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Analyzing the Innovativeness of German Firms during the Second Industrial Revolution (1877-1932)

(This paper is an application for the ISS-prize)

Harald Degner

(University of Hohenheim)

Jochen Streb

(University of Hohenheim)

Abstract

Using a dataset covering every long-lived patent granted to German firms between 1877 and 1932, this paper investigates the determinants of German firms' innovativeness during the Second Industrial Revolution. Several regressions reveal that a firm´s innovative experience has a persistent, highly-significant positive impact. Because different firms have different innovative experiences, the capability to innovate at one specific point in time is unequally distributed among them. In fact, the data show an extreme skewness of distribution of valuable patents across firms. Only a few firms accounted for more than 50 percent of all long-lived German firms' patents. To explain this remarkable result, we argue that having developed successful innovations in the past strongly increases the respective firm´s current capability to develop additional innovations.

Keywords: Innovation, Technology, Patents, Experience, Unequal Distribution

JEL-Classification: N73, N74, O3

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Introduction

The Second Industrial Revolution in the late 19th century can be seen as an era of intense technological progress, especially with regard to the chemical, electrical-engineering and machine-construction industries. Chandler (2006) points out the rise of both the chemical and electrical-engineering sectors and their important innovations, such as the technology of synthetic dyes as well as the wireless telegraphy and the telephone.

With respect to Germany's development, Broadberry and Burhop (2010) state that German industrial labor productivity caught up to the British level around the turn of the century. Focusing on the German Empire, Labuske and Streb (2008) show that the international competitiveness of German machine builders was driven by their technological creativity. With these insights in mind, it would be helpful to know what factors influenced innovativeness and, therefore, caused Germany´s rise to a leading industrial power.

As a first step, this paper tries to identify the main drivers of innovation by analyzing several important determinants of the innovativeness of German firms. In contrast to many other studies, which focus on a short time period or a specific region, this paper provides a long-term analysis based on the total number of long-lived patents granted to German firms between 1877 and 1932.

A very interesting finding is that firms' innovative experience has a sector-independent and time-invariant, positive impact on innovativeness. This leads to the hypothesis that, due to different degrees of innovative experience at the firm level, innovativeness should be unequally distributed across firms.

Revealing an extremely skewed distribution of innovations, this paper argues that having developed successful innovations in the past strongly increases the respective firm´s capability to develop the next generation of innovations. This path-dependent upward spiral explains why innovations are very unequal distributed among economic actors.

Literature Survey

a) Determinants of Firms' Innovativeness

Analyzing the determinants of firms' innovativeness provides a variety of possible variables. Most of them are controversial in the literature.

The impact of firm size was discussed years ago and evoked a large debate, summarized by Kamien and Schwarz (1982). Despite the fact that huge databases are available today, the relationship between firm size and innovativeness is still not clear. First, several investigations—e.g., Baten et al. (2007), Audretsch and Acs (1991) and Pagano and Schivardi (2003)—find a positive impact of firm size. Interpreting firm size in a wider context, Smyth (2001) finds a positive impact of a high level of industry concentration, and Nicholas (2003) finds a positive impact of market power. Second, that the impact of firm size may vary across sectors is found by Spoerer et al. (2007), and across size classes by Nahm (2001) and Pavit et al. (1987). Third, whereas Broadberry and Crafts (2001) and Geroski (1990) find a negative impact of firm size, Acs and Audretsch (1988a and b) find a negative impact of market concentration.

