES	NO
Constant	1.15 (0.70)	-1.55* (0.62)	41.57** (18.32)	56.70** (27.27)	31.8*** (17.7)
Observations	26,055	37,724	2,407	717	2,407
Pseudo R^2	0.23	0.24	0.28	0.26	0.17

Notes: Standard errors in brackets. Symbols *, **, *** besides parameter estimates indicate, respectively, statistical significance at the 1%, 5% and 10% levels.
Test for column 3: alpha=7.51 SE(alpha) 1.72; Likelihood-ratio test of alpha=0: chibar2(01) = 218.82 Prob>=chibar2 = 0.000
Test for column 4: alpha=6.15 SE(alpha)=1.57; Likelihood-ratio test of alpha=0: chibar2(01) = 168.23 Prob>=chibar2 = 0.000
Test for column 5: alpha=17.4 SE(alpha)= 4.08; Likelihood-ratio test of alpha=0: chibar2(01) = 304.85 Prob>=chibar2 = 0.000

While Beaudry and Breschi found a positive effect of the number of workers in innovative firms only within the same industry and cluster (OWNINN), and a negative effect of the employment in non-innovative firms (OWNNOINN), this cannot be said on the basis of our results. In the case of Baden 1907-13 those variables did not have a significant influence, and their coefficients were signed as expected, but very small. One possibility to interpret this is concluding that this relationship might have been less pronounced in the early 20th century, compared with Beaudry and Breschi's results. But we also have to note that our number of observations is smaller. Furthermore, it might be the case that innovations of lower importance (that were not prolonged for 10 years)—including imitating patents—were stronger influenced by OWNINN, while our 10-year patents were not.

We conclude that the influence of these variables OWNINN and OWNNOINN is not generally valid to the extent that it would show up in smaller samples (as ours) from other periods and regions. This contrasts with the results for firm size. Larger firms were granted more patents in Italy and the UK during the 1990s, and this holds as well for southwestern Germany during the 1900s. While this would have been expected (given that large firms have more employees who could produce innovations), the differences in coefficient size are interesting. In our regressions, the coefficient is even considerably larger than the coefficient in the 1990s study. This could either be caused by (a) a stronger concentration of important patents on large firms, or (b) by the fact that we included many more small firms, or (c) perhaps by omitted variables. When we restrict our analysis to only the larger firms (those with 50< workers), the coefficient remains virtually unchanged, so (b) is not a likely candidate for explanatory power. Of course, the possibility that the different results between our and previous studies might be due to omitted variables cannot be ruled out, although our model takes into account more variables than previous empirical studies did. We find that size is also an important determinant of ten-year-surviving patents registered by Baden residents.

The higher propensity of large firms to innovate, and therefore to patent, might also have various other explanations. These can be summarized in the Schumpeterian argument that large firms with market predominance are in a better position to undertake innovative activity. This requires high fixed costs and can therefore be undertaken by firms holding comparable financial resources. Small firms might make themselves more vulnerable if they were to invest a high portion of their profits in innovating. Moreover, increasing returns to scale associated with innovation, particularly innovation yielding cost reductions of a given percentage, result in higher profit margins for larger firms than for smaller firms (Acs and Audretsch, 1990, pp. 39-40).

Previous patenting is clearly another crucial characteristic for innovative firms. We confirm earlier studies such as Baptista and Swann, Beaudry and Breschi as well as others in this point. Flaig and Stadler (1998) discussed this effect as "intertemporal spillovers". Beaudry and Breschi distinguished further between the rapidly discounted stock of patents KSTOCKFI (discount rate 0.3) and the previous patenting dummy variable PATPREV as we employ it as well. Thus the difference is whether a firm patented at all (PATPREV), and the number of discounted earlier patents that proxies its propensity toward repeated patenting. They interpreted the positive coefficient for KSTOCKFI and the negative one for PATPREV as evidence that not only previous patenting, but more importantly recent and repeated previous patenting plays a major role, whereas controlling for this, just one patent could have an adverse effect. We cannot test this, because we had extreme multicollinearity between PATPREV and KSTOCKFI.

In our case, the concentration of a region on one or few industries EMPHERF had a significant positive effect (again, holding other factors constant). This stresses the importance of M-A-R within-industry externalities for our region and period, which is very close to Marshall's. It is possible that this variable might contain some measurement error in its specification, especially as it refers only to eleven different regions within Baden (in order to keep the smaller industries at a meaningful size). However, we also experimented with EMPHERF on the level of 52 *Amtsbezirke* (smaller districts), and it remained robust, positive and significant. On the other hand, Jacobs externalities were also visible in Baden, as the positive coefficient for urbanization GCONC indicates.

Another variable that was not taken into account in some previous studies was innovation-specific human capital. We find that the number of pupils in commercial and technical schools (secondary and tertiary level, in the 52 districts) per population has a strong and significantly positive effect when using the whole sample, whereas the variable is not significant when restricting the analysis to large firms. This finding points toward the argument supported by Winter, and following studies, according to which innovative advantage of small firms is associated with a wider knowledge base. This finding also indicates the importance of government investment in this type of schools, which have a positive impact on patents, and via positive knowledge externalities, on economic growth in the better-equipped regions.

In contrast, taxation (TAXHIGH) does not turn out to be significant. The taxes were generally quite moderate in Germany around 1900, and the regional differences relate only to municipal taxes that account typically for half or less of the tax burden for firms. One cost variable that does matter is WAGE. In turn high wages can be interpreted as congestion costs and therefore our result points out a negative impact of such costs. In chapter 2, we have found out that railway density is closely related to regional innovation. In this chapter, the slightly puzzling result of RAILWAY being significantly negative in Baden region might be explained by the bulkiness being a comparative advantage that is normally not associated with highly innovative products. In Baden around 1900, there were highly innovative regions in the Black Forest without railway access, whereas less innovative textile industry and cigar-making firms were situated in large numbers near major railway lines.

AGE did not have a significant influence on patenting, which might offer support to the argument set forth by Winter whereby innovations that pertain to "an entrepreneurial regime" are favorable to innovative entries, whereas those pertaining to a "routinized regime" are favorable to established firms.[106]

4.7 CONCLUSIONS AND POLICY IMPLICATIONS

This chapter offers several contributions. One of its major merits lies in the original dataset on which it is based. The dataset helps overcome what Kuznets (1962) considered one of the greatest obstacles to understanding the role of innovation in economic processes, i.e. the lack of measures of inputs and outputs of inventive activity (Kuznets, 1962, pp. 31-41; Acs and Audretsch, 1990, p. 37). This dataset is even more

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[106] Some of the outcomes of our research on firms in Baden do not necessarily confirm the results of our study of Prussian regions in chapter 2. For example, in this chapter, we find that result of railway is significantly negative in Baden region. Several factors might cause these discrepancies. Firstly, in this chapter we use patents by firms while in chapter 2 we use patents by regions. Secondly, in this chapter, we

important as it allows us to study a state like Baden, which in the period under analysis presented an industrial structure similar to the German average, and therefore offers insights into a fundamental determinant of economic growth in one of the world's largest economies.

This study is one of the few based on firm-level data (most work on patents uses regional units) and offers a contribution to various controversial issues concerning the determinants of innovation, as well as pointing out factors that had been overlooked by previous empirical studies. We find evidence of not only a positive impact of externalities of the M-A-R type as well as the Jacobs type, but also of "inter-temporal spillovers" measured by previous patenting. However, the stronger impact of M-A-R externalities confirms Glaeser et al. (1992) suggestion that intra-industry externalities might matter more in periods of fast industry growth. This study points out that clusters might also yield a negative impact on the innovative activity of firms, due to congestion costs of which high wages are an important example. Moreover, our results do not confirm a positive association between innovative activity and proximity to means of transport, as suggested by Sokoloff (1988).

On the contrary, we find a positive impact played by human capital formation, particularly on smaller firms in our sample, consistently with Winter's theory of "technological regimes". This result has important implications for European countries seeking to regain international competitiveness in manufacturing,[107] and for the current debate on the right means to re-vitalize the German innovation potential in particular. Firstly, the excellent state of the technical and commercial schools of 19th-century Baden significantly increased firms' successful patenting activities. This suggests that the overdue upgrading of the current German higher education system would improve the overall productivity of the economy, and more specifically would increase the output of investment in research and development. Secondly, small and medium-sized firms seem to profit more from knowledge spillovers from technical and commercial schools or universities than big business does. This implies that public spending in favor of these institutions can also be regarded as an effective competitive policy that would help the former to stand up to the latter in Schumpeterian competition.

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limit our scope to Baden region while in chapter 2, we use all regions in Prussia. Indeed, as we have argued, Baden is representative of Prussia. Yet still, Baden might possess some specific regional features.

[107] On this point, see O'Mahony (1992) and Bean and Crafts (1995).

Chapter 5

The Spillover Effect on Innovation across Regions in Prussia 1877-1914

Abstract

It has been argued that distance plays a role in knowledge spillovers as knowledge (especially tacit knowledge) is often accessible mostly via direct interaction among people. This chapter estimates the spillover effect on innovation across 37 Prussian regions and how this effect evolves over time from 1877 to 1914. Patents registered by patentees in Prussian regions are used as proxy for innovation. Firstly, we study the spillover effect of human capital on innovation. Number of students in technical and commercial schools is used as proxy for human capital. We find that: (1). Human capital at one region has great impact on innovation in the same region, (2). Across regions, human capital has various spillover effects on innovation in other regions, (3). In general, the effect of human capital spillovers diminishes over distance. Normally, spillovers become insignificant over around 265 kilometers. Furthermore, we try to control the impact of production. This modification does not change the regression results greatly. Then we control for some special industries (chemical and electrical). The results remain rather robust in general. We modify the model to study the inter-firm spillover, which is the spillover effect of patents in one region on patents in other regions, as patents can serve both as input and output of innovation. This modification yields similar results.

5.1 INTRODUCTION

Innovation has been constantly regarded as key to economic growth in most endogenous growth models (Solow 1957; Romer 1986, 1990; Verspagen, 1992; Grossman and Helpman, 1994). The theory of endogenous economic growth is based on the very premise that accumulated knowledge will eventually find its way to productive applications, and hence lead to economic growth. Nevertheless, the mechanism behinds innovation remains elusive, despite some scholarly aspiration (for example, Rosenberg 1982, 1994) to open the black box of innovation. Innovation, as output, is largely the outcome of Research and Development (R&D), as input. Human capital is one important factor of R&D input. Human capital is the knowledge and skills that humans carry around in their heads. And human capital makes people valuable to an economy. The concept of human capital was advanced by Becker (1962), who regards human capital as a critical input to production as well as innovation.[108] Moreover, human capital and knowledge in general have externalities.[109] They can travel over distance and exert impact on innovation in other regions. Thus, in the spatial perspective, local development of new ideas depends on the innovative efforts conducted locally and also on the ability to exploit external ideas through information spillovers.[110] Griliches (1992) defines knowledge spillovers as working on similar things and hence benefiting much from each other's research. Lucas (1988) proposes that knowledge spillover externalities are the premier driving force behind economic growth. Griliches and Hjorth-Andersen (1992) argue that spillovers account for up to half of the growth in output-per-employee and about 75 percent of the measured total factor productivity (TFP) growth in the US.

Although evidence favors the existence of knowledge externalities, its effectiveness has been found to dissipate with distance.[111] Grossman and Helpman (1992) argue that geography plays a role in knowledge creation and spillovers. Here, it is useful to distinguish information from knowledge. Information can be easily codified and transmitted at low cost (especially low marginal cost). A piece of information does not become knowledge until someone is able to understand it, to combine it with other

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[108] There is a clear association between a country's stock of human capital (usually measured by the educational attainment of its population) and per capita national income. Mankiw (1995) finds out that the average citizen of a high-income nation is better educated than the average citizen of a low-income nation. One explanation of this phenomenon is that educated people make a nation prosperous. However, conversely, another explanation might be that rich nations have higher expenditure on education. Barro (1991) and Barro and Lee (1996) address this issue by showing that a nation's economic growth is significantly related to its pre-existing stock of human capital, measured by the level of educational attainment of its citizens. This outcome is consistent with the notion that a higher level of human capital causes per capita GDP to grow faster. Fagerberg (1994) surveys empirical studies on the importance of technology gaps for differences in economic growth across countries. He observes a consistent pattern that lagging countries can converge toward higher income countries, but only if they possess the social capability (a large number of people capable of managing the necessary resources, including investment, education, and R&D). He argues that investment in education is an important complement to economic growth.

[109] Arrow (1962a) shed light on the particular characteristics of the knowledge good and on the idea that knowledge spills over.

[110] For elaborations of this argument, see Martin and Ottaviano (2001), Grossman and Helpman (1991), Coe and Helpman (1995).

[111] One representative study is Antonelli (1999).

knowledge, to use it and to stock it. The case with knowledge is more complicated. While some knowledge can be codified, a substantial portion of knowledge cannot be easily codified so that its cost of transmission rises as distances grows. This is why technological knowledge is often localized: it is the result of a learning process, which is specific for each innovator (Antonelli 1999). Polanyi (1967) has been known as the first one to suggest that a major part of human knowledge is difficult to explain with words ("tacit knowledge"). To be exact, he defined tacit knowledge as the knowledge that dwells in a comprehensive cognisance of the human mind and body. He argued that tacit knowledge is related to the context in which it is presented and the individual's own interpretation of it. Thus, this individual interpretation gives tacit knowledge a personalized quality that needs to be articulated in order to be communicated (One of Polanyi's famous aphorisms is: "We know much more than we can tell."). In contrast to tacit knowledge, Polanyi (1967) defined explicit knowledge as the codified knowledge that is transmitted using orderly formal languages, which are fairly comprehensible. Polynyi's idea has been further modified and developed by other scholars subsequently. In discussing their model of organizational knowledge creation, Nonaka et al. (1994) called the process of transforming tacit knowledge into explicit knowledge "externalization." They also defined the process of turning explicit knowledge into tacit knowledge "internalization." Foray and Lundvall (1996) even argue that a large part of technological innovation represents an effort to codify tacit knowledge. Castillo (2002) strives to consolidate and synthesize the broad spectrum of literature on tacit knowledge by presenting a four-fold topology of the concept. He sorted the various ideas on tacit knowledge into four dimensions (non-epistle, socio-cultural, semantic, and sagacious). Castillo's (2002) categorization of tacit knowledge and Nonaka's (1994) concepts of knowledge creation help us understand the mechanisms of knowledge transfer and distinguish tacit knowledge from explicit knowledge.

The notion tacit knowledge carries great significance for knowledge management and organization science. Tacit knowledge is fundamental to the core competencies of individuals, organizations, and regions. The classical examples of tacit knowledge are typically individual practical skills (such as biking and swimming) that cannot be made explicit and that cannot be transmitted through, for instance, telecommunication networks. But it is important to note that there are other kinds of tacit knowledge that are more at the core of economic dynamics. Managers use experience-based tacit knowledge when taking complex decisions, and scientists use personal and tacit knowledge in their research. In both cases, it is mainly a question of interpreting complex sets of information and seeing patterns.

While both the practical and analytically oriented tacit knowledge is impossible to codify and to transfer through telecommunication media, it can be learned through experience. It is typically learned in an interaction with other people, through a master-apprentice or collegial relationship. This also implies that tacit knowledge can be shared through a process of interaction and cooperation. Interactive learning is a key to shared tacit knowledge and this implies, of course, that the social context is important for this kind of learning.

Tacit knowledge is not to be found only at the level of the individual. An organization, with its specific routines, norms of behavior, etc., can be regarded as a unit that carries with it knowledge, a substantial part of which is tacit. Management may have an incentive to codify the knowledge that constitutes the organization, for instance, in order to make it less vulnerable to the risk that key persons leave the organization. But normally they will realize that it can only be done successfully when the firm operates in a simple and static environment. Yet in reality, virtually everything in an organization experiences constant changes.

Industrial networks and inter-firm cooperation may also be seen as repositories of tacit knowledge embedded into common procedures and codes, not reflected in formal contracts or any other written documents. Some of these procedures might be possible to codify while others would lose their meaningfulness if they were written down (getting together for a chat may be a fundamental element in bringing people from different organizations together for interactive learning). This is a problem similar to the formation of trust in a market economy. Arrow has made the point that trust cannot be bought and if you could buy trust, it would have no value whatsoever (Arrow 1971). This implies that the broader context (the presence and form in society of social capital) will affect the learning process. In a community or society that is extremely individualistic or where the loyalties are narrowly confined to the very small circle, it might be especially difficult to engage in interactive learning.

The diverging stories of the Route 128 area in Massachusetts and Silicon Valley in California (narrated in Saxenian, 1994) vividly illustrate the importance of social capital. In the Route 128 area, suits were the only proper attire during business hours for the professionals. Employees socialized only within the company and social contacts with people outside of the company were viewed with suspicion as potential leaks of trade secrets. In contrast, in the Silicon Valley, dress codes were looser and communities of friendships existed across company lines. The sense of community that existed among the technical people of the Silicon Valley was not just a pleasant social phenomenon. It enabled Silicon Valley firms to solve technical problems more easily and rapidly than technical people who were limited to contacts with other employees of their own company. This flexibility and adaptability in the long run gave Silicon Valley an adaptability and flexibility that was more important to the survival of the industry than any possible loss of trade secrets. At Palo Alto area, people think of themselves as working for Silicon Valley rather than a particular company. At national level, the case of Russia demonstrates the importance of social capital. Russia has one of the highest literary rates among world nations.[112] Yet the present state of the Russian economy illustrates that physical facilities and human capital have little value if not based on social capital (such as trust), which guarantees that one society moves forwards smoothly. Russia needs to build social capital in civil society, such as institutionally supported trust relationships.[113]

Institutions and individuals interested in knowledge creation and innovation strive to acquire knowledge, be it tacit or explicit, within a social context. Yet we should note that distinct types of knowledge differs in its accessibility. Accessibility is related to an individual's knowledge creation process, and access to knowledge of other people affects one's own knowledge.

Tacit knowledge is not easily accessible to others. There are different reasons why knowledge can be inaccessible. It could be because the knowledge has not been expressed by the holder (non-epistle), or because the knowledge is dispersed in the surrounding social culture, or is semantic to a particular group while incomprehensible to outsiders, or because it is a personal insight or mental model that enables a person to understand and absorb other knowledge (sagacious). Figure 5.1 uses flow chart to help us visualize the accessibility of tacit and explicit knowledge.

Figure 5.1 Knowledge accessibility of tacit and explicit knowledge

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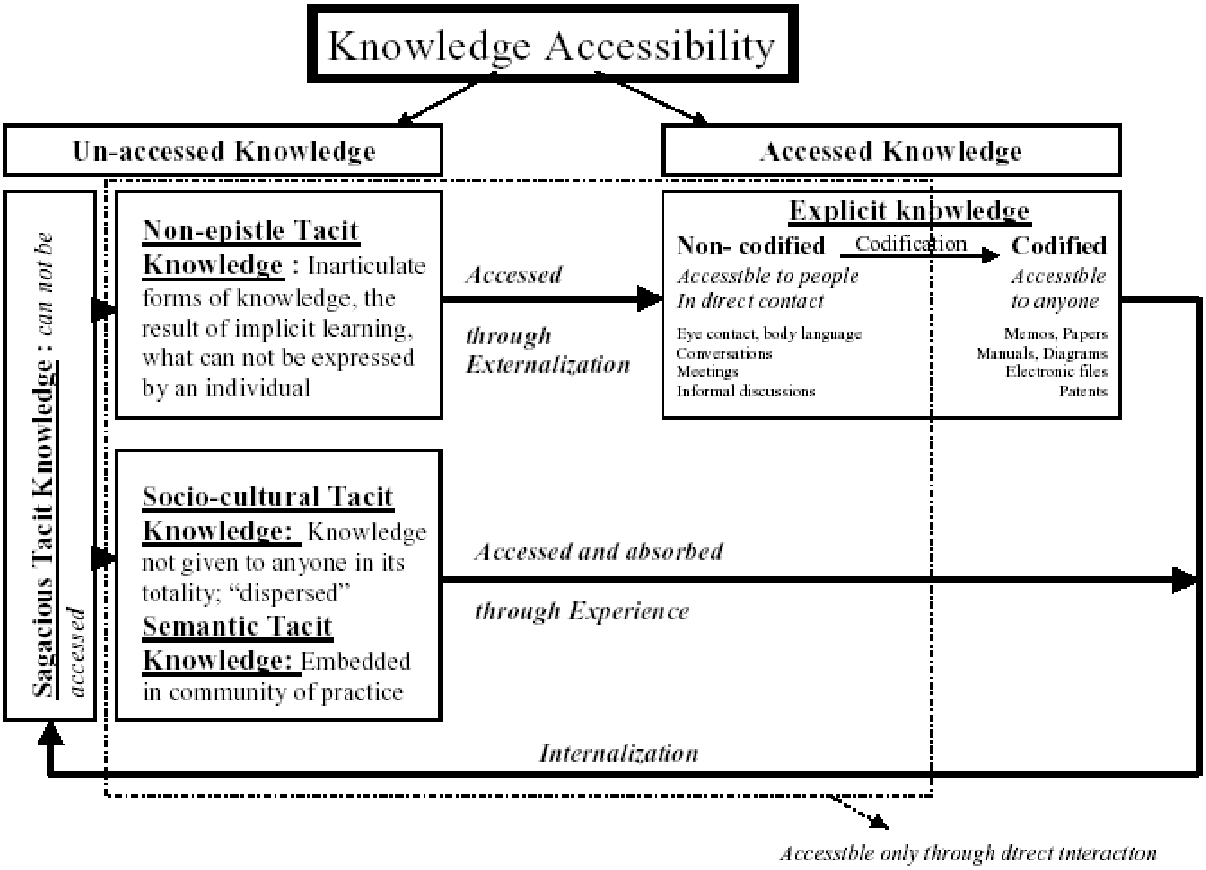
[112] *The world factbook 2004.*

[113] For the importance of social capital in post-Soviet transition, see Rose (1999), Marsh (2000), Gibson (2001), and Kornai, Rothstein, and Rose-Ackerman (2002).

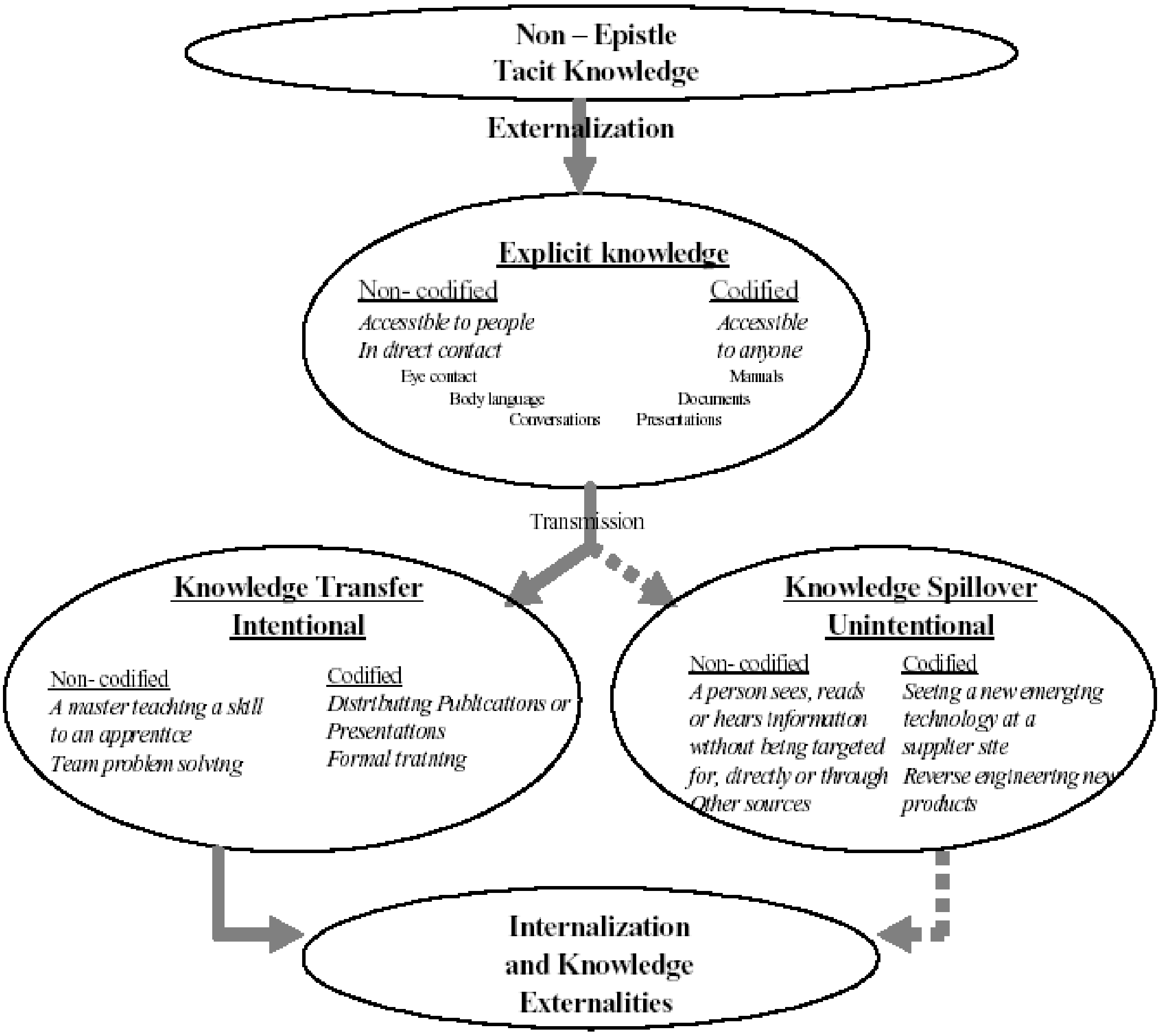


Source: Fallah and Ibrahim (2004)

In figure 5.1, the area contained in the dotted lines identifies the types of knowledge that is best acquired through direct interaction. All inventions and new ideas start as tacit knowledge residing in somebody's mind. Often, the fastest, easiest, least expensive, accurate and, sometimes, the only way to access that knowledge are through direct (often face-to-face) interaction. Therefore, opportunities for direct interaction among people are most easily facilitated when they work and live close together.

It is important to distinguish knowledge spillover from knowledge transfer. Spillovers are the unintentional transmission of knowledge to others. In contrast, if knowledge is exchanged with the intended people or organizations, the case is knowledge transfer. Figure 5.2 depicts the flow of knowledge from the holder to receivers via knowledge transfer and spillover respectively.

Figure 5.2 Knowledge transfer versus spillover



Source: Fallah and Ibrahim (2004)

Technology surely has impact on knowledge accessibility. New information and telecommunication technologies such as video conference and Internet facilitate remote interactions among people. However, the effectiveness of such communication technologies should not be exaggerated. As Feldman and Audretsch (1999) point out, advances in communication technologies may lower the cost of transmitting information, but the transmission of complex and non-codified knowledge still increases with distance. In other words, returns to knowledge may be spatially bound; hence inventions tend to cluster spatially.[114] Glaeser et al (1992) and Henderson (1997) have underlined the importance of geographic proximity for sharing innovative efforts across cities. However, the effect of these spillovers across regions deserves further careful study. How important are spillovers of ideas and knowledge? And how far can spillovers travel? This chapter tries to answer these questions. These questions are important as it can well be argued that the engines of national economic performance are sub-national districts that are characterized by strong ties between regional actors (Storper 1995; Scott 1993).

Krugman (1991) argues provocatively that economists should not waste their time in attempting to measure knowledge spillovers as knowledge spillovers are invisible, they do not leave paper trial by which they can be measured and tracked. Nevertheless, several approaches have been considered to track knowledge spillovers. Jaffe, Trajtenberg and Henderson (1993) point out that knowledge flows do sometimes leave a paper trail, in particular, in the form of patent citations. They find evidence of the localization of citations, that is, patents cite other patents that originate in the same city with greater frequency.

The most important empirical approach to analyze the process of innovation creation is the knowledge production function, originally formalized by Griliches (1979) and Pakes and Griliches (1984). Griliches (1979) introduced the econometric model to measure the effect of R&D investment on technology stock and economic growth. Jaffe (1986) built on this model, considering that the total relevant productivity of other firms influence innovation of a particular firm. Jaffe (1989) then used the same model to measure geographical spillovers between neighboring firms and universities using American states as geographical units. Anselin et al. (1997, 2000) used the same model in similar studies, but used U.S. Metropolitan Statistical Areas (MSAs) instead. Smith (1999) studied inter-state knowledge spillovers within the United States.[115] To sum up, empirical estimations of the model of the knowledge production function have been carried out for different levels of aggregation with a common result of a positive and significant effect of research spillovers on innovation activity. However, most of these studies are applied to the US case, such as the ones by Acs et al. (1994), Jaffe (1989), Jaffe et al. (1993), Audretsch and Feldman (1996), Anselin et al. (1997). At the level of regions in various European countries, previous attempts are those by Maurseth and

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[114] This contrasts with immediate knowledge diffusion, an assumption made by the neoclassical growth model. Immediate knowledge diffusion implies that technology gaps between regions do not exist.

Verspagen (1999) and by Bottazzi and Peri (2003). Among the studies applied to areas within a single European country, we find the works by Autant-Bernard (2003) for the French departments, Fischer and Varga (2003) for Austrian political districts, Andersson and Ejermo (2003) for Swedish regions. All these studies have successfully detected the knowledge spillover.

This chapter analyzes the importance of geographic proximity in the diffusion of knowledge in 37 Prussian regions from 1877 to 1914. The rest of the chapter is organized as follows. Section 2 discusses the model. Section 3 describes data and variables. Section 4 presents the estimation outcomes; we modify the basic model and present the corresponding research outcomes. In section 5, we explore another type of spillover, namely inter-firm spillover. Section 6 concludes the chapter.

5.2 BASIC MODEL

The famous Cobb-Douglas function is the most widely used production function.[116] It can be modified to study the creation of ideas. Based on the Cobb-Douglas function, Romer (1990) and Jones (1995) proposed an innovation function, namely the production function of new knowledge. Bottazzi and Peri (2003) generalized and modified the function. This paper basically adopted the innovation function used by Bottazzi and Peri (2003).

The very idea of this innovation function used in Bottazzi and Peri (2003) is simple. Innovation in one region is associated with local human capital and the spillovers of human capital in other regions. The basic concept can be expressed as follows.

Innovation = β_0 + β_1*Local human capital + β_2*Spillovers of human capital in close regions + β_3*Spillovers of human capital in distant regions + Residual (1)

To be exact, we split distant regions into several intervals. We get the following equation[117]

$$\text{Ln(Patent)}_i = \beta_0 + \beta_1\text{Ln(Human Capital)}_i + \beta_{[dist0,\, dist1)}[m'_{i1}\text{Ln(Human Capital)}] + \beta_{[dist1,\, dist2)}[m'_{i2}\text{Ln(Human Capital)}] + \beta_{[dist2,\, dist3)}[m'_{i3}\text{Ln(Human Capital)}] + \beta_{[dist3,\, dist4)}[m'_{i4}\text{Ln(Human Capital)}] + \ldots + \beta_{[distn,\, distk)}[m'_{ik}\text{Ln(Human Capital)}] + \varepsilon_i \qquad (2)$$

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[115] For a comprehensive and updated review on knowledge production and spillovers within the geographical space, see Audretsch and Feldman (2003).

[116] For historical origin and later development of the function, see Douglas (1976).

[117] The step-by-step procedure to reach equation (2) is explained in detail in Bottazzi and Peri (2002).

Here, the dependent variable is proxied by the average number of patents per capita in one region in its natural log form. As for the independent variables, the input of innovative activities, human capital (abbreviated as HC), is measured by the share of vocational school (commercial and technical school) pupils of total population in its natural log form in the local region. Then we introduce factors connected with human capital in other regions. These regressors are constructed as follows: Row vector m'_i is an 37*1 row vector whose jth entry is zero if distance is not within the range k, while it is $(1/n_{ik})$ if that distance is within the range k. Ln(Human Capital) is a 1*37 column vector whose i entry is $\ln(\text{Human Capital})_i$. The product of these two vectors gives the average ln(Human Capital) for regions in the kth distance interval from region i. ε_i is assumed to be a well-behaved random i.i.d. error capturing other unobservable determinants of innovative output. In this equation, β_1, $\beta_{[dist0,\ dist1)}$, $\beta_{[dist1,\ dist2)}$, $\beta_{[dist2,\ dist3)}\ldots$, $\beta_{[distn,\ distk)}$ all measure elasticity. Coefficient β_1 shows the impact of local human capital on innovation, and $\beta_{[dist0,\ dist1)}$, $\beta_{[dist1,\ dist2)}$, …, $\beta_{[distn,\ distk)}$ capture the effect of human capital in other regions (up to 2000 kilometers) on innovation due to spillovers.

The effect of human capital spillovers changes over distance. We divide the distances between regions into five bands in kilometers: (0-265), (265-420), (420-610), (610-840), and (840-2000). We base this division on two criterions: (1). Every band contains at least one pair of regions, and (2). Each band contains approximately the same number of pairs. Prussia had 37 districts. Accordingly, there are 37*(37-1)=1332 distances. There are about 266 (1332/5) distances in each band.[118]

We express the function (2) listed above mathematically as follows.

$$\text{Ln(Patent)}_i = \beta_0 + \beta_1\text{Ln(HC)}_i + \beta_2[m'_{i[1\text{-}265)}\text{Ln(HC)}] + \beta_3[m'_{i[265\text{-}420)}\text{Ln(HC)}] + \beta_4[m'_{i[420\text{-}610)}\text{Ln(HC)}] + \beta_5[m'_{i[610\text{-}840)}\text{Ln(HC)}] + \beta_6[m'_{i[840\text{-}2000)}\text{Ln(HC)}] + \varepsilon_i \qquad (3)$$

We would expect the following outcomes.

1. local human capital should have great impact on innovation.

2. human capital in other regions should have some, if little, impact.

3. the impact of human capital in other regions might diminish over distance if tacit knowledge plays a role. If it is too far away, spillovers are insignificant.

We will see whether the outcomes meet our expectations. Before we estimate this model, we describe the data used in this empirical study.

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[118] We also tried several other divisions. The regression results remain largely intact.

5.3 DATA

Various geographic and administrative units of analysis have been used to study innovation. As regions are connected within themselves, they serve our research objective well. In this paper, we use Prussian regions as unit of analysis mainly because of the available data are split are regional level. Prussia had 37 regions (called Regierungsbezirk in German). We need to control the impact of regional size on economic variables. It is quite natural that large regions have more patents and schools pupils than small regions. Because Prussian regions differ substantially in size, we use regional population to standardize all variables to eliminate the possible cause of distortion due to the issue of regional size.

R&D is input that might lead to innovation output. R&D data are available on a broad scale only after the World War Two. It is impossible for us to obtain R&D data for the time period studied in this research. However, we can use other measures. Schooling is one important component of R&D input and it is an interesting determinant of patents by itself. Human capital can be measured by the educational achievements of its population. With discretion, we use students of technical and commercial schools.[119] We gather the numbers of students at technical and commercial schools. Then, we divide the numbers by population. Afterwards, we take natural log.

Of course, we would like to extend the current research to Germany as a whole. However, data for technical schools and commercial schools at district level are absent or not homogenous in German statistical yearbooks. Hence we concentrate are Prussia. We divide the years from 1877 to 1914 into the following time periods: 1877-1885, 1886-1895, 1896-1905, 1906-1910, and 1911-1914.[120] We would like to compare the spillover effects over various periods. Using the mean number of patents for each interval reduces inter-annual variances in patent numbers, which is especially troublesome in areas that often receive only few patents in a given year.

The distance between regions is a complicated issue. There are two measures. The first one is border-to-border distance. Two regions that have a common border are assigned zero as distance. Regions without a border are assigned a distance measured between their closest borders. Bottazzi and Peri (2003) adopted this approach. The second approach is point-to-point distance. We use this approach. Prussia has 37 administrative

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[119] See chapter 1 for reasons behind this selection.

districts. We locate the largest city of these districts. Then, we take the distance between these cities.[121] A table of regions and their central cities is in the appendix one.

5.4 REGRESSION RESULTS

We use OLS method to estimate equation (3). The regression results for various time periods are in the appendix two.

We put the final regression outcomes of various periods into one table to render a comparison over time possible.