The geographical proximity to educational institutions (universities and technical colleges) is an often-discussed factor in the literature. Two aspects are especially important: first, the opportunity for R&D cooperation between firms and universities, as in Powell and Grodal (2006); and, second, the possibility of recruiting qualified employees. Because higher education is particularly important to developing innovations (Aghion, 2008), only universities and technical colleges are taken into account. Based on 2114 observations of Swedish firms between 1998 and 2000 Lööf and Broström (2008) show that cooperation between firms and universities has a positive impact on the innovativeness of producing firms. Anselin et al. (2000) also point out this aspect of university research's spillover. The authors show that such technological transfers have a significant impact only on specific sectors (electronics and scientific instruments). Showing that external R&D has a negative impact on large firms, Kafouros and Buckley (2008) also point out the importance of spillover effects. The authors argue that large firms prefer to rely on themselves and use their own R&D capabilities. Notable is the authors' result that spillover effects contribute more than internal R&D does to the productivity of small and medium-sized firms. Analyzing the patenting activity in 20 OECD countries between 1982 and 2001, Jaumotte and Pain (2005) conclude that innovativeness is driven mainly by the availability of scientists and engineers. Therefore, they find, recruiting capabilities are very important.

The next factor that may influence innovativeness is a firm's access to the capital market. This leads to the question: How do financial constraints influence firms' innovativeness? A firm with better access to the capital market can be more innovative because it will find funding sources more easily than in a financial market dominated by banks. Aghion and Howitt (2005) show that innovative activities require more market-based, risk-prone institutions, and not long-term banking funding. The authors argue that a greater reliance on market finance allows for better screening of innovative projects and less innovative—i.e., less profitable—ones. Hence, through an increase in its capital stock, a joint stock company may find it easier than a partnership firm to secure new capital.

Streb and Kollmer (2010), referring to Neuburger and Stokes (1975), Burhop (2006) and Guinnane (2002) also point out the importance of equity capital, in comparison to debt capital as a source of financing innovation. Working on the pre-1913 Germany, Fohlin (2007) finds that firms often relied on internal funds to finance their project despite a well-established financial system.

Analyzing East and West German firm-level data of the 1990s, Felder et al. (1995) observe only a low negative influence of financial constraints on firms' innovative activity. Freel (2007), however, finds that banks overestimate the risks of innovative activities in comparison to their future returns. Therefore, applications for credit by small, non-innovative firms are more successful. Working with a dataset containing 256 small firms in Northern Britain (1998-2000), Freel concludes that small innovators are more credit-rationed than non-innovative small firms.

Studying Italian firms between 1992 and 2001, Angelini and Generale (2008) find that firms suffering from financial constraints are, on average, smaller. The authors calculate that firms with financial constraints grew between one- and two-percent more slowly than firms without such constraints. Explaining only a small share of the firm's size distribution, Angelini and Generale point out that financial constraints cannot be seen as a major obstacle for firms' growth.

Urbanization is the next important exogenous variable discussed in the literature. Following Sokoloff (1988), a location in an urbanized area—seen as a large market, reachable without transportation costs—could be an incentive to innovate. Brenner and Greif (2006), analyzing

German patent data for 1999, observe much more innovative activity in large cities than in other regions. The authors argue that the higher density of firms in a relatively small area allows those firms to benefit from knowledge spillover. Both aspects—access to a large market and spillover effects, possibly caused by cooperation between firms—explain the importance of urbanization as an exogenous (explanatory) variable. In addition to that, Romer (1986) shows the existence of external effects due to knowledge spillovers between firms. The author argues that the knowledge developed by a firm investing in R&D cannot be kept completely secret or perfectly patented. Hence, externalities follow investments in knowledge creation naturally.

Another factor that may have an impact on the innovativeness of firms is the industrial or sectoral structure of the district in which the particular firm is located. Marshall (1890) sees districts dominated by only one sector's firms as advantageous to the development of innovation. His argument is twofold: First, specialization advantages result from cooperation between firms belonging to the same sector; and second, the specialized labor market in the region creates innovation-friendly conditions.

In contrast, Jacobs (1970) interprets regional diversification as an important driver of innovation. She argues that intersectoral knowledge exchange is an important factor fostering innovation. It is the demand for improvements by many different sectors' firms that leads to a larger number of innovations developed in the region. If a region's firms concentrate on the needs of only one sector, Jacobs argues, fewer innovations would be developed.