Table 5.1 Regression results of spillover

Variables	**1877-1885**	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
M′[0]ln(HC)	0.432*** (0.095)	0.884*** (0.180)	1.013** (0.419)	1.064*** (0.162)	1.123*** (0.164)
M′[1-265)ln(HC)	0.352* (0.175)	0.829* (0.470)	0.935* (0.536)	0.712* (0.371)	1.004*** (0.346)
M′[265-420)ln(HC)	2.991E-02 (0.144)	-0.430 (0.335)	-0.255 (0.595)	-0.309 (0.404)	7.811E-02 (0.346)
M′[420-610)ln(HC)	7.213E-02 (0.274)	0.253 (0.465)	1.252 (0.939)	0.690 (0.529)	0.829 (0.397)
M′[610-840)ln(HC)	-3.579E-02 (0.222)	-0.235 (0.335)	-0.775 (0.558)	-0.273 (0.423)	0.202 (0.398)
M′[840-2000)ln(HC)	5.377E-02 (0.150)	0.175 (0.259)	8.063E-02 (0.410)	-0.338 (0.334)	-0.419 (0.315)
R Square	0.655	0.677	0.466	0.751	0.806
Number of observations	37	37	37	37	37

Notes:

1. Dependent variable: Ln(annual patents which survived for more than ten years)

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[120] Some variables are averaged over shorter intervals due to the unavailability of the whole series.

[121] Data for such distances between these cities are largely available. *Der grosse ADAC-Generalatlas* has information for distances between 100 German major places. *Deutscher Generalatlas: Masstab 1:200000*, published by West Germany, also includes the distances between major cities in West Germany. We mostly rely on these two data. However, the past one hundred years witnessed the rise and fall of German cities. Many economic centers in Prussia become unimportant now. Moreover, many places are relocated to other countries. We measure some distances that are not readily available.

2. Standard errors are given in parenthesis under coefficients
3. * means statistically significant at 10 % level, ** means statistically significant at 5 % level, and *** means statistically significant at 1 % level.

The estimations yield high degree of explanatory power. Our regression outcomes are rather similar to those of Bottazzi and Peri (2003), which are contained in table 5.2. However, some caution should be called for in this comparison as we have rather different model specifications.

Table 5.2 Regression results of Bottazzi and Peri (2003)

	Dependent variable: Ln (yearly patent applications)	
	Basic specifications using R&D employment (private and public)	**Basic specifications using R&D expenditure (1985 ECU)**
ln(R&D)	0.83** (0.07)	0.80** (0.06)
M´[1-300]ln(R&D)	0.025** (0.012)	0.025** (0.011)
M´[300-600]ln(R&D)	-0.008 (0.019)	-0.007 (0.013)
M´[600-900]ln(R&D)	0.010 (0.013)	-0.004 (0.012)
M´[900-1300]ln(R&D)	-0.005 (0.012)	-0.007 (0.012)
M´[840-2000]ln(R&D)	-0.02 (-0.017)	-0.018 (0.012)
R Square	0.87	0.89
Number of observations	86	86

According to our research results, local human capital has great impact on innovation. Human capital in regions no farther than 265 kilometers away has impact on local innovation. According to our study, adding 10 % students in technical and commercial schools in a Prussian region would increase the output of new ideas in other regions within 265 km by as much as 4-9 %, while it would increase the innovation of the own region often by 4-10 %. The magnitude of the elasticities is rather remarkable. We have to admit that there are some omitted variables that are correlated with schooling and account for a share of the impact. In the time period under the study of Bottazzi and Peri (2003), aided by modern technology (especially technology in transport and telecommunications), ideas can spread more easily today. The contemporary proponent of New Economy such as Paul Krugman even talks about "death of distance".[122] However, we should also note that around 1900, Prussia was a society of high regional mobility. Migration (especially young people migrating from eastern Prussia to western Prussia to work) occurred frequently. In this social context, this high diffusion effects are more plausible. We find that human capital in other regions farther than 265 kilometers away has little impact on local innovation. This outcome well demonstrates that across distance, spillovers are bound by physical distance and can not travel infinitely. And these results are relatively robust when we add in independent variables one by one.

We now modify the basic model. Part of the correlation we have found between human capital and patents and between other regions' patents and local patents could be spurious and due to omission of relevant variables. There are many factors that affect innovation. Production is such a factor. Technological discoveries are more likely to occur to those who work in an industry than to outsiders, because insiders should possess more knowledge about problems and opportunities in the industry and are also better positioned to benefit from their knowledge. We use horsepower (both steam engine and electrical) as a measure of physical capital formation, which is closely associated with production. Another complementary proxy for production in a region is its industrial labor force. For this region, we include industrial labor force per population as an explanatory variable. We run the regressions above again after adding these two explanatory variables.

Table 5.3 Regression results of spillover after controlling production

Variables	**1877-1885**	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
M′[0]ln(HC)	0.261** (0.100)	0.547** (0.256)	0.327* (0.166)	0.606** (0.245)	0.957*** (0.296)
M′[1-265)ln(HC)	0.199* (0.110)	0.493* (0.289)	0.151* (0.367)	0.480* (0.278)	0.838** (0.326)
M′[265-420)	-4.172E-02	-0.214	-0.418	-0.285	5.764E-02

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[122] *The Economist*, September 30-October 6, 1995. Paul Krugman believes that knowledge spills over unlimitedly across geographic distances.

ln(HC)	(0.099)	(0.299)	(0.371)	(0.344)	(0.299)
M´[420-610)ln(HC)	0.140E (0.207)	0.181 (0.399)	0.348 (0.610)	0.434 (0.458)	0.621 (0.346)
M´[610-840)ln(HC)	-0.174 (0.150)	-0.277 (0.299)	-0.612 (0.356)	-0.211 (0.372)	0.243 (0.349)
M´[840-2000)ln(HC)	-3.350E-02 (0.095)	0.163 (0.232)	0.160 (0.260)	7.692E-02 (0.195)	-0.412 (0.272)
Horsepower	9.278E-02 (0.071)	4.572E-02 (0.114)	0.245 (0.236)	7.692E-02 (0.195)	-0.347 (0.285)
Share of industrial Workers	0.250* (0.144)	0.338 (0.199)	0.438 (0.306)	4.908E-06 (0.301)	0.656 (0.389)
R Square	0.856	0.756	0.800	0.832	0.827
Number of observations	37	37	37	37	37

After controlling production, our regression outcomes remain largely the same. However, the coefficients of spillover become smaller as we now control for production. It means that previously, we had contributed some undue effect to spillover due to omitted variable bias. Nevertheless, the effects are clearly visible from our regression and tend to grow over time.

Above, we considered aggregate patenting from all industries. Yet patents are not homogenous across industries. Therefore we should control for the fact that different industries have different properties concerning patents. Both chemical (including dyes) and electrical industries are very special industries. And these two industries are very active in registering patents. They occupy more than 20% patents in our patent pool from 1877 to 1914. We exclude patents from these two industries and run the regression again.

Table 5.4 Regression results of spillover
(excluding patents from chemical and electrical industries)

Variables	**1877-1885**	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
M´[0]ln(HC)	0.244** (0.087)	0.389*** (0.129)	0.400** (0.196)	0.332*** (0.110)	0.677** (0.296)
M´[1-265)	0.215**	0.369*	0.322*	0.319*	0.663*

ln(HC)	(0.100)	(0.211)	(0.146)	(0.167)	(0.357)
M′[265-420)ln(HC)	-3.853E-02 (0.091)	0.243 (0.129)	0.224 (0.291)	-0.166 (0.295)	0.121 (0.311)
M′[420-610) ln(HC)	0.155 (0.184)	0.220 (0.303)	0.192 (0.455)	0.120 (0.389)	0.713 (0.353)
M′[610-840)ln(HC)	-0.211 (0.140)	-0.329 (0.231)	-0.507 (0.311)	-0.218 (0.328)	0.247 (0.336)
M′[840-2000)ln(HC)	6.418E-02 (0.096)	6.650E-02 (0.167)	0.312 (0.224)	-0.365 (0.235)	-0.369 (0.286)
Horsepower	0.103 (0.068)	8.119E-02 (0.085)	0.143 (0.195)	0.191 (0.137)	-0.277 (0.292)
Share of industrial workers	0.196 (0.200)	0.388** (0.148)	0.617** (0.249)	5.614E-06*** (0.000)	0.827** (0.384)
R Square	0.864	0.756	0.838	0.854	0.841
Number of observations	37	37	37	37	37

Omitting patents from chemical and electrical industries do not change the picture drastically. The concern that patents from these two industries would distort the picture should not be exaggerated. After the exclusion, local human capital and human capital in other regions still have positive and statistically significant impact on local innovation. However, we do observe some differences. The effects of spillover are in general smaller then the effects when we use patents from all industries. This means that for chemical and electrical industries, the human capital generated in the technical and commercial schools is probably even more important. This outcome is not surprising. It is well expected that students from vocational schools entered firms that registered a lot of patents (in our case, mostly the firms in chemical and electrical industries). In contrast, firms in older technological activity did not benefit so much from human capital spillovers compared with firms in chemical and electrical industries. Their patenting activities were stimulated by a high share of industrial workers.

5.5 SPILLOVERS BETWEEN FIRMS

Firms are the main unit of production and innovation in a market-based economy. Above, we have investigated the spillover of knowledge from schools to firms by using the number of technological and commercial school pupils as a proxy for human capital. We now experiment with another human capital proxy. There are also inter-firm spillovers.[123] Jaffe (1986) found that a significant fraction of the total flow of spillovers that affect a firm's research productivity originates from other firms. Patents can serve as both input and output of innovation. One firm's patents can be used by other firms to generate more patentable ideas. If a firm has an innovative labor force, another firm might hire its staff. Therefore, knowledge spillovers can easily move across firms and inter-firm spillovers may well be geographically mediated. To explore this inter-firm spillover as a logical extension of the inquiry concerning spillover, we slightly modify the model used in section 2.

$$\mathrm{Ln(Patent)}_i = \beta_0 + \beta_1\mathrm{Ln(HC)}_i + \beta_2[m'_{i[1\text{-}265)}\mathrm{Ln(Patent)}] + \beta_3[m'_{i[265\text{-}420)}\mathrm{Ln(Patent)}] + \beta_4[m'_{i[420\text{-}610)}\mathrm{Ln(Patent)}] + \beta_5[m'_{i[610\text{-}840)}\mathrm{Ln(Patent)}] + \beta_6[m'_{i[840\text{-}2000)}\mathrm{Ln(Patent)}] + \varepsilon_i \quad (4)$$

Here, the only modification is that we substitute patents for human capital in other regions in function (3). The estimation outcomes for various periods are as follows.

Table 5.5 Regression results of inter-firm spillover

Variables	**1877-1885**	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
M´[0]ln(HC)	0.174* (0.100)	0.288* (0.151)	0.389* (0.205)	0.427*** (0.094)	0.710** (0.308)
M´[1-265) ln(HC)	0.125* (0.110)	0.467* (0.271)	0.435* (0.215)	0.263*** (0.077)	0.762** (0.354)
M´[265-420) ln(HC)	-.108 (0.064)	-0.259 (0.272)	-0.157 (0.356)	-0.350 (0.227)	-0.320 (0.307)
M´[420-610) ln(HC)	0.122 (0.088)	0.537 (0.424)	0.866 (0.558)	-5.237E-03 (0.300)	0.518 (0.359)
M´[610-840) ln(HC)	-9.698E-02 (0.082)	-0.253 (0.305)	-0.495 (0.324)	-7.486E-02 (0.268)	0.187 (0.395)
M´[840-2000)	-2.399E-02	0.127	0.208	-0.203	-0.440

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[123] Several representative works focusing on inter company spillovers are Jaffe, Trajtenberg and Henderson (1993), Audretsch and Feldman (1999), Verspagen and Schoenmakers (2000).

ln(HC)	(0.073)	(0.223)	(0.237)	(0.134)	(0.301)
Horsepower	4.867E-02 (0.066)	4.311E-02 (0.116)	0.147 (0.219)	-0.109 (0.154)	-0.551 (0.369)
Share of industrial workers	0.474*** (0.164)	0.523*** (0.181)	0.564** (0.271)	9.682E-06*** (0.000)	1.127*** (0.384)
R Square	0.872	0.797	0.836	0.878	0.833
Number of observations	37	37	37	37	37

We do detect that patents in other regions have positive and statistically significant externalities on local patenting. And the effects tended to grow over time and reached its peak at the end of the period. To control for the special features of chemical and electrical industries concerning patenting, we exclude patents from these industries and run the regression again.

Table 5.6 Regression results of inter-firm spillover
(excluding patents from chemical and electrical industries)

Variables	**1877-1885**	**1886-1895**	**1896-1905**	**1906-1910**	**1911-1914**
M´[0]ln(HC)	0.180* (0.099)	0.364** (0.146)	0.146* (0.071)	0.271* (0.142)	0.608** (0.308)
M´[1-265) ln(HC)	0.117* (0.069)	0.230** (0.092)	0.227* (0.126)	0.236** (0.104)	0.311** (0.149)
M´[265-420) ln(HC)	-9.706E-02 (0.064)	-0.117 (0.097)	-5.877E-02 (0.125)	-1.657E-02 (0.132)	9.208E-03 (0.125)
M´[420-610) ln(HC)	0.111 (0.090)	0.159 (0.107)	-2.310E-02 (0.128)	-6.153E-02 (0.132)	0.251 (0.159)
M´[610-840) ln(HC)	-0.104 (0.082)	-0.195 (0.116)	-0.206 (0.127)	-0.154 (0.144)	-2.828E-02 (0.184)
M´[840-2000)ln(HC)	-5.193E-02 (0.078)	3.082E-02 (0.079)	0.168 (0.153)	2.957E-02 (0.111)	-3.437E-02 (0.130)
Horsepower	6.771E-02 (0.066)	0.111 (0.077)	7.779E-02 (0.238)	0.198 (0.142)	0.142 (0.248)
Share of	0.399**	0.149	0.459	5.879E-06**	0.385

industrial workers	(0.167)	(0.181)	(0.271)	(0.000)	(0.236)
R Square	0.862	0.838	0.781	0.835	0.806
Number of observations	37	37	37	37	37

Our results remain rather robust. Omitting patents from chemical and electrical industries does not affect the previous regression outcomes greatly. After the exclusion, local human capital and patents registered by patentees in other regions still have positive and statistically significant impact on local innovation. And the effects also grow over time. The effects of spillover are in general smaller then the effects when we use patents from all industries. This means that chemical and electrical industries are better at exploiting existing patents than industries in general.

5.6 CONCLUSION

In this chapter, we estimate the spillover effects on patents across Prussian regions from 1877 to 1914. In terms of the spillovers of human capital, we found that the spillovers are very localized and exist only within a distance of 265 kilometers. However, the size of these spillovers is substantial. Adding 10% students in commercial and technical schools in a region would increase the output of new ideas in other regions within 265 km by as much as 4-9 %, while it would increase the innovation of the own region often by 4-10 %. The development of telecommunications increasingly facilitates the diffusions of ideas and knowledge over short distances. Yet this does not mean the “death of distance”; the opposite is true, as we can see that the spillovers rarely exist over 265 kilometers anyway. We modify this basic model to control for production and special industries. The regression outcomes remain rather robust. After investigating this spillover from schools to firms, we examine inter-firm spillovers. Again, we find that spillovers are rather confined in nearby regions no farther than 265 kilometers. And this outcome is also fairly robust amid modifications to control for production and patents from special industries.

Appendix 1

Prussian regions and their central cities

No.	region	center	No.	region	center	No.	region	center
1	Aachen	Aachen	14	Kassel	Kassel	27	Osnabrueck	Osnabrueck
2	Allenstein	Arys	15	Koblenz	Koblenz	28	Posen	Posen
3	Arnsberg	Dortmund	16	Cologne	Cologne	29	Potsdam	Potsdam
4	Aurich	Emden	17	Koenigsberg	Koenigsberg	30	Schleswig	Kiel
5	Breslau	Breslau	18	Koeslin	Koeslin	31	Sigmaringen	Sigmaringen
6	Bromberg	Bromberg	19	Liegnitz	Goerlitz	32	Stade	Bremervoerde
7	Danzig	Danzig	20	Lueneburg	Lueneburg	33	Berlin	Berlin
8	Duesseldorf	Duesseldorf	21	Magdeburg	Magdeburg	34	Stettin	Stettin
9	Erfurt	Erfurt	22	Marienwerder	Graudenz	35	Stralsund	Stralsund
10	Frankfurt a/o	Frankfurt a/o	23	Merseburg	Halle	36	Trier	Trier
11	Gumbinnen	Gumbinnen	24	Minden	Bielefeld	37	Wiesbaden	Frankfurt a/m
12	Hannover	Hannover	25	Muenster	Muenster			
13	Hildesheim	Goettingen	26	Oppeln	Oppeln			

Appendix 2

Regression results of spillover over various periods

(1). 1877-1885

Variables	I	II	III	IV	V	VI
M´[0]ln(HC)	0.532*** (0.077)	0.465*** (0.082)	0.445*** (0.093)	0.422*** (0.093)	0.433*** (0.093)	0.432*** (0.095)
M´[1-265) ln(HC)		0.274* (0.146)	0.257* (0.151)	0.350** (0.161)	0.356** (0.161)	0.352* (0.175)
M´[265-420)ln(HC)			6.735E-02 (0.134)	7.125E-02 (0.132)	3.206E-02 (0.138)	2.991E-02 (0.144)
M´[420-610)ln(HC)				0.361 (0.245)	0.257 (0.267)	7.213E-02 (0.274)
M´[610-840)ln(HC)					-0.198 (0.200)	-3.579E-02 (0.222)
M´[840-2000) ln(HC)						5.377E-02 (0.150)
R Square	0.577	0.617	0.620	0.644	0.655	0.655
Number of observations	37	37	37	37	37	37

(2). 1886-1895

Variables	I	II	III	IV	V	VI
M´[0]ln(HC)	0.953*** (0.130)	0.850*** (0.158)	0.953*** (0.171)	0.907*** (0.177)	0.889*** (0.179)	0.884*** (0.180)
M´[1-265) ln(HC)		0.412* (0.387)	0.655* (0.415)	7.90* (0.437)	0.741* (0.448)	0.829* (0.470)
M´[265-420) ln(HC)			-0.476 (0.324)	-0.437 (0.326)	-0.453 (0.330)	-0.430 (0.335)
M´[420-610) ln(HC)				0.414 (0.421)	0.319 (0.451)	0.253 (0.465)
M´[610-840) ln(HC)					-0.205 (0.329)	-0.235 (0.335)

M´[840-2000) ln(HC)						0.175 (0.259)
R Square	0.623	0.635	0.658	0.668	0.672	0.677
Number of observations	37	37	37	37	37	37

(3). 1896-1905

Variables	**I**	**II**	**III**	**IV**	**V**	**VI**
M´[0]ln(HC)	1.277*** (0.354)	1.201*** (0.358)	1.387*** (0.384)	1.143*** (0.374)	0.984** (0.386)	1.013** (0.419)
M´[1-265) ln(HC)		0.546 (0.475)	0.450 (0.476)	1.047** (0.512)	0.911* (0.514)	0.935* (0.536)
M´[265-420) ln(HC)			-0.619 (0.487)	8.130E-02 (0.543)	-0.249 (0.585)	-0.255 (0.595)
M´[420-610) ln(HC)				1.869 (0.787)	1.280 (0.883)	1.252 (0.939)
M´[610-840) ln(HC)					-0.760 (0.544)	-0.775 (0.558)
M´[840-2000) ln(HC)						8.063E-02 (0.410)
R Square	0.271	0.299	0.331	0.432	0.465	0.466
Number of observations	37	37	37	37	37	37

(4). 1896-1910

Variables	**I**	**II**	**III**	**IV**	**V**	**VI**
M´[0]ln(HC)	1.222*** (0.153)	1.199*** (0.143)	1.221*** (0.142)	1.150*** (0.147)	1.101*** (0.158)	1.064*** (0.162)
M´[1-265) ln(HC)		0.746** (0.304)	0.676** (0.305)	0.912*** (0.335)	0.855** (0.343)	0.712* (0.371)
M´[265-420) ln(HC)			-0.402 (0.299)	-0.130 (0.341)	-0.320 (0.404)	-0.309 (0.404)
M´[420-610)				0.704	0.519	0.690

ln(HC)				(0.455)	(0.502)	(0.529)
M´[610-840) ln(HC)					-0.366 (0.413)	-0.273 (0.423)
M´[840-2000) ln(HC)						-0.338 (0.334)
R Square	0.647	0.700	0.716	0.736	0.742	0.751
Number of observations	37	37	37	37	37	37

(5). 1911-1914

Variables	**I**	**II**	**III**	**IV**	**V**	**VI**
M´[0]ln(HC)	1.375*** (0.151)	1.136*** (0.155)	1.139*** (0.156)	1.111*** (0.152)	1.119*** (0.166)	1.123*** (0.164)
M´[1-265) ln(HC)		0.984*** (0.316)	0.978*** (0.318)	1.061*** (0.324)	1.063*** (0.329)	1.004*** (0.346)
M´[265-420) ln(HC)			-0.204 (0.266)	-4.146E-02 (0.272)	-1.358E-02 (0.343)	7.811E-02 (0.346)
M´[420-610) ln(HC)				0.632 (0.348)	0.651 (0.379)	0.829 (0.397)
M´[610-840) ln(HC)					5.305E-02 (0.387)	0.202 (0.398)
M´[840-2000) ln(HC)						-0.419 (0.315)
R Square	0.704	0.770	0.774	0.795	0.796	0.806
Number of observations	37	37	37	37	37	37

Notes:

1. Dependent variable: Ln(annual patents which survived for more than ten years)
2. Standard errors are given in parenthesis under coefficients
3. * means statistically significant at 10 % level, ** means statistically significant at 5 % level, and *** means statistically significant at 1 % level.