These two approaches—regional specialization vs. regional diversification—shape the context of van der Panne (2004). Studying innovative Dutch firms, the author concludes that specialization fosters innovation in a region. Hence, his result—that intrasectoral, more than intersectoral, spillovers lead to innovation—provides support for Marshall's approach. Analyzing patent applications of Swedish firms between 1982 and 1999, Ejermo (2005) reaches the same conclusion. With respect to all firms in their data base Baten et al. (2007) find a positive impact of regional specialization. Concentrating only on small firms, the authors observe that regional diversification has a positive impact on firms' innovativeness.

The relationship between market concentration and firms' innovativeness is also discussed in the literature. Swann (2009) argues that a firm will be innovative if it has, first, the incentive and, second, the opportunity. Swann shows that in the case of perfect competition, firms have strong incentives to innovate, but their opportunities to do so are very limited. A monopolist however, with many opportunities to innovate, has only weak incentives. Although monopoly or perfect competition are rare in the real world, a process of concentration or de-concentration is observable in many sectors. A positive impact of concentration on innovation would cause further concentration (see Swann, 2009).

After Donsimoni et al. (1984) have shown that market structure need not to be exogenous—i.e., that it can be shaped by market actors' behavior—other authors contributed significantly. Bassanini and Dosi (2006) explain why specific technology could dominate the market, and, therefore, a specific firm controlling this technology could also dominate and even hold a monopoly. Using mathematical models such as the Polya urns, the authors show that in cases of fast-changing basic technologies, technological monopolies can often be observed. They conclude that monopolies or market-dominating firms are much more likely than the coexistence of different technologies developed by different firms.

Also closely related to the evolution of market forms is Smythe's (2010) theory that firms sometimes need to reduce competition to implement important innovations. The author argues that firms must merge to be able to realize large capital investments because such investments are too risky and expensive for smaller firms. Examining the great merger movement in the American manufacturing sector (1895-1904), Smythe finds historical evidence that contributes to our understanding of firms' incentive to merge and the role innovations can play in this context.

Last but not least, innovative experience might influence firms' capability to innovate. Investments in R&D originally dedicated to one specific project can also be very useful for further projects. Thinking about both investments in scientific facilities and human capital, the long-term character of these investments are obvious. In addition to some administrative knowledge on the process of patent applications, the availability of both scientific facilities and experienced researchers determines the firm's innovative experience. Consequently, innovation experience cannot be measured by the mere age of firms. Especially, in contrast to its age, a firm's innovative experience can be both accumulated and devaluated over time.

Showing that innovation processes are path-dependent because an innovation often creates a solid base for additional research projects, Cantwell (1989) supports the abovementioned argument. Analyzing the technological creativity of machine-construction firms, Labuske and Streb (2008) measure innovative experience with the help of sector-specific patent stocks that were both accumulated and devaluated over time like real capital. Baten et al. (2007) also show that past innovativeness has a highly significant positive impact on a firm’s present innovativeness.

b) Systemic Approaches

Systemic approaches to explain innovation are another important component that shapes the context of this paper. The literature on regional innovation systems, for example, focuses on regional interactions between market participants and educational/research institutions. Analyzing the Silicon Valley case, Finegold (1999) points out the high level of interdependence among the system’s actors. Even if the nature of the innovation process differs between rather basic research and engineering efforts to solve current problems, Asheim and Gertler (2006) show that the spatial clustering in both cases is observable, allowing the economic actors many different kinds of interactions. According to the authors, two elements of the regional innovation system play an important role: 1) the regional and social codified manner of communication, which cannot be transported over long distances (Polanyi, 1958, 1966), and 2) the high number of interactions among the system’s participants, such as suppliers and competitors.

Analyzing Canadian regions, Doloreux (2004) reaches a different conclusion. The author shows that innovative firms, located in different regions, are very similar, and local cooperation has no significant impact.

Linking the degree of a region’s specialization to the degree of inter- or intraregional cooperation, Cantner and Graf (2004) analyze the German case for the years between 1995 and 2000. The authors conclude that in a region showing a high degree of diversification, a higher share of interregional cooperation—i.e., cooperation with a firm outside that region—can be observed.