Chapter 6

What Impact the Survival Rates of German and Foreign Patents (1879-1900)?

Evidence from Patent Renewal Data[124]

Abstract

The major objective of this chapter is to answer the question: To what extent do patentee's nationality and legal status (firm or person) and patent's technology field impact the patent survivals versus the patent renewals in Germany at the end of the 19th century. In order to conduct the empirical analysis, we constructed a data base of patent survival from the *Verzeichnis der im Vorjahre erteilten Patente* published by the German Patent Office. The data set consists of 2,563 foreign and domestic patents that were registered in Germany from 1879 to 1885. We employ a Cox proportional hazard regression to predict the renewal chances of newly granted patents between foreign and German patentees.

The main finding suggests that patent renewal rates differ significantly across different technology fields and countries of origin. Additionally, patents registered by German patentees tend to die sooner than foreign patents, while the differences among the foreign countries included in the analysis are not significant. The various technology fields show different impact on the patent renewal rate. In comparison to the patents from the instrument industry, which serve as a reference group in our analysis, those patents in dyes, chemical, and electrical industries tend to have higher propensity of being renewed. Moreover, the patents registered by individuals tend to survive the patents registered by firms although this difference is not statistically significant. Finally, our empirical outcomes will enable the use of attaching weights to patents, and on the other side of producing weighted patent count indices, which are more precise measures of innovative output than raw patent counts.

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[124] See also Streb, Baten, Fertala and Yin (2005) on these issues.

6.1 INTRODUCTION

Given the essential position that patent systems have in encouraging invention and innovation, information about the factors driving the renewal process is fundamental in order to understand how valuable a particular patent right is. On the other side, patent rights are not frequently traded, and even if they are, information about their pricing value is not easily available to the public. In this context, as direct information about the patent value is sparse, economists have turned to other sources of information, while examining their actual contribution to the economic development. For instance, significant evidence on the importance of patent protection comes from survey data (Taylor and Silberston, 1973; Mansfield, Schwartz, and Wagner, 1981; Levin et al., 1987).

Additionally, most patent systems require holders, individuals and firms, of patents to pay a renewal fee at a specific interval (often one year) to keep their patent rights in force. If the required fee is not paid in any one year, the patent will be permanently cancelled. Assuming that renewal decisions follow economic criteria, the decision-making process, therefore, will be tied to the value of the patent right. In other words, patentees will renew their protection rights only if the value of asserting them an additional year exceeds the cost of renewal. Observations on the proportion of survival versus renewal rates at different patent's age will thus contain information on the distribution of the holding values of particular patent and on the evolution of this distribution over the life span of the patent. For instance, based on historical data for the period 1852-1876, Sullivan (1994) estimated the value of patent rights in Britain and Ireland and compared them with similar empirical results of Schankerman and Pakes (1986) for the period 1950-76 in United Kingdom, France and Germany. As far as we are concerned historical evidence for Germany is not existent, so the main motivation of this chapter is to provide historical facts about the value of intellectual property rights based on survival analysis.

Additional objective of this chapter is to explore the potential error in simple patent counts as measurement of invention. Using patents as an indicator of innovation has fascinated many economists in their attempts to understand the determinants of inventive behavior, largely due to its availability (Sullivan, 1989, 1993). However, their efforts are hindered by various shortcomings of patents. One considerable drawback is the fact that inventions being patented differ to the highest degree in their quality. The patent count as measure has been used both as an indicator of the output value of patentable ideas (and more generally of the value of inventive output as a whole), and on the other side as an indicator of the proprietary rights value created by the patent laws (Scherer 1980). Pure patent counts, in this sense, will allocate the same weight to every patent, no matter whether it has high or a low economic value for the patentee or for the society. Employing the number of patents as an indicator for new technological knowledge suitable to foster economic growth will lead to a potentially very large measurement error. To decrease this measurement error it is necessary to distinguish patents with a high from those with a low economic value.

As patent counts are very imperfect measures of innovative output, this chapter discusses how additional data (the number of years a patent survived) can be used to improve the quality of patent count data. A patent holder was supposed to decide to renew the patent only when the costs of doing so were lower than the expected future return of the patent. Following this contemporary assumption about the behavior of a patentee we will use information on the actual life span of a patent as an indicator for its private economic value.[125] In this sense, patents that had survived longer time are regarded as high value patents.

Analyzing patent renewal rate yields several benefits to innovation research. Firstly, it allows us to attach weights to patents and produce weighted patent count indices, which are more precise measures of innovative output than raw patent counts. Thus, the outcome of this research may well prove to be invaluable to future works, especially for studies based on German historical data. The second reason of interest in renewal data is the direct reflection of the incentive underlying the application and renewal process. Patents represent the legal right to exclude others from using the invention. As a result, the private value of a patent will be determined by the difference in the returns that would accrue to the innovation with and without patent protection. Since it is the value that determines both application and renewal decisions, application and renewal data contain information on the value of proprietary rights created by the patent laws, that is on the value of patent protection.

Economist's interest in patent renewal data goes back at least to Nordhaus' thesis (1969). Pakes and Schankerman (1984) stimulated broader interest in patent renewals by showing how to apply these data to uncover characteristics of the value of patent protection. Pakes (1986) goes further in his analysis and allows a patentee to be uncertain

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[125] Schankerman and Pakes (1986) were the first who used the life span of patents to estimate their private economic value.

about the sequence of returns that would be earned were the patent to be kept in force. This additional detail facilitates us to obtain a deeper understanding about the nature of the innovative process.

In this sense, the current chapter is based on patent renewal rates. It intends to do preparation for subsequent works on the value of patent protection, as initial descriptive statistics have shown great diversity in the life spans of patents. Why do some patents die young while others live longer? What factors are behind the heterogeneity of patent mortality versus renewal? Applying Cox regression techniques to perform survival analysis, this chapter strives to shed light to the above-stated inquiry.

The rest of the chapter is organized as follows. Section 2 explains the renewal decision of a patentee and shows under which circumstances the different life spans of patents can be used to identify the high-value patents of the German industrialization. Section 3 describes the renewal data and descriptive statistics. Section 4 introduces the econometric method. Section 5 presents the estimates, and Section 6 concludes the chapter.

6.2 DECISION OF PATENTEE TO RENEW A PATENT

Under the patent law of the German Empire, patentees had to decide annually if they were going to renew their patent for another year or not. The outcome of this decision depended on the patentee’s expectations about the future returns and costs of holding the patent. The latter were determined by the renewal fees demanded by the patent office and therefore most of the time certainly foreseeable. In contrast, the future returns of a patent were highly uncertain. They could arise from two major sources. On the one hand, patentees could use a patent to increase their profits by selling their innovation as a temporary monopolist or by licensing another producer to do so. On the other hand, patentees could also use their patent to prevent sales of competitors’ innovations that had the potential to decrease the market share of their own already established products. In 1911, for example, Siemens succeeded in developing the first light bulb with a metallic filament based on tantalum. Two years later Siemens was granted the two long-lived German patents no. 153328 and 154527 that proved to be the base from which the German firm gained the leading role in the world market. The sales of tantalum light bulbs gradually increased from 240,000 units at the beginning to almost

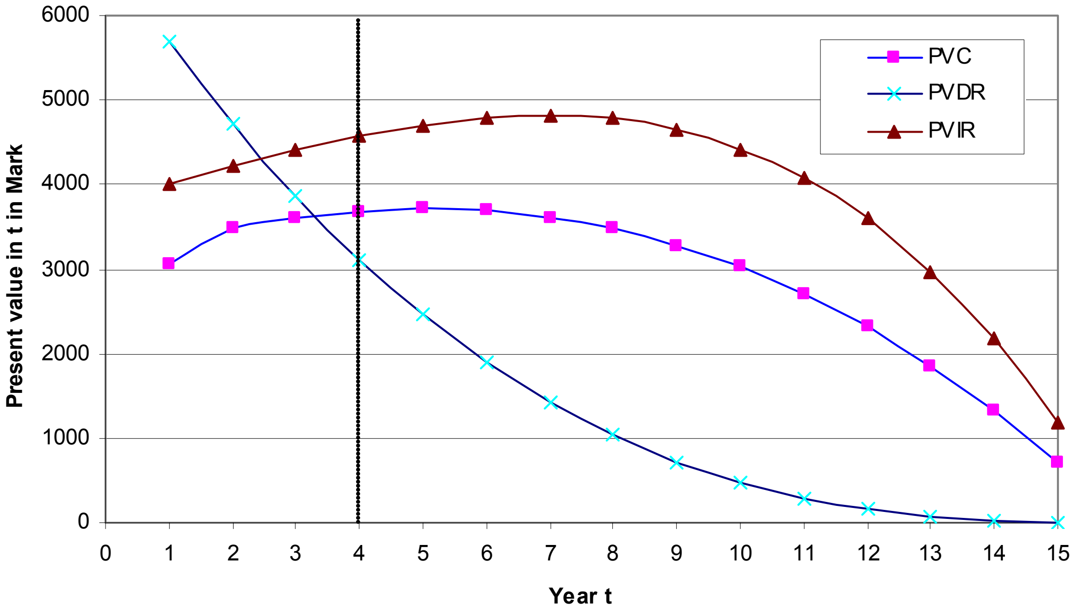
10 millions units in 1912. Even after General Electric discovered the superior wolfram light bulb the tantalum light bulb patents did not loose their high economic value since Siemens was able to barter them for the very valuable patents of General Electric. The American firm was forced to accept this patent exchange by Siemens' threat to use its own patents to hinder General Electric's entry into the German market.[126]

We assume that the patent holders renewed their patent if and only if the present value of the expected future returns exceeded the present value of the future costs either for the remaining maximum life span of the patent or for at least one shorter sub period. This condition is satisfied when the following inequality holds for at least one combination of t and T.

$$\sum_{t}^{T} E(R_t)(1+r)^{T-t} > \sum_{t}^{T} C_t(1+r)^{T-t} \quad with \;\; t=\{1,\ldots,15\},\, T=\{1,\ldots,15\},\, T \geq t$$

$E(R_t)$ denotes the expected returns in year t, C_t the costs in year t, T the remaining life span of the patent, t the first year of the remaining life span and r the interest rate used to discount the future values.

Figure 6.1 The renewal decision of the patentee



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[126] See Erker (1990), p. 75-77.

Figure 6.1 shows for every year the respective present value[127] of the historical renewal costs (PVC) and the expected returns of two hypothetic patents, one with increasing returns (PVIR) and another one with decreasing returns (PVDR) over time. In year 1, the present values of the returns of both patents are higher than the present value of their costs. That is why the inventor applies for both patents. In the following years the patent holder always renews the patent with increasing returns since the curve representing the discounted returns stays above the curve of the present values of the costs for the whole maximum life span of the patent. In the case of the patent with decreasing returns, however, the patent holder decides at the beginning of year 4 not to prolong this patent because in this year the present value of the expected returns has sunk under the discounted value of the renewal fees. In general, patent holders renew their patent until the year when the present value of the expected future returns is lower than the present value of the remaining renewal fees. They never apply for patents whose discounted expected returns are already lower than the present value of their costs in the first year.

Since patents can generate increasing or decreasing revenues over time it is unavoidable to compare the expected present values of future costs and revenues for both the maximum life span and all shorter sub periods. Let's first consider the case of a patent that produces very high returns in the last years of its maximum life span but very low returns in the years before. As a result, the present value of the expected net revenues of the maximum life span might be positive but the ones of shorter sub periods might be negative. That is why patent holders who base their renewal decision only on their expectations about the next year could make the mistake to give up an apparently worthless patent which would be in fact very profitable in the future. In the case of a patent with decreasing returns over time, the opposite is true because this kind of patent might have a negative present value of expected net revenues for its maximum life span but a positive one for shorter sub periods.

A long life span of a historical patent undoubtedly indicates its comparatively high private economic value. This conclusion, however, does not imply that all high-value patents had a long life span. There might have been patents with fast decreasing returns over time that were given up after just a few years but nevertheless yielded high returns to the patent holder in their comparatively short life span. That is why the criterion life span

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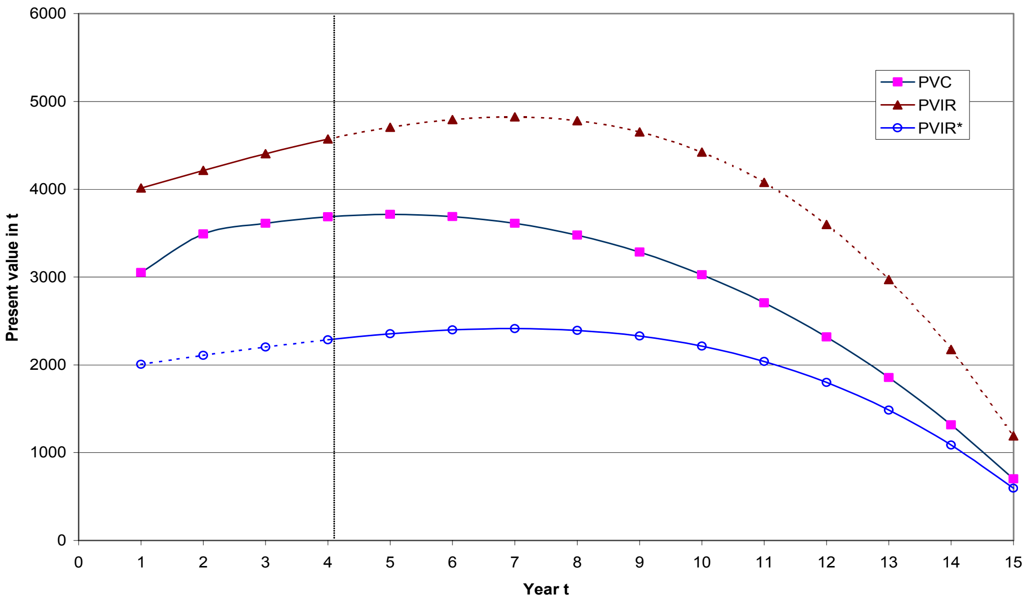
[127] In this example, we used an interest rate of five percent to discount the future values.

that systematically sorts out all short-lived patents is not a perfect measure to identify high-value patents.[128] However, using the life span of patents to distinguish low-value from high-value patents is a reasonably working procedure because it identifies all high-value patents with increasing returns and all long-lived high-value patents with decreasing returns. This method is additionally justified by the fact that the distribution of life spans of patents is highly skewed to the right.

Figure 6.1 implicitly assumes that the inventor's prior expectations about the future returns of his patents built up at the beginning of year 1 of the life span are accurate and do not need to be corrected at any point in time. This assumption is rather unrealistic. In an early stage of an innovation process, inventors are often highly uncertain whether or not their idea can be profitably exploited in the future. The low renewal fees at the beginning of a patent's life allows the inventors to use the patent as a comparatively cheap option that protects their new knowledge and gives them the time to learn more about the technological and economic prospects of their invention. Figure 6.2 shows a possible outcome of this learning process.

Figure 6.2 Correcting the expectations downwards



In year 1, the inventor speculates that the present values of the expected returns of the potential patent are correctly described by the curve PVIR. That is why he applies for

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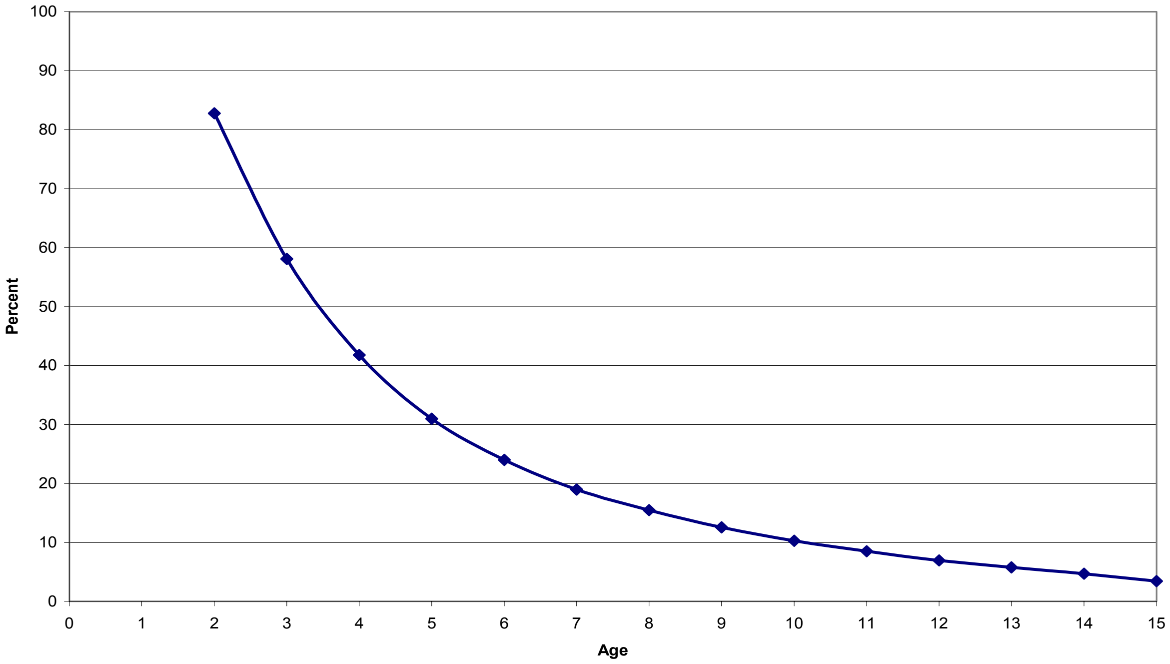
[128] The extent of this selection bias depends on the actual share of patents with fast decreasing returns in the population of all high-value patents. Schankerman and Pakes assume decreasing returns for all patents to make their math works. See Schankerman and Pakes (1986), p. 1054.

the patent. In the following years, he gathers more information that finally forces him to correct his expectations down to PVIR*. As a result, he doesn't renew the patent in year 4.

Pakes (1986) states, first, that this learning process of the patent holders is concentrated in the early years of a patent's life span, and second, that most of these options turn out to be worthless. These assumptions were supported by our finding that about seventy percent of all German patents granted between 1891 and 1907 were already cancelled after just five years. After the fifth year the speed of patent cancellation was decelerating. About 10 percent of all patents were still in force after 10 years, 4.7 percent of all patents reached the maximum age of fifteen years.

Figure 6.3 The survival rate of German patents[a]

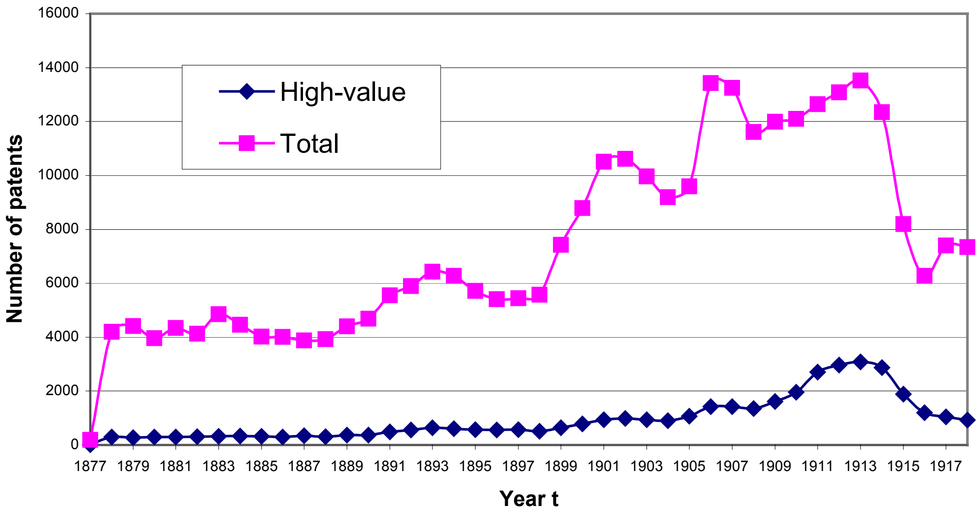


[a] This calculation is based on information on the patent cohorts 1891-1907. See *Blatt für Patent-, Muster- und Zeichenwesen* (1914), p. 84.

A basic question of the life span approach is how many years a patent had to be in force to be interpreted as a high-value patent. Schankerman and Pakes, who also used survival rates as an indicator for high-value patents, came to the result that most of the value of the patent stock built up in the post World War II period in Britain, France and

Western Germany was concentrated in the upper five percent of the long-lived patents.[129] Following this hint had meant in our case to select only those patents that reached the maximum life span of 15 years. To decrease the potential selection bias caused by high-value patents with decreasing returns we instead chose to follow Sullivan, who explored British and Irish patents of the second half of the 19th century, and to interpret the upper 10 percent of the long-lived patents as the high-value patents of our total patent population.[130] Exploiting the information given by the survival rate of figure 6.3, we therefore selected all patents that survived at least ten years.[131] This selection process resulted in a sample of 39,343 patents that we interpret as the high-value patents of the German Empire in the following. Figure 6.4 shows how many patents and high-value patents respectively were annually granted between 1877 and 1918.

Figure 6.4 Patents and high-value patents annually granted between 1877 and 1918



The number of patents granted annually quickly rose to about 4,000 after establishing the German patent law and kept this level until the late 1880s. The patent rush of the 1890s was probably triggered by a change in patent law that especially improved the patent protection of chemical inventions. The patent law of 1877 had

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[129] See Schankerman and Pakes (1986), p. 1067.

[130] See Sullivan (1994), p. 49.

determined that chemical firms could only patent new processes but not the new products made by these processes. As a result, foreign chemical firms were able to circumvent this kind of patent protection by producing the new products with the new processes abroad and selling them then in the German market. To impede such behavior the new German patent law of 1891[132] stipulated that patents granted for new chemical processes also protected the products produced by these processes.[133] Thereafter the number of patents in the technological fields of chemicals increased considerably. The growing number of patents was probably also caused by the fact that the new German patent law of 1891 improved the efficiency of the patent office by making the technicians, who decided about the novelty of patent application, and had until now only worked as a side job for the patent office, to full-time and life-long employees.[134] At the beginning of the 20th century the number of patents granted per year for the first time exceeded 10,000. The patent boom of the pre-World War I years coincided with the rise of the electrical engineering industry that in these years became a major focal point of patenting activity.

The average share of high-value patents in the total of all patents granted between 1877 and 1918 was 11.14 percent. As we can see in table 6.1, the actual annual share, however, was not constant over time. Rather, the annual share of high-value patents slowly increased between 1877 and 1893 from 5.3 percent to 10 percent, stagnated in the following 15 years, and skyrocketed then up to more than 23 percent on the eve of World War I.

Table 6.1 The share of high-value patents in all patents granted per year

Year	Share	Year	Share	Year	Share
1877	5.3 %	1891	8.8 %	1905	11.1 %
1878	7.1 %	1892	9.5 %	1906	10.6 %
1879	6.2 %	1893	10.0 %	1907	10.7 %
1880	7.5 %	1894	9.7 %	1908	11.7 %
1881	6.8 %	1895	9.9 %	1909	13.5 %
1882	7.5 %	1896	10.2 %	1910	16.2 %
1883	6.7 %	1897	10.4 %	1911	21.4 %

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[131] We hadn't the personnel to find out for each of more than 300,000 patents the individual life span.
[132] See Patentgesetz vom 7. April 1891, *Reichsgesetzblatt* (1891), pp. 79-90, especially § 4.
[133] See Bruchhausen (1977). See also Fleischer (1984), pp. 164-7.
[134] See Kaiserliches Patentamt, *Geschäftsthätigkeit*, p. 158.

1884	7.4 %	1898	9.2 %	1912	22.7 %
1885	7.9 %	1899	8.7 %	1913	22.8 %
1886	7.4 %	1900	9.0 %	1914	23.2 %
1887	8.9 %	1901	9.0 %	1915	23.1 %
1888	8.0 %	1902	9.3 %	1916	19.1 %
1889	8.2%	1903	9.4 %	1917	14.1 %
1890	8.0 %	1904	9.8 %	1918	12.6 %

How can the slow rise in the share of high-value patents between 1877 and 1893 be explained? It is conceivable that the contemporary inventors, who weren't familiar with the newly introduced patent law at the beginning, step by step improved their capabilities to judge the future economic prospects of their inventions correctly. As a result of this individual learning process the share of low-value patents actually applied for would have decreased automatically. An alternative explanation, however, is based on the patent office's observation that the relation of firms' professional research workers and private amateurish inventors who more likely applied for low-value patents wasn't the same in every technological class.[135] Classes like hat making (41), haberdashery (44) or harnesses (56) were rather dominated by over-optimistic amateurs, and had therefore a below-average lifespan of patents. Most inventions of technological classes with an above-average life span of patents like dyes (22) or chemicals (12) were developed by industrial R&D departments. Since, as we will show below, the share of the latter classes in the total number of patents considerably increased in the 1880s the growing share of high-value patents was probably caused by the relatively decreasing inventing activity of amateurish inventors.

The uncertainty of inventors, however, cannot be totally reduced. Mokyr points out: "After all, technological change ventures into the unknown, not into the uncertain. The risk cannot be diversified away."[136] That is why firms were still forced to invest in some patents that finally turned out to be worthless to preserve a reasonably high probability to get one of the rare high-value patents. The stable share of high-value patents in the patent population of about 10 percent in the 1890s and early 1900s might imply that the patenting firms had found an appropriate compromise between the goals avoiding costs for low-value patents and keeping the chance to get a high-value patent.

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[135] See Kaiserliches Patentamt, *Geschäftsthätigkeit*, pp. 205-207.

This success rate of ten percent is, of course, not an independent empirical fact but resulted from our decision to define high-value patents as those patents that lasted at least ten years. Nevertheless, it is an interesting coincidence that Pavitt (1991) holds the view that usually about 10 percent of all industrial R&D projects lead to a commercial success.

The boom of high-value patents in the pre-World War I years could be interpreted as an anomaly brought about by the German inflation of the post-World War I years. Table 6.2 shows that in this period the wholesale prices increased much faster than the renewal fees of the patents which means that the deflated present values of the patent costs considerably decreased between 1914 and 1923. As a result more patents could have been judged to be worth to renew than it would have been the case in a situation without inflation.

Table 6.2 Wholesale prices and renewal fees during the German industrialization 1914-1923, 1913=100[a]

Date	Wholesale prices	Renewal fee for the 10th year
1914	105	100
1915	142	100
1916	152	100
1917	179	100
1918	217	100
1919	415	100
1920	1,486	100
June 1921 / July 6, 1921[b]	1,428	156
June 15, 1922 / June 27, 1922[b]	6,775	667
November 25, 1922	122,919	3,333
March 24, 1923	482,700	46,667
July 10, 1923 / July 9, 1923[b]	4,864,400	222,222
Sept. 4, 1923/Sept. 2, 1923[b]	298,153,200	11,111,111
Oct. 30, 1923 /Oct. 29, 1923[b]	1,865,850,000,000	69,111,111,111

a Statistisches Reichsamt (ed.), *Statistisches Jahrbuch für das Deutsche Reich* (Berlin 1923), pp. 284 f. *Blatt für Patent-, Muster- und Zeichenwesen*, various years.

b The first date refers to the wholesale prices, the second to the renewal fee.

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[136] Mokyr (1990), p. 284.

A detailed analysis of the annual mortality rates of the patent cohorts 1902 to 1924, depicted in table 6.3, however, shows that this inflation story is wrong. The rows of table 6.3 show the annual mortality rate of a particular patent cohort during its life span. For example, the number 17.4 in the upper left cell means that of all the patents first granted in 1902 only 82.6 percent were renewed at the beginning of the year 1903. Of those prolonged patents, in 1904 again 26.9 percent were not prolonged. The columns present for different patent cohorts the annual mortality rate in a particular age of the patents. Column 1, for example, reveals that the mortality rate of the patent cohort 1902 was in the first year higher than the respective rate of the patent cohort 1903 that was only 15 percent. In table 6.3 the years 1915 to 1918 were coloured grey. So we can easily see that with respect to both the columns and the rows the annual mortality rates already decreased in 1915, kept their low level during the whole First World War, but increased again during the years of high inflation. This sharp drop in mortality rates resulted from a governmental decision to exempt the patentees from the renewal fees during wartimes.[137] Obviously, a lot of patentees that would otherwise have decided to give up their patents took the chance to prolong them for free thereby creating the boom of high-value patents between 1910 and 1917. This behavior very well goes with our basic assumption that the increasing renewal fees were the major reason for a patentee's decision not to prolong his patent.

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[137] See Bekanntmachung, betreffend vorübergehende Erleichterungen auf dem Gebiete des Patent-, Gebrauchsmuster- und Warenzeichenrechts vom 10. September 1914, *Blatt für Patent-, Muster- und Zeichenwesen*, (1914), p. 290, Bekanntmachung, betreffend weitere Erleichterungen auf dem Gebiete des Patent- und Gebrauchsmusterrechts vom 31. März 1915, *Blatt für Patent-, Muster- und Zeichenwesen*, (1915), p. 118.

Table 6.3 Mortality rates of the patent cohorts 1902-1924 in year t of their life span, in percent of the patents still alive in the preceding year (the years 1915-1918 marked grey)[a]

Cohort	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1902	17,4	26,9	27,5	24,5	21,8	23,0	19,3	16,9	14,2	15,7	15,6	18,6	18,4	9,7
1903	15.0	24.4	25.7	24.3	24.0	22.4	17.2	19.5	16.3	18.3	17.5	16.3	16.7	9.6
1904	14.1	22.6	26.6	26.9	23.2	20.4	18.1	15.6	17.0	27.7	26.4	10.3	7.2	24.0
1905	14.2	25.5	28.0	27.7	23.3	19.9	17.1	18.1	24.3	24.9	11.1	6.0	8.4	45.2
1906	15.1	28.4	28.4	26.7	23.2	19.6	18.3	24.6	26.4	10.4	4.9	10.3	18.6	30.3
1907	15.7	26.7	27.8	24.0	20.8	19.5	24.0	25.3	10.6	3.6	6.1	8.0	17.4	31.4
1908	15.5	25.2	26.1	24.0	19.8	28.7	23.1	8.9	3.1	11.4	9.4	15.8	26.8	29.0
1909	15.4	22.8	24.3	24.3	27.4	21.0	14.1	3.9	11.0	20.6	23.8	24.5	40.4	47.6
1910	14.6	22.4	24.5	32.3	29.5	5.7	2.9	7.2	11.3	15.6	27.3	19.0	23.9	16.5
1911	15.5	24.2	34.4	24.3	6.0	3.9	7.5	13.6	19.2	31.8	19.7	26.4	24.7	9.7
1912	15.1	36.1	22.5	6.2	3.1	5.1	14.1	23.4	35.8	15.9	37.8	36.6	10.9	7.8
1913	16.5	30.1	5.4	3.3	6.1	9.3	20.6	34.2	18.3	22.6	28.8	19.2	20.1	12.5
1914	10.8	15.9	3.8	3.3	11.4	13.1	37.9	17.7	23.4	23.3	11.1	17.0	15.6	10.9
1915	9.2	7.4	2.7	5.0	20.9	31.0	19.9	28.6	25.3	17.6	16.7	12.7	16.1	13.3
1916	6.7	3.7	4.3	13.3	28.1	28.5	25.5	31.9	21.5	19.5	15.7	17.2	22.4	22.1
1917	6.3	3.5	13.2	27.3	24.7	32.2	43.1	23.0	25.2	20.3	24.7	28.3	39.5	39.4
1918	0.8	1.4	8.7	25.4	23.1	24.7	41.1	28.7	18.1	17.0	17.9	18.5	22.6	32.6
1919	0.3	5.3	20.0	22.8	21.4	35.3	22.5	28.3	15.7	17.8	18.7	21.2	30.0	19.1
1920	1.2	11.2	15.5	21.2	31.5	21.9	15.7	13.0	13.7	17.1	17.3	25.5	17.2	20.5
1921	1.5	8.8	17.1	32.0	24.5	18.9	15.9	16.3	19.3	22.5	31.3	20.6	22.2	17.5
1922	1.4	9.8	25.2	22.3	18.9	16.9	17.1	17.8	21.4	30.6	22.7	21.0	13.7	11.3
1923	1.7	13.4	17.2	17.4	16.2	17.6	18.6	20.3	29.0	21.8	21.3	14.2	9.3	9.6
1924	2.4	9.6	13.8	14.8	16.4	18.7	20.4	28.0	23.2	22.2	14.6	21.1	2.1	

[a] Blatt für Patent-, Muster- und Zeichenwesen, various years.

6.3 DATA AND VARIABLES

In the first five chapters of this dissertation, we used only that patents that had survived for more than ten years. In this chapter, we modified our database in order to study patent mortality and survival. The following changes were made to our database.

(1). We focus on patents from four technological classes (chemical, electrical engineering, dyes, and instruments);

(2). We focus on patents registered by patentees from six nations (Germany, USA, England, France, Switzerland, and Austria);

(3). We focus on patents registered from 1879 to 1885 (in total 7 years)[138];

(4). We are no longer bound by the ten-year limitation of survival. We include all the patents that meet the requirements above into our new data bank (no matter in which year these patents died).

Now we discuss these modifications one by one. The patent yearbook lists all patents granted in the preceding years that are still valid. Therefore, we know the life span of each patent when we subtract a patent's birth year from the patent's death year. We decided for 1879 as a starting year of our analysis due to the fact that for patents registered in 1877 and 1878, the residence places of patentees were not recorded in the patent yearbook, thus we do not know the patent's countries of origin.

The patent office assigned a technology class to each patent. In our research, we use four prominent technological classes as examples: Chemical, electrical engineering, dyes, and instruments. These four classes together accounted for 29% of all patents that were renewed for at least ten years (high-value patents).[139] More precisely, during the period 1877-1918, 8.51 % of patents granted in the class of electrical engineering survived longer than ten years, followed by chemical patents (7.22 % surviving more than ten years), dyes (5.61 %) and scientific instrument (4.03%). For the patents in the remaining technological classes, less

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[138] As patents can be maintained maximally for 15 years, the longest-living patents in this new data bank survived till 1900. We would like to extend this data bank (1879-1885) to include patents that were registered after 1885. Yet we do not have the necessary labor to handle the additional work of data compilation.