Brenner and Greif (2006) also contribute significantly to the topic of regional innovation systems. The authors show that a firm’s innovativeness is not independent of its location. The positive effects, from which firms of a specific region can benefit, lead Brenner and Greif (2006, 37) to develop the so-called theory of “Co-Location.” The authors point out that not all sectors’ firms can benefit equally from these effects. They find that firms in the automotive and electrical-engineering sectors benefit much more than firms in the scientific-instruments sector, for example.

In some cases, it seems to be necessary to distinguish between a regional innovation system and a cluster. Analyzing Northern European regions, Asheim and Coenen (2004) make this distinction very clearly. The authors define a cluster as a region dominated by one sector. In comparison, a regional innovation system can contain different sectors. Therefore, according to Asheim and Coenen, the two elements can co-exist. However, a regional innovation system can cover several clusters.

With respect to sector-specific effects, Malerba (2002) sees sectoral innovation systems as an important concept to explain innovations. The main elements in Malerba's theory are basic technologies, several types of interactions, institutions and learning processes. The author defines a sectoral innovation system as a complex relationship network around both known and new products of a special function. In such a complex network, plenty of different transactions are happening. This approach's main strength is its focus on a specific sector and on the relationships and interactions between the above-mentioned elements.

To compare whole countries, the concept of national innovation systems plays a prominent role in the literature (Stern et al., 2000, for example). For the German case, Grupp et al. (2005) make an important contribution. The authors analyze the relationship between the standard of living and the available human capital, measured by the amount of private and public investment in R&D and by the number of scientists. For the time between 1850 und 1913, Grupp et al. identify a linear impact of human capital on technological progress.

To summarize this subsection, systemic approaches provide important aspects that shape the context of the present paper. Like the education-related variables discussed above, urbanization, and regional diversification play a crucial role in regional innovation systems, while market concentration is important in sectoral innovation systems.

The Data

Measuring the innovativeness of firms is far from trivial. Smith (2006, 152-153) divides his measure of innovativeness into three main categories. The first category contains indicators around the firm's R&D expenditures. Kleinknecht (2002) mentions that these indicators capture only the input side (i.e., the effort) and do not provide any information about the output side (i.e., the success).

Measures using bibliometrical data belong to Smith's second category. Citation-frequency is one of the best-known indicators in this group. Smith (2006) concludes that these indicators measure a science's dynamics rather than innovativeness itself.

The third category covers indicators around patent data. Within this category, the number of patents granted indicates something *new* much better than the number of patent applications does because not every application leads to a patent granted. Another, and probably the most important, advantage of patent data is the fact that they really measure innovative output. Controlling for changes in the patent law, the use of patent data offers the possibility of investigating innovativeness over a long period of time. In comparison to R&D data—especially for the observation period (1877-1932)—the availability of patent data provides another argument for using this indicator.

Interpreting patents as both innovative input and output, Griliches (1990) points out the importance of patent data as an innovation indicator. However, Smith (2006, 160) mentions that patents, in general, probably reflect inventions rather than innovations. Using Freeman's and Soete´s (1997) criterion to distinguish between inventions (the original knowledge) and innovations, an innovation can be defined as an economically successful invention. Hence, only those patents that protect a novelty that also finds success in the market and, therefore, generates monopoly profits or royalties can be seen as valuable patents. This is the output measure we are interested in.

Analyzing the value of European patents, Gambardella et al. (2008) observe a high positive skewness—e.g., the valuable patents are represented by the distribution's right tail. Due to the default of monetary information about a patent's value—in contrast to Gambardella et al. (2008)—alternative estimates must be used to identify the real innovations. Here, Schankerman and Pakes (1986) make an important contribution. They conclude that it is possible to infer a patent's private net value from its lifespan, given a periodic renewal fee to keep a patent in force for one more period.