[139] Please see table 1.1 in chapter 1 for the ranking of high-value patents by technological classes.

than 5 % patents lived for more than 10 years during the period indicated above. As a matter of fact, these four sectors are still pillar industries of the German economy.

Regarding the foreign patents, their representation in the patent pool is of significance, that is about 27 percent of the total high-value patents. The patent yearbook also clearly specifies each patent's country of origin. In this chapter, we use patents from six countries of origin: Germany, USA, UK, France, Switzerland, and Austria, the top six ranked countries that were holding patents in Germany during the period under investigation (see table 6.4 below). Among the high-value foreign patents, those of American origin account by far for the most patents granted in Germany during the period 1877-1914. Their share is 1.6 times higher compared to the English patents, and 1.9 times than the French ones.

Table 6.4 Ranking of foreign patent's country of origin 1877-1914

Rank	Country of Origin	Number of High-Value Patents	Share in All Foreign Patents	Cumulated Shares
1	USA	2,676	28.92%	28.92%
2	England	1,646	17.79%	46.71%
3	France	1,400	15.23%	61.84%
4	Switzerland	892	9.64%	71.48%
5	Austria	782	8.45%	79.93%

Given these circumstances, we could assume that the net returns for USA patent holders were quite high in comparison to the remaining patentees, and thus it paid off to renew the intellectual property right. Additionally, the countries listed in table 6.2 comprise for more than 80 percent of all high-value patents in Germany.

Renewal Rates by Technological Class

The patent renewal rates vary across technology classes and nationalities, respectively. Figure 6.5 to figure 6.10 represent the renewal rates in different technology classes, for each of the six nationalities, which are of significance for the present study. Several features call for our attention. Firstly, we observe that for each technology field and nationality, there is substantial mortality as patents age. About 50 percent of the patents die before reaching the age of five years. This phenomenon indicates a concentration of low-value patents granted in Germany during the period 1877-1888. Additional explanation for those developments could be the fact, that the majority of patentees during the indicated periods were individuals. This in combinations with the high renewal fees led to the above-described situation. Contrarily, Schankerman (1998) finds out that about 50 percent of the French patents registered from 1969 to 1982 drop out before they reach age ten. Those results should be taken into consideration more cautiously due to differences between the German and French protection regulations.

For instance, among the patent holders of German origin the technological class dye comprises for the greatest renewal rate. More precisely, 48.29 % of the dye patents have been renewed after the fifth year, and 33.08 % after the tenth year (see figure 6.5 below). The dye patents held by German patentees have by far the highest likelihood to survive longer period, thus we could assume that the net returns from holding a dye patent were among the most profitable. We observe similar developments for patentees of American and Swiss origin, while for the remaining nationalities, dye patents do not account for the highest survival rates during the period under investigation. Electrical engineering and instrument patents have the lowest renewal rate among the patentees of German origin.

Figure 6.5 Renewal rates in percent, Germany

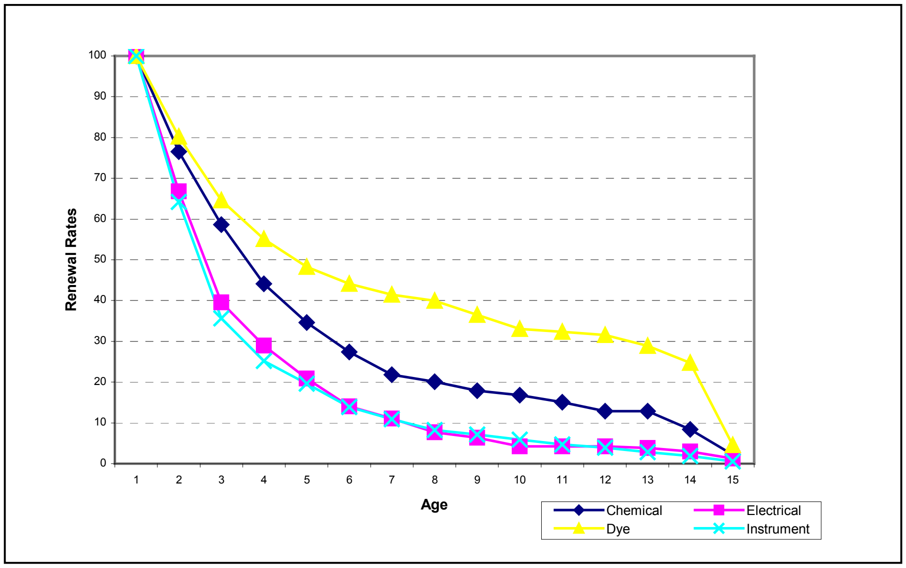
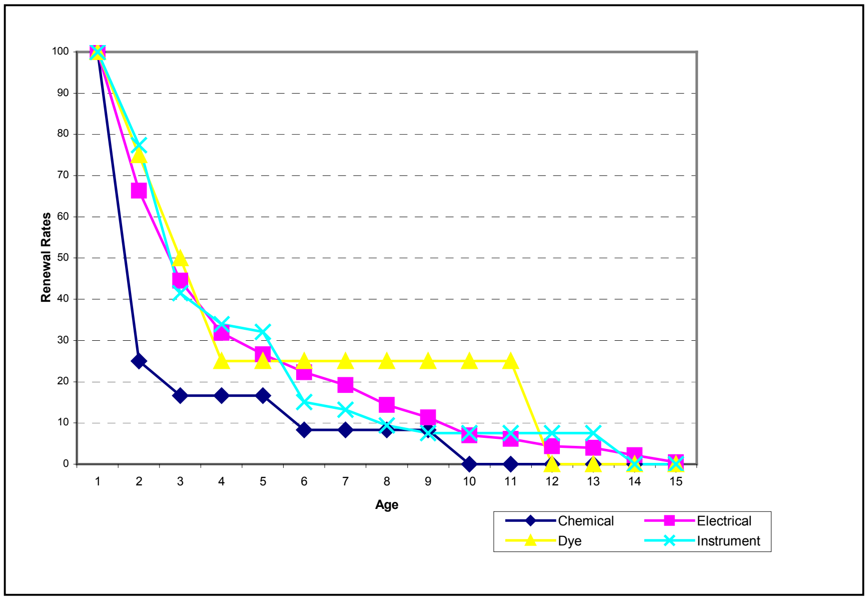


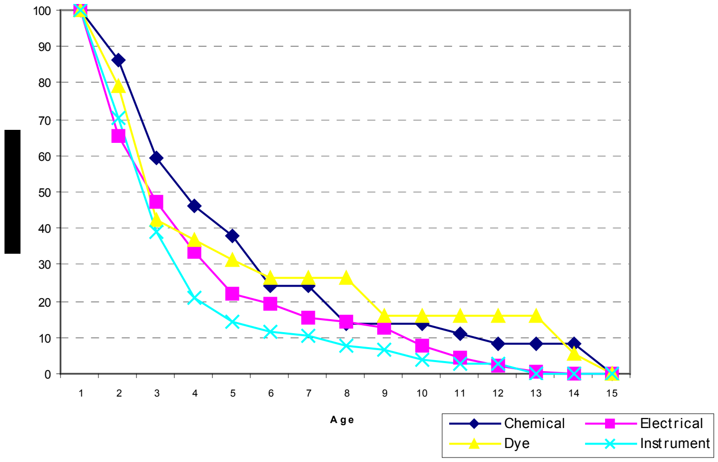
Figure 6.6 Renewal rates in percent, USA



Regarding the American patentees registering in Germany (see figure 6.6), the chemical class indicates the lowest survival rates, in particular, only 25 % of the chemical patents have been renewed after the second year. A possible cause for that development might be the better quality of the domestic patents that might lead to stronger competition in the chemical sector, and lower net returns for American patent holders. The situation among the English and French inventors patenting in Germany differs from the American and German ones. The highest propensities of being renewed within the first four years have the patents in the chemical class (see figure 6.7 and 6.8). In the long term, the greatest chance to survive has the chemical class regarding the English patent holder, and among the French patentees the dye patents.

Figure 6.7 Renewal rates in percent, England

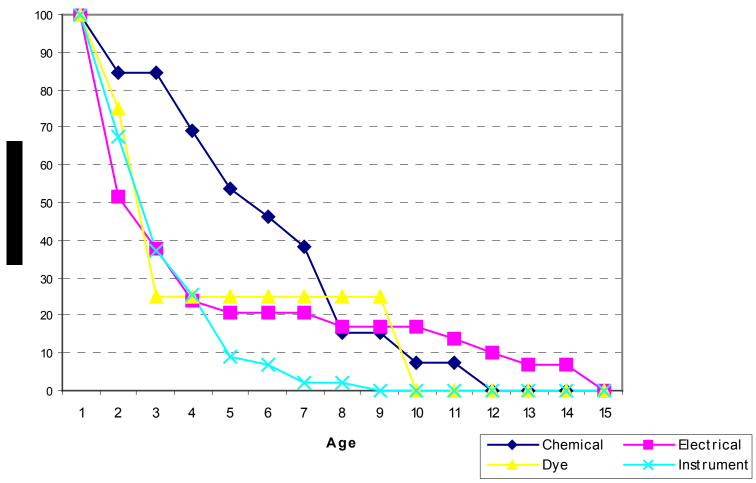
Figure 6.8 Renewal rates in percent, France



As for patent holders of Austrian and Swiss origin, the developments seem to be quite turbulent (see figure 6.9 and 6.10 below). Additionally, for either nationality the worst survival chances have the instrument patents. Electrical engineering patents indicate stable renewal rates after reaching age of four.

Figure 6.9 Renewal Rates in percent, Switzerland

Figure 6.10 Renewal rates in percent, Austria



Secondly, the ranking of technology classes in terms of mortality rates varies across nationalities. Instrument sector has higher mortality rates than other sectors in all six countries. Survival rates for dyes and chemicals are higher than for electrical and instrument industries for Germany, France, Switzerland, and Austria. But it is not the case for the USA and England.

Renewal Rates by Patentee's Nationality

Based on the patentee's nationality, there exist differences in the survival time measured by the median during the period under investigation (see table 6.5). For instance, the highest survival rate indicates patents of Swiss origin, an on the other side foreign patents tend to live out German ones.

Table 6.5 Median survival time of patents from different countries

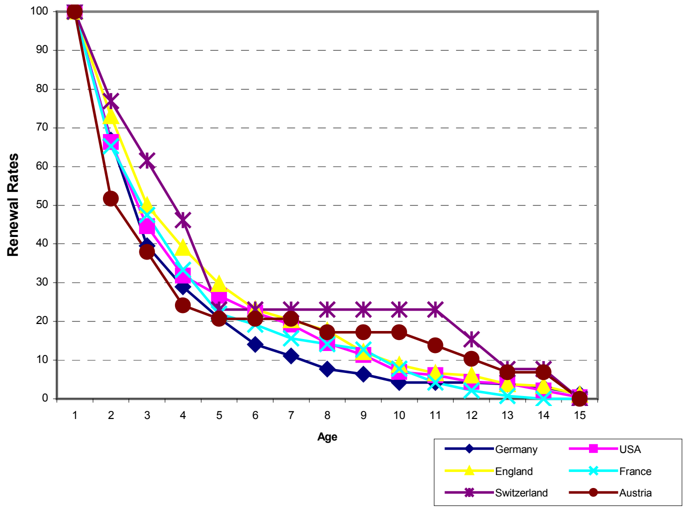
Country	Austria	England	France	Germany	Switzerland	USA
Median survival time	2.70	2.90	2.85	2.76	3.38	2.72

Figures 6.11 to 6.14 illustrate the differences in renewal patterns across nationalities. More precisely, in the chemical technology class, Austrian-owned patents have the highest likelihood to reach age of seven, followed by patents of Swiss, German and French origin. The lowest renewal rate in this technological class accounts for USA-patentees. For instance, only 25 percent of the American-owned chemical patents have been renewed after the first year.

In similar vein, Swiss- and Austrian-owned patents in the electrical class show the highest survival, thus we can imply that those patents pay off the initial investments and yield valuable net returns to their patentees.

Figure 6.11 Renewal rates in percent, chemical

Figure 6.12 Renewal rates in percent, electrical



Additionally, German-owned patents do not stand out except in the dyes sector. In comparison to the Swiss-owned patents in this class, they indicate higher propensity to survival in the long run, e.g. longer than five years. But in the period of five years, Swiss patent holders amount to the greater renewal rates among the six countries of patentee's origin.

Figure 6.13 Renewal rates in percent, dye

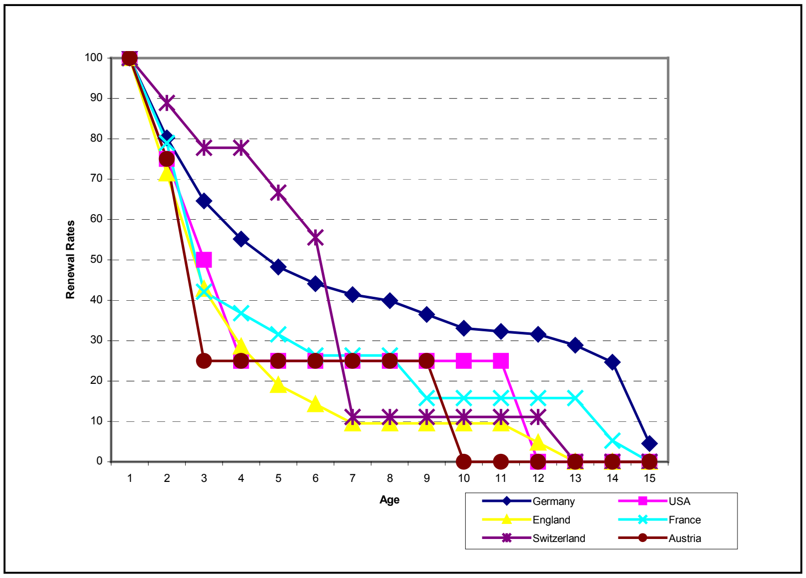
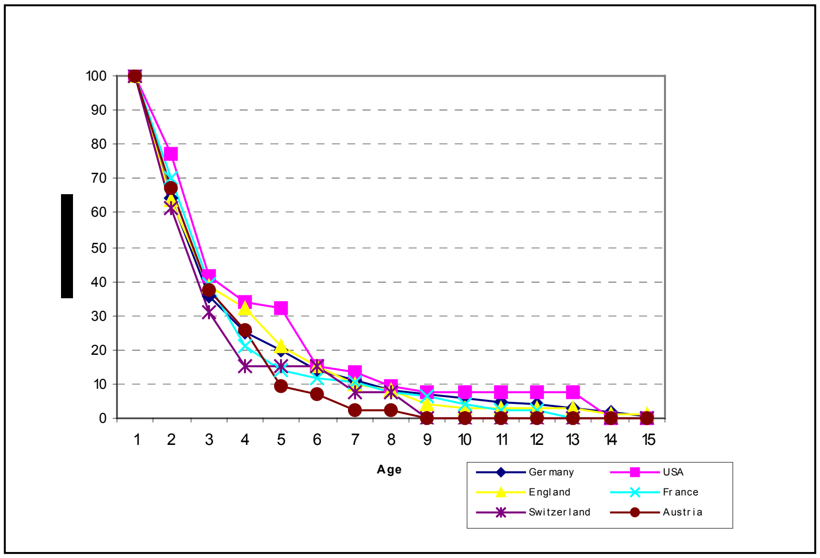


Figure 6.14 Renewal rates in percent, instrument



Finally, USA-patent holders account for better survival chances in the instrument technological class. However, as the slope of the curves (see figure 6.10) depicts, all six countries do not fare well in the stated technology class. The hazard rate in the first three years after granting the patent right is extremely high for all countries considered in the analysis. We will apply next econometric techniques to explore what are behind the above-addressed differences.

6.4 METHOD OF ESTIMATION

The techniques of survival analysis or event-history (Blossfeld, Hamerle and Mayer 1989; Blossfeld and Rohwer, 1995) are used to test the outlined theoretical arguments. More precisely, to maintain intellectual property protection the patentee has to pay a particular annual renewal fee, otherwise the patent lapses permanently. The renewal fees following the German Patent Law alter with age and possibly with the cohort of the patent. The basic assumption of the patent survival model is that renewal would take place if the cost of renewal were less than the discounted expected revenue steam obtained by that renewal process, otherwise the protection assured by the patent right would lapse. In this context, the variable of interest in the analysis of patent survivals is the length of time that elapses from the beginning of intellectual property protection either until its end (liquidation) or until the measurement is taken into consideration (censoring), which may precede termination. The process under observation may have begun at different points in time; therefore, censoring is a pervasive and usually unavoidable problem in the analysis of duration data. In the present analysis, we apply right censoring, which requires us to take year 1888 as event year (as the average survival time of patents is three years).

In modeling survival likelihood of patents' survival, the quantity of fundamental interest is the so-called hazard rate, which can be defined variously as:

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr(T \le t + \Delta t \mid T \ge t)}{\Delta t} = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{S(t)} \qquad (1)$$

where t denotes time, T is the random variable for the time of the event and $f(t), F(t)$ and $S(t)$ depict the density, cumulative distribution, and the so-called survival probability respectively.

The quantity $\Pr(T \le t + \Delta t \mid T \ge t)$ in equation (1) gives the probability of having the event (patent lapse) between time t and $t + \Delta t$, conditional on yet being accounted. Hence, this quantity provides the probability that the event will emerge between "now", as indexed by t, and some time in the future, as indexed by $t + \Delta t$. For event appearing in conditional time, it is desirable to define over all possible positive denoted by the limit in (1).

The hazard rate, however, is more interesting to be modelled than the survival rate of the density. Various model specifications can be applied for this purpose. Therefore, for reasons pertaining to the theory on the one side, and on the other due to the data set used in the present study, the Cox's proportional hazard model represents significantly the data on patents granted versus not been renewed in Germany during the period 1879-1888. Moreover, models such as the log logistic, the Weibull and the exponential respectively have been estimated. Sometimes theory provides ground to motivate a particular choice, but more often practical considerations underlie these choices. Unfortunately, estimated effect of covariates can vary across different functional forms, complicating matters for the analysis. One reason for this sensitivity is that the models differ in their specification of time variation in the baseline hazard rate.

In the single transaction case, the Cox's model is not based on any assumption concerning the nature or shape of the underlying survival distribution. The model assumes that the underlying hazard rate is a function of the covariates; no assumptions are made about the nature or shape of the hazard function. Thus, in a sense, Cox's regression may be considered to be a nonparametric method. The model of estimation may be written as:

$$h\{(t),(x_1,x_2,\ldots,x_n)\} = h_0(t).\exp(\beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n) \qquad (2)$$

where $h(t,\ldots)$ denotes the resultant hazard rate, given the values of the n covariates for the relevant case $(x_1,x_2,\ldots,x_n)$ and the respective survival time (t). The term $h_0(t)$ indicates the baseline hazard rate; it is the hazard rate for the respective patent when all independent variable values are equal to zero. $\beta_1,\beta_2,\ldots,\beta_n$ are the regression coefficients to be estimated.