To measure the innovativeness of firms, this paper uses the Baten-Streb dataset, which contains more than 66,500 innovations between 1877 and 1932 (Streb et al., 2006; Streb at al., 2007; Baten et al., 2007). Following Sullivan (1994), the authors interpret patents with a minimum lifespan of ten years as the valuable patents of the German Empire and the Weimar Republic. Using this criterion, they select 66,500 valuable patents out of the basic population of 800,000 patents granted during this period. This dataset contains information about the name and location of the patent holder, as well as each patent's technological class. The main idea behind this procedure is the fact that in 1877—for the first time in German History—a patent law was enacted providing patent protection valid throughout the German Empire.[2] For this reason, the observation period begins in 1877 and not in 1871, the year the German Empire was founded. It is important to note that the maximum patent protection was for 15 years. To keep a patent in force, however, the patent holder had to pay an annually increasing fee at the beginning of each year—50 Marks for the first year, increasing to 700 Marks for the fifteenth year. Hence, the decision of whether or not to renew the patent was based on a comparison between the patent's costs (the annual renewal fees) and its private returns (monopoly profits and royalties). The most important characteristic of the Baten/Streb dataset—that it contains only those patents with a minimum lifespan of ten years[3]—is consistent with Schankerman's and Pakes' (1986) conclusion that it is possible to infer a patent's private net value from its lifespan.

There is more than one way to measure firm size: by its number of employees, by its revenue or by its capital stock. These three measures, of course, have specific advantages and disadvantages. Possibly more than the other indicators, employment measures the social component of firm size. Especially with respect to local politics, it is both interesting and important to note the number of people that can earn their living because of one specific firm. In contrast, a firm's revenue measures the value of its sold goods. These two indicators of firm size can point in different directions; banks, for example, can often create high revenues with relatively few employees, while mining firms generally employ many more people. Finally, the

[2] For more details, see Seckelmann (2006, 198).
[3] Due to their project's budget constraints, Baten and Streb were not able to identify the exact lifespan of each of the 800,000 individual patents. Instead, they identified only the patents with a minimum lifespan of ten years.

current capital stock may capture, first, the firm's past success and, second, the confidence of the owners and investors in its future success. If a firm has been very successful, it might be easier to find investors to participate in an increase in its capital stock. Hence, planned investments or even a takeover of other firms, financed by an increase in capital stock, is possible only if both old and new investors have confidence in the firm's future.

In this study, firm size is measured by the capital stock because of the better availability of these data. The most important sources are the *Handbücher der deutschen Aktiengesellschaften* from 1896 to 1936, annually documenting information about thousands of firms, both joint stock companies and firms of other legal forms. This source, also used by Kling et al. (2009), provides information about a firm's capital stock on an annual basis. These data, along with the inventories of several firm and state archives, have enabled the establishment of an additional data bank comprising information about the size development of 1418 German firms. It is important to mention that, regarding the capital stock, the lowest observed value is 5000 Marks. Hence, the analysis includes many small firms.

An additional dataset was developed, providing additional information about the annual population per district and the annual number of students per district at both universities and technical colleges. All the data about university students are taken from Titze (1987), who published two important books on the history of education from 1820 to 1944 in Germany, compiling the annual number of students for each university. Titze is considered a reliable source because he took these data primarily from the official data published in the university archives. The data on the technical-college students were taken directly from the colleges' archives and from several specific publications about the development of German educational institutions, often published by the institutions themselves.

The information about both the annual urbanization per district and the number of firms per sector is taken from the statistical yearbook published annually by the German statistical office.

Table 1 provides some summary statistics. The exact construction of the variables will be presented in detail in the next section, discussing the empirical model.