We can linearize the model by dividing both side of equation (2) by $h_0(t)$, and then take the natural logarithm of both sides:

$$\begin{aligned} h\left\{(t),(x_1,x_2,\ldots,x_n)\right\}/h_0(t) &= \exp(\beta_1 x_1+\beta_2 x_2+\ldots+\beta_n x_n) \\ \log\left[h\left\{(t),(x_1,x_2,\ldots,x_n)\right\}/h_0(t)\right] &= \beta_1 x_1+\beta_2 x_2+\ldots+\beta_n x_n \end{aligned} \tag{3}$$

While no assumptions are made about the shape of the underlying hazard function, the model equations shown above do imply two assumptions. First, they specify a multiplicative relationship between the underlying hazard function and the log-linear function of the covariates. In practical terms, it is assumed that, given two observations with different values for the covariates, the ratio of the hazard functions for those two observations does not depend on time t. Second, there is a log-linear relationship between the independent variables and the underlying hazard function.

Additionally, when examining the explanation strength of the covariates that are included in the model, likelihood theory provides straightforward test for determining the best model for the observed data and for comparing parameter values among different treatments. Both types of tests are carried out by calculating the differences of the log-likelihood obtained under a constrained null hypothesis from the value obtained under a less constrained alternative hypothesis. The magnitude of the difference is estimated under the null hypothesis and the value of under the alternative describes the strength of the evidence again the null hypothesis. Significance tests are carried out by noting that has a distribution with degrees of freedom (df) equal to the number of additional constrains in the null hypothesis. This method is sufficiently general to provide test of hypotheses that least-squared methods (including non-linear regression) do not allow.

Finally, Cox proportional-hazards regression allows analyzing the effect of several risk factors on patent survival. It provides information whether the patent survival rate is influenced in a positive or a negative way by the independent variable(s). As it fits our research objective and on the other side the proportional assumption holds for the data set employed, we use the Cox regression to perform a survival analysis. In our model, the hazard indicates the probability of a patent to die after a time t. The data on patent registration is available for the birth years from 1879 to 1885. Correspondingly, the death years are from 1880 to 1888. We use the year 1888 as an event one. Moreover, two model specifications are estimated: First, we explore the impact of different technology fields on survival of patents, while distinguishing between foreign and German patent holders. Among the patents with different countries of origin, we use foreign patents as reference group. The econometric specification of the model is as follows:

$$\begin{aligned}&\log\left[h\left\{(t),\left(x_{german},x_{chemical},x_{electrical},x_{dye},x_{patentee}\right)\right\}/h_0(t)\right]=\\&=\beta_1 x_{german}+\beta_2 x_{chemical}+\beta_3 x_{electrical}+\beta_4 x_{dye}+\beta_5 x_{patentee}\end{aligned} \tag{4}$$

where x_{german} is a dummy indicating that the patent holder is of German origin. $x_{chemical}$, $x_{electrical}$, and x_{dye} are covariates indicating the influence of the particular technological class on the hazard rate. $x_{patentee}$ is a dummy estimating the effect on survival cause by the nature of patentee, individual versus firm.

Second, we examine the survival likelihood among all six countries of origin accounting for technology diversity (instrument industry serves as a reference group among the technology classes), while we distinguish between individual and firm as a patentee.

6.5 EMPIRICAL RESULTS

6.5.1 Test for Proportional Assumption

The Cox proportional hazard model is based on the assumption that the effects of given two observations with different values for the independent variables, the ratio of the hazard functions of those two observations are constant over time. Does this assumption hold in our case? Before we proceed with survival analysis employing the Cox model, we will first test for the proportional assumption. The above indicated test is conducted for both German and foreign patent holders and the results are depicted in table 6.6. Additionally, we distinguish between individual and firms as a patentee.

Table 6.6 Test for proportional assumption of German and foreign patents

Patents held by German firms			Patents held by German individuals		
	Coefficient	Significance		Coefficient	Significance
Test	0.032	**0.698**	Test	0.032	**0.698**
Foreign	0.019	0.717	Foreign	0.019	0.717
Individual	0.036	0.568	Firm	-0.036	0.568
Chemical	-0.407	0.000	Chemical	-0.407	0.000
Dyes	-0.693	0.000	Dyes	-0.693	0.000
Electrical	-0.178	0.002	Electrical	-0.178	0.002
Log-likelihood	27305.063		Log-likelihood	27305.063	
Chi-square	86.848		Chi-square	86.848	
Significance	0.000		Significance	0.000	

Note: The reference group regarding the technological classes included in the analysis is instruments.

In testing this proportional assumption, the null hypothesis that the effects are constant cannot be rejected, as the test variable including in the analysis is insignificant. Thus, we can go further to apply the Cox regression.

6.5.2 Factors Influencing the Survival of Foreign and German Patents

We have shown in a descriptive manner above that foreign patents tend to survive longer than German patents. This outcome is well expected as the patent registering procedure for patentees of foreign origin involves extra administrative bureaucracy such as contacting an intermediary representative in Germany, and as a consequence of it, the foreign holder has to anticipate higher fix costs prior to patent granting. Given that foreign patentees face higher costs than German patentees, it hypothesizes that the foreign patent has higher returns in comparison to the German ones in general. Thus we can conclude that the decision-making process regarding the patent application of non-German origin is well thought-out assuming the costs, which have to be paid, and on the other side, the quality of the foreign patents has to be better.

Does the country of origin, foreign versus German patentee, have an impact on the patent mortality rates? Two different econometric specifications of the Cox's proportional hazard model have been estimated. First, we distinguish between foreign and native patentees, while the group of the foreign ones is taken as a reference in the empirical analysis. Second, we consider the impact of the different countries on the survival rates of patents granted by the German Patent Office. The empirical results are depicted in tables 6.7 and 6.8.

Table 6.7 Cox regression results for the survival of German patents, hazard rate

Covariates Included	**Model with Individual as a Patentee**		
	Coefficient	**Std. Error**	**Exponential Value**
German Patentee	0.019	0.053	1.019
Individual Patent Holder	-0.036	0.062	0.965
Chemical Class	-0.408***	0.082	0.665
Dyes	-0.695***	0.082	0.499
Electrical Class	-0.177***	0.058	0.837
-2 Log-Likelihood	**27305.214**		
Chi-square	**86.675**		
Significance	**0.000**		

NOTE: *** Statistically significant at 1 % level; ** Statistically significant at 5 %; * Statistically significant at 10 %. The reference group regarding the technological class dummies is scientific instruments.

As assumed, the Cox regression results for the hazard rate confirm our hypothesis that patents of German origin do not tend to survive longer compared with these of foreign origin. The relative risk of German patents in comparison to the foreign patents to die is higher and accounts for 1.019. This result should be taken into consideration cautiously due to the fact that the estimated covariate is insignificant. Moreover, patents granted to individuals show better survival likelihood. The estimated hazard for individual patent holders is 0.965 of that of patents granted to firms, that is a 3.5 percent decrease in the risk of death, even though the estimated covariate for the legal status of the patentee (whether it is a firm or an individual) is not significant. One explanation for the better survival chances of individual patentees is the fact that they need highly possible longer tenure to figure out the actual value of the patent, therefore, the lower hazard rate.

The technological class appears to enhance the mortality rates of patents granted in the period under investigation. The dye technology class accounts for the best survival contrasted with the scientific instruments (reference group in our analysis), followed by chemical industry and electrical engineering. The relative risks for the above-addressed technologies are 0.499, 0.665 and 0.837 respectively. In other words, the decline in the mortality rates computed in percentage is 50.1 percent for the dye, 33.5 percent for the chemical, and finally 16.3 per cent for the electrical technology class. The outstanding performance of dye patents is not surprising at all, as in 1900, for instance, the German dyestuff industry held already 90 percent of the global market within that sector (Ziegler, 2000). Additionally, this share indicates a stronger competition among the patentees in the day technological class, which in turn lead to higher renewal rates versus longer survival.

Table 6.8 Cox regression results for the survival by country variation, hazard rate

Covariates Included	**Model with Individual as a Patentee**		
	Coefficient	**Std. Error**	**Exponential Value**
Technological Classes			
Chemical	-0.412***	0.082	0.662
Dyes	-0.693***	0.082	0.500
Electrical	-0.163***	0.059	0.849
Countries of Origin			
Austria	0.152	0.135	1.164
England	-0.012	0.094	0.988
France	0.074	0.096	1.076
Germany	0.097	0.080	1.058
Switzerland	0.025	0.205	1.025

Individual Patent Holder	-0.038	0.063	0.963
-2 Log-Likelihood	**27303.164**		
Chi-square	**88.775**		
Significance	**0.000**		

NOTE: *** Statistically significant at 1 %; ** Statistically significant at 5 %; * Statistically significant at 10 %. The reference group regarding the technological class dummies is scientific instruments, and United States for the country ones.

While including country dummies in the Cox regression analysis, the already discussed above results do not change considerably. For instance, the impact of renewing a patent by individual holder improves slightly from 0.965 to 0.963, but its influence on the hazard rate remains negative and statistically insignificant. Among the countries incorporated in the present study (United States as reference group), the lowest mortality rate has patents of English origin, whilst Austrian patents account for the highest one with comparison to American patents (see the estimated survival functions, Figure 2, Appendix).

Finally, the survival chances of dye patents deteriorated slightly after considering the country of origin effects. The estimated relative risk is 0.500, that is a decline of 50 percent in the mortality rate compared with the scientific instruments. All technology class effects are highly statistically significant.

6.6 CONCLUSION

Using unique German patent data set consisting of 2,563 patents for the period 1878-1888, we aim to provide econometric evidence on the factors that influence the survival of patents for different technology fields and countries of origin in this chapter. Why do some patents die young while others survive longer? What factors are behind the heterogeneity of patent mortality?

The main findings suggest that firstly, patents by German patentees tend to die sooner than foreign patents. Secondly, patents from different countries have different median survival time. For example, patents registered by Swiss patentees tend to live longer than patents from the remaining countries included in the analysis, even though the differences among patentee's country of foreign are not statistically significant in the Cox regression. Thirdly, industry sectors show to impact significantly the patent renewal rate, and dye patents account for the best survival given the scientific instrument as a reference group in our estimation. Fourthly, patents registered by individuals tend to survive patents registered by firms, although the difference is not statistically significant. In total, renewal rates of patents granted by the German Patent Office during the period of 1779-1888 differ regarding technology fields and country of patentee's origin. Nevertheless, further analysis on the private value of the patents is required in order to gain more comprehensive insight.

Finally, one possible implication of our results is the distinction between measures of the quantity and the value of patents. The noise to signal ratio in the patent count as a measure of the value of patents, for instance, is considerable and calls for caution. Lanjouw, Parkes, and Putnam (1996) argue that if they are used properly, patents weighted with renewal data may remove half of the patent counts as a measure of innovation output, a rather considerable improvement. In this sense, our empirical outcomes will enable use to attach weights to patents and to produce weighted patent count indices which are more precise measures of innovative output than raw patent counts, which are very imperfect measures of innovative output.

APPENDIX

Table 1 Mortality table for German patent holders, 1880-1888

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	1411	0	1.0000	0.000
1	1411	0	0.6889	0.3684
2	972	0	0.4415	0.4376
3	623	0	0.3395	0.2613
4	479	35	0.2953	0.1390
5	384	39	0.2597	0.1285
6	301	21	0.2373	0.0899
7	255	23	0.2256	0.0505
8	220	18	0.2192	0.0288
9	196	24	0.2180	0.0054
10	171	14	0.2180	0.0000
11	175	12	0.2180	0.0000
12	145	16	0.2180	0.0000
13	129	28	0.2180	0.0000
14	101	78	0.2180	0.0000

Table 2 Mortality table for foreign patent holders, 1880-1888

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	1002	0	1.0000	0.0000
1	1002	0	0.6966	0.3576
2	698	0	0.4581	0.4131
3	459	0	0.3373	0.3036
4	338	24	0.2763	0.1990
5	255	27	0.2442	0.1231
6	200	18	0.2251	0.0817
7	167	23	0.2135	0.0528
8	136	25	0.2066	0.0329
9	107	30	0.2066	0.0000
10	77	14	0.2066	0.0000
11	63	15	0.2066	0.0000
12	48	13	0.2066	0.0000
13	35	15	0.2066	0.0000
14	20	16	0.2066	0.0000

Table 3 Mortality table for Austrian patents

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	90	0	1.0000	0.0000
1	90	0	0.6556	0.4161
2	59	0	0.4333	0.4082
3	39	0	0.3111	0.3284
4	28	2	0.2189	0.3478
5	18	1	0.2064	0.0588
6	16	0	0.1677	0.2069
7	13	1	0.1275	0.2727
8	9	1	0.1275	0.0000
9	8	2	0.1275	0.0000
10	6	1	0.1275	0.0000
11	5	2	0.1275	0.0000
12	3	1	0.1275	0.0000
13	2	0	0.1275	0.0000
14	2	2	0.1275	0.0000

Table 4 Mortality table for British patents

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	303	0	1.0000	0.0000
1	303	0	0.7228	0.3218
2	219	0	0.4752	0.4132
3	144	0	0.3696	0.2500
4	112	10	0.2971	0.2176
5	81	9	0.2544	0.1549
6	61	6	0.2368	0.0714
7	51	5	0.2319	0.0208
8	45	11	0.2202	0.0519
9	32	8	0.2202	0.0000
10	24	4	0.2202	0.0000
11	20	3	0.2202	0.0000
12	17	5	0.2202	0.0000
13	12	4	0.2202	0.0000
14	8	5	0.2202	0.0000

Table 5 Mortality table for French patents

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	274	0	1.0000	0.0000
1	274	0	0.7044	0.3649
2	193	0	0.4635	0.4125
3	127	0	0.3175	0.3738
4	87	8	0.2525	0.2282
5	62	5	0.2228	0.1250
6	50	4	0.2135	0.0426
7	44	6	0.2031	0.0500
8	36	3	0.1913	0.0597
9	31	9	0.1913	0.0000
10	22	7	0.1913	0.0000
11	15	4	0.1913	0.0000
12	11	4	0.1913	0.0000
13	7	3	0.1913	0.0000
14	4	4	0.1913	0.0000

Table 6 Mortality table for Swiss patents

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	35	0	1.0000	0.0000
1	35	0	0.7429	0.2951
2	26	0	0.5429	0.3111
3	19	0	0.4286	0.2353
4	15	2	0.3673	0.1538
5	11	0	0.3340	0.0952
6	10	1	0.1933	0.5333
7	5	0	0.1933	0.0000
8	5	1	0.1933	0.0000
9	4	0	0.1933	0.0000
10	4	0	0.1933	0.0000
11	4	1	0.1933	0.0000
12	3	2	0.1933	0.0000
13	1	0	0.1933	0.0000
14	1	1	0.1933	0.0000

Table 7 Mortality table for US patents

Interval start time	Numbers entering this interval	Numbers withdrawing during this interval	Cumulated proportion of survival at end	Hazard rate
0	300	0	1.0000	0.0000
1	300	0	0.6700	0.3952
2	201	0	0.4333	0.4290
3	130	0	0.3200	0.3009
4	96	2	0.2829	0.1229
5	83	12	0.2536	0.1096
6	63	7	0.2450	0.0342
7	54	11	0.2349	0.0421
8	41	9	0.2349	0.0000
9	32	11	0.2349	0.0000
10	21	2	0.2349	0.0000
11	19	5	0.2349	0.0000
12	14	1	0.2349	0.0000
13	13	8	0.2349	0.0000
14	5	4	0.2349	0.0000

Figure 1 **Survival functions by German and foreign patentees**

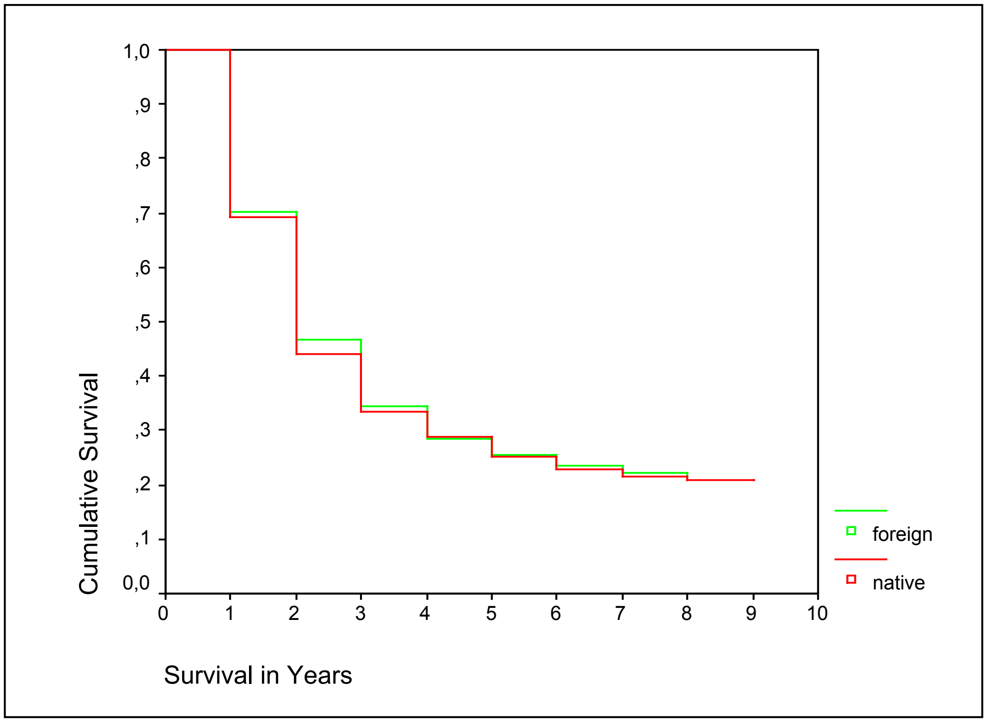
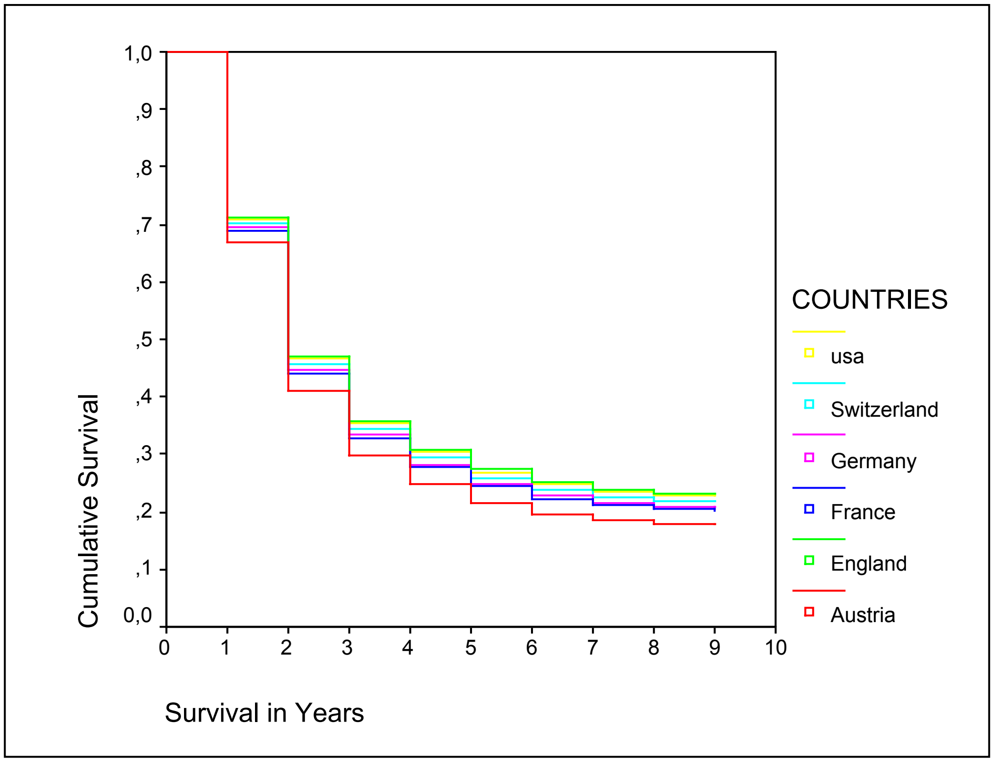


Figure 2 **Survival functions by country of patentee's origin**



Conclusion

This Ph.D. dissertation examines several major aspects of innovation in Germany (1877-1914), a time period when German underwent industrialization. We must acknowledge that our research is by no means conclusive. Though the reader may find this scholarly cliché disappointing or even frustrating, knowing and acknowledging "what we don't know" is the beginning of wisdom, and also a guide to avoid fallacies in public policy.

A few general facts about innovation are relatively clear. Our analysis of patent data confirms a variety of widely held views about the German industrialization. We have successfully identified several waves of patents from various technological classes. Patenting activities had been dominated by railway, dyes, chemicals, and electrical engineering sectors consecutively. The order well corresponds with the industrial development in Germany during the time period. Moreover, we found out that inter-industry knowledge spillovers between technologically, economically and geographically related industries were a premier source for innovative activities during the German industrialization.

In terms of the geography of innovation, we learnt that patents come in the main from the industrial belt that runs from west to east across Germany from the Ruhr area via Berlin to Saxony. We observe convergence of regional patents over time. In general, regions with high human capital and better infrastructure tend to be more innovative. Industrial diversity is conducive to innovation. Knowledge spillovers are geographically bound.

These broad findings seem quite robust, and have policy implications for both public policy-makers and corporate decision-makers on fostering innovation. Innovation policy can be defined as public action that influences technical change and other kinds of innovations. It includes elements of R&D policy, technology policy, infrastructure policy, regional policy, and educational policy.

It is certainly true that the market mechanism and capitalist firms best fulfill most economic functions in a modern society. The private sector has a track record of funding successful innovations over several centuries.[140] In contrast, governments seem poor at

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[140] Kealey (1996) points out that, throughout the nineteenth century, British academics complained about the lack of government support for research and looked jealously at their French counterparts who enjoyed state

allocating money for innovation.[141] Koppel (1995) presents an overview of induced innovation theory. This is the view that consumer demand and the supply of different inputs determine the course and speed of innovation.[142] Koppel's book assumes that the free market can allocate resources to innovations that make economic sense and divert funds away from those that do not. He questions whether political and ethical agendas should supersede economic determinants of the direction of innovation. However, his view treats innovation as a normal commodity and ignores the fact that innovation has unique properties that cause market solutions to be sub-optimal in many cases, an unsatisfactory situation that suggests a possible role for government in fostering innovation.

It is almost indisputable that market should play the premier role in allocating scarce resources. Yet government exists because sometimes it is necessary to complement the market and capitalist firms through public policy. This is true in the areas of defense[143], justice, environment, infrastructure, education, social security, income distribution, etc. After all, there is no pure market economy in the real world, perhaps with Hong Kong (a former British colony) as the only exception.[144] What is at issue here is what should be performed by the state or public sector and what should not. This is an issue that is not only subject to ideological judgments, but could and should be discussed in an analytical way as much as possible.

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subsidized research schemes. Yet, the British economy outpaced the French economy by every measure of growth during that century, and British scientists performed privately-financed, path-breaking basic and applied research. Kealey argues that, although French scientists did important work, their research had little economic impact because the free market did not guide it.

[141] Until recently, Japan's Ministry of International Trade and Industry (MITI) was considered as perhaps the sole exception. MITI had been credited with the Japanese economic boom. It was thought to have chosen winners early on, financed them generously, and created globally competitive Japanese firms. We now know that this is totally true. In the first quantitative study of MITI's allocation of capital to firms, Beason and Weinstein (1996) find that MITI mainly subsidized losers, and that firms that received subsidies from MITI tended to perform worse afterwards.

[142] An example is that the falling price of fertilizer relative to that of rice led to the development of highly fertilizer-responsive rice varieties, which induced the "green revolution" (Koppel, 1995).

[143] A group of individuals might pool their resources to build a missile defense system. But they could not prevent a neighbor, who claims that she has no need for such a system even though she does, from enjoying the protection that they are paying for.

[144] See Friedman (1997) for an argument that the economic freedom in Hong Kong has contributed significantly to Hong Kong's prosperity.

What, then, are the reasons for public policy intervention in a market economy? Regarding innovation, normally two conditions must be fulfilled for there to be reasons for public intervention in a market economy.

(1). the market mechanism and capitalist players must fail to achieve the objectives formulated, that is, a problem must exist;

(2). the state (national, regional, local) and its public agencies must also have the ability to solve or ease the problem.

The term "market failure" came into frequent use by economists during the 20th century. Arrow (1962) clearly articulates the problems with the allocation of resources by market force to invention. The paper emphasizes that, more than most other economic goods, the production of new economic knowledge generally suffers from three sources constituting market failure: indivisibilities and monopoly, uncertainty, and externalities. The first source of market failure emanates from the propensity for knowledge to be a discrete rather than a continuous commodity. As a result, both economies of scale and scope are often associated with the production of knowledge (Mueller and Tilton, 1969). The second source of market failure involves the extraordinarily high degree of uncertainty inherent in new economic knowledge. While virtually every economic good is subject to uncertainty, almost none is exposed to the degree of risk involved knowledge-based new technologies. There are two additional elements of uncertainty inherent in innovative activity that are not present in other goods. The first is in the realm of production. How a new good can be technically produced is typically shrouded in uncertainty. The second element involves marketing the product. Whether a demand for the new product exists is not known. Even if the knowledge can result in a new product, it is not at all clear that the product can be profitably sold. Knowledge leading to a new economic good can be produced, but there is no guarantee that the new knowledge is economic knowledge. Therefore, not only is it uncertain, ex ante, how a particular research project may turn out, but it may also be uncertain, ex post, whether results obtained have interesting commercial possibilities. The market for genuinely new products may not be immediately recognized.[145] Griliches (1979) and Nelson (1982) further argue that

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[145] For example, the fundamental innovation embodied in the now ubiquitous Post-it sticker was essentially an adhesive substance that was not highly adhesive, originally developed by the American company 3M in 1968.

unlike the physical capital, the market prices for knowledge do not exist which could guide R&D investment decisions. Consequently, innovation is especially risky and therefore it is undersupplied.

The third source of market failure stems from the public good nature and non-exclusive externalities inherent in knowledge-based economic activity. The production of knowledge does not preclude other economic agents from applying that knowledge for economic gain. It is difficult to delineate and enforce property rights to newly created knowledge. The externalities associated with the production of new knowledge make it difficult for firms undertaking such activities to appropriate the economic returns accruing from their investment. Therefore, Arrow's paper suggests that there exists under supply of innovations because the social benefits of innovative ideas are bigger than private benefits. Mansfield et al. (1981) report that 60 percent of successful patented innovations were imitated within four years of introduction. For a sample of 100 US manufacturing firms, Mansfield (1985) reports survey evidence indicating that rivals have information about R&D decisions in 12-18 months, and information about new products or processes in 12 months or less. Such leakages occur because input suppliers and customers are important channels (since they pass on a great deal of relevant information), patent applications are scrutinized very carefully, and reverse engineering is carried out. In still other industries, the diffusion process is accelerated by the fact that firms do not go to great lengths to keep such information secret, partly because they believe it would be futile in any event (Mansfield, 1985, p. 221). Sometimes, simply knowing that some lines of research work, while others do not, will allow follow-after firms to carry their own independent work forward more rapidly and at a lower cost than first innovators. Knowledge spillover is not unambiguously bad, from a social point of view. But it does reduce the incentives of firms to invest in innovation.

After identifying these three sources of market failure, Arrow (1962) concludes that government should play a role in innovation.[146] Other scholars have identified more sources

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The product was not introduced into market until 1980, 12 years later. For more information, see URL http://www.3m.com/about3M/pioneers/fry.html.

[146] World War One brought home to every government involved the importance of having its armed forces equipped with the most advanced scientific techniques. Since then it has been generally accepted that it is frequently desirable to encourage research and development for reasons of economic growth as well as national security. Arrow wrote his paper five years after the Soviet Union launched the artificial satellite Sputnik and

of market failure in generating innovation. For instance, there are a set of reasons to believe that financing investment in innovation is subject to market failure owing to a combination of asymmetric information and moral hazard under uncertainty.[147] Similar arguments may also apply to investments in human capital and can be used to make the case for subsidies to various forms of education and training. Moreover, some have argued that certain industries are "strategic", in the sense that they are either important for national security, or for advances in many other industries. This might imply targeting of research subsidies towards such industries. Finally, it is fair to say that technological standards (even those as simple as weights and measures) are a public good, and will therefore often be subject to government policy. This fact has the obvious implication that investment in standards will face the same tradeoffs as other innovation investments: either insufficient incentives or monopoly provision. Either outcome has welfare consequences.

Can government facilitate innovation by adopting sensible government policies? To a certain extent, it can. As market does not have the omnipotent power in managing innovation, we need innovation policy. One implication of endogenous growth model is that economic policies, such as R&D subsidies, can affect long-term economic growth.[148] Because of technology's contribution to economic growth, technology promotion is now an important element of state's economic development initiatives (Coburn and Berglund 1995). As a matter of fact, innovation policy is now an integral and important part of public policy in most industrialized nations. For instance, the transformation of Ireland from a relatively

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inaugurated the Space Age. The Soviet success threw the US government into crisis. The Sputnik crisis was a turning point of the Cold War. Shocked by the Soviet success (which is aggravated by the Cold War atmosphere), the US federal government started infusing money lavishly into R&D efforts. In the years prior to Sputnik, the US's investment in R&D as a percentage of the GDP stood at approximately 1.5%. Private sector investment represented nearly half of that total. By 1964, total R&D spending reached nearly 3.0% of GDP with nearly two-thirds funded from federal coffers. For 1959, the US Congress increased the National Science Foundation (NSF) appropriation to $134 million, almost $100 million higher than the year before. By 1968, the NSF budget would stand at nearly $500 million. The US government also initiated some educational programs to foster a new generation of scientists and engineers. In 1969, the Pentagon started building a computer network project called ARPANET (mainly for military use), which would later turn into the Internet. See Dickson (2002) for the various effects of the Sputnik shock. Today the US federal government remains the largest supporter of R&D activities in the world, although compared with other countries, the US invests a large share of its R&D fund for military use (which has spillover effect on civil activities).

[147] See Hall (2002) for a survey of evidence and the policy solutions.

[148] See Poot (2000) for a survey of literature on the impact of government policies on long-run economic growth.

backward country into a rich, high-tech state leads many countries to imitate. The success story of Ireland has been attributed to good policy, good timing and good luck.[149] In the United States, innovative regions are prominent and economic boosters make painstaking efforts to promote silicon deserts, farm, forests, and prairies to compete with California's Silicon Valley, Massachusetts' Route 128, and North Carolina's Research Triangle, to name a few. However, most of these efforts have not been very successful.[150] Historians Leslie and Kargon (1997) conclude that there are too many unique factors that created Silicon Valley to ever duplicate its success.[151] Although this claim might sound disappointing, we have to accept the fact that innovation is a rather complicated process. It is not the product of lone individuals nudging technology forward, but encompasses a broad landscape of many interdependent people, firms, and institutions working within networks of social and economic relations (Arthur, 1989; Nelson and Wright, 1992). An understanding of the conditions that advance the innovative capacity of regions and nations is slowly emerging. Innovation is ubiquitous. The regional innovation approach evolves around the fact that one can expect to find regional innovation systems everywhere. Therefore, although it is not clear to what extent we can generalize from this case study of German regions, we should be able to draw some policy implications from this research.

The conventional menu of innovation policy responses to the presence of market failure is the following: (1). internalize the externality, (2). tax or subsidize the activity, or (3). regulate the activity. In this arena, the last option is rarely used, perhaps because of the difficulty of regulating an activity that is still highly unpredictable and spreads across a very large number of actors. It is difficult to argue that quotas (mandating technological performance) or price controls (on the wages of scientists and engineers) would be an effective way to deliver more innovation cheaply. Perhaps the only area where the regulatory

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[149] For the case of Celtic Tiger (a nickname for the Republic of Ireland during its period of rapid economic growth after the 1990s), see Sweeny (1999). Opinions vary about the extent to which the Irish growth is sustainable and whether it has alleviated poverty, increased inequality, or indeed done both. See Battel (2003) for a detailed discussion of various opinions.

[150] For German government's efforts, see Dohse (2000). For British government's endeavors, see DTI (1999).

[151] Becker (2000) even claims that government subsidy and intervention thwarts innovation. On the contrary, he argues that it is people's genuine entrepreneurship and liberal economic environment that fosters innovation ultimately.

approach is used in an affirmative way to encourage innovation is in the determination of technological standards.

The second option, the policy of encouraging private R&D expenditure via tax credits and/or subsidizing R&D projects, is used sometimes. This type of policy requires taxation at some level to sustain it, which may have its own welfare costs. Moreover, direct public subsidies for private R&D run the risk that government-funded R&D will simply pay for the R&D that the private sector would have paid for in any case.

In the case of innovation (unlike pollution), the externalities that result from market failure are usually positive and involve the spillover of information and ideas from the entity that paid for them to other entities. Internalizing the externality implies designing a mechanism whereby the inventor receives the social surplus from his or her invention in order to induce him or her to make it. This can be done either by allowing firms to form joint research ventures without the antitrust enforcement, or by granting an individual or firm a limited right to exclude others from using its ideas, that is, by granting it intellectual property protection in the form of patent on its invention.

To be specific, we put a few examples of innovation policies in table 1. The list is by no means exhaustive. Yet it does give us some concrete, common policy measures.

Table 1 Domains and common measures of innovation policies

Policy domain	**Measure**
Fiscal/financial	corporate taxation and subsidies
Information/education	technical training, library, database
Organizational/political	international cooperation
Infrastructure	railway investment
Legal/regulatory	patent laws
Science and research	research labs
Industrial/commercial	trade agreements

How well do these policies function? To answer this question, considerable efforts have been devoted to the evaluation of the effectiveness and efficiency of innovation policy. Some of these efforts have resulted in more conclusive evidence than others. For instance, Hall and van Reenen (2000) find that the level of industrial R&D is positively influenced by the existence of R&D tax credits, although whether the tax credits reduce the gap between the social and private return to R&D is less clear. The productivity of direct government R&D subsidy is more controversial, with large but very diffuse benefits seen in the hard-to-measure areas of basic scientific research, and considerably more mixed evidence on the social benefits of funding research nearer to commercialization (David et al., 2000; Klette et al., 2000).[152]

The results of our research show that both education and infrastructure have great impact on innovation. And the effects are statistically significant. Thus, in order to boost regional innovativeness, governments should be committed to education and infrastructure. Lucas (1988) showed that the private return of investments in human capital is inferior to the social one. So, as we have argued human capital is a relevant driver of innovation and economic growth, public intervention is very probably needed in this field. Our research also shows that capital intensity is closely related to innovativeness. One implication is that government can provide support for technology financing to boost regional innovativeness. The association between firm size and innovation is not conclusive in this research. There is no firm evidence that regions with big firms tend to innovate more. Thus, our research results do not lend powerful support to some governments' mania of big firms (such as Korean chaebols), at least from the viewpoint of innovation. Nor do our outcomes back up the "small is beautiful" thesis as put forward originally by Schumacher (1973). Our research results are echoed by other researchers. For instance, Poot (2002) argues that human capital policies that focus on education, on-the-job training and policies that enhance regional infrastructure are likely to be more effective in knowledge economy than tax cuts or local demand stimuli.

Innovation is an extremely complicated subject. This Ph.D. dissertation is a rather comprehensive study of innovation in the German context. It has investigated innovation at various geographic units: Baden region (chapter 4), Prussian regions (chapter 2 and chapter 5), German cities (chapter 3), and German regions (chapter 1). And it has examined various topics: spillover (all chapters except chapter 6), clustering (chapter 1, chapter 3, and chapter

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[152] For a survey of earlier evidence on this topic, see Hall (1996), and for a proposal to improve the evaluation of government R&D programs, see Jaffe (2002).

4), regional convergence of patenting activities (chapter 2), determinants of innovation (mainly chapter 2, chapter 3, and chapter 4), and patent survival (chapter 6). Yet still, the dissertation is by no means conclusive or exhaustive. So many meaningful works remain to be done. In future, we will strive to contribute more to our understanding of innovation policy with our empirical research. The economic return to innovation is surely an intriguing topic worth exploring. We will use firm's market value to study this subject. The private value of patent protection for different technology fields is also a fascinating subject. As we have already compiled patent survival data, we are well positioned to do further research on this issue. It is our sincere hope that our research helps to further our understanding of innovation, an interesting and important subject whose truth takes prodigious genius and endeavor to discover.

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