Table 1: Summary Statistics (1877-1932)

Variable	Mean	Median	Std. Dev.
New valuable patents per firm per year	0.267	0	2.985
Capital stock per firm per year (Marks or Reichsmark)	1,090,000	2,600,000	5,090,000
University students per 1000 inhabitants per district per year	1.357	0	1.775
Students at technical colleges per 1000 inhabitants per district per year	0.483	0	0.765
Urbanization rate per district per year	0.484	0.404	0.307
Industrial diversification per district per year	0.478	0.375	0.290
Innovative Experience per firm per year	2.569	0.250	19.13
N = 1418 firms * 56 years = 79,408			

The Model

The following section presents the empirical model in detail. The model tests the different determinants' impact on the innovativeness of German firms between 1877 and 1932. The basic empirical model can be written as

$$INNOV_{it} = \beta_1 SIZE_{it} + \beta_2 SIZESQ_{it} + \beta_3 SIZECUB_{it} + \beta_4 GENHC_{jt} + \beta_5 TECHC_{jt} + \beta_6 CAPMA_{it} + \beta_7 URBAN_{jt} + \beta_8 INDIV_{jt} + \beta_9 MACONC_{kt} + \beta_{10} EXPER_{it} + \beta_{11} SECTOR_{kt} + \beta_{12} YEAR_t + u_i$$

The endogenous variable $INNOV_{it}$ represents the innovativeness of firm i in the year t, measured by the number of new patents granted in the year t. It is important to note that to measure firms' annual innovativeness, we have to use the annual number of new patents granted and not the total number of patents over time.

The size of firm i in the year t ($SIZE_{it}$), the first explanatory variable, is measured by the firm's capital stock in year t. $SIZESQ_{it}$ (size squared) and $SIZECUB_{it}$ (size cubed) are two non-linear terms of firm size that are included in the model. The ideas behind these variables are the following: if for example size squared shows a significant negative impact, the curve, describing the relationship between firm size and innovativeness has a parabolic form with its open side downwards, i.e. it is shaped like an inverted U. This reflects the idea of an optimum firm size. Extending firm size beyond this point (the right wing of the inverted U) would always result in a decreasing innovativeness.

To measure the local opportunity of cooperation between firms and research institutions, two variables are used. The availability of general human capital ($GENHC_{jt}$) is measured by the annual number of students at universities per thousand inhabitants in the respective district j. The variable measuring the availability of technical human capital ($TECHC_{jt}$) is constructed in the same way, only using the number of students at technical colleges instead of at universities. The idea behind this indicator is that it might be possible that firms, needing engineering support, prefer to cooperate with a technical college rather than with a university.

To measure a firm's access to the capital market ($CAPMA_{it}$), a dummy variable is used, realizing the value one if the firm is a joint stock company, and zero otherwise. Hence, the legal form of a joint stock company is used as a proxy to measure a firm's access to the capital market. This procedure is consistent with Aghion's and Howitt's (2005) claim that innovative activities need to be financed by flexible and market-based institutions (stock exchanges) rather than by long-term banking credit.

To cover the urbanization effects, the respective variable ($URBAN_{jt}$) is constructed as the share of district j's inhabitants living in a city with a population of more than 20,000 in year t. To avoid ignoring the possibility that a firm located in a small town can benefit from a large nearby city, it is important to mention that the degree of urbanization was calculated per district, and not per town, in which an innovator was located.

The variable $INDIV_{jt}$ represents the industrial diversification of district j in year t. To calculate this indicator, at the level of all 77 districts, the number of all innovative firms (firms with at least one patent granted in year t) was observed in the respective years. Next, each firm was identified as belonging to a particular sector. The result of this procedure is exact information about the number of innovative firms belonging to a specific sector in each district in every year. Hence, it is possible to calculate the share of every sector's innovative firms at the district level. This information is needed to calculate the variable $INDIV_{jt}$. This indicator is constructed as a Herfidal-Hirschmann-Coefficient (HHC). If a district shows innovative firms of only one specific sector, the HHC realizes the value 1. The more innovative firms from other sectors are in a particular district, the smaller are the HHC's realized values. This indicator is calculated annually for all 77 German districts.

Another exogenous variable in the analysis is $MACONC_{kt}$ measuring the market concentration in sector k in year t. This indicator should capture the possible effect of a concentration process in a sector and is constructed as a dummy variable realizing the value one for all these years, the total number of the sector's firms increased (decreasing level of concentration). Hence, for a decreasing number of firms in this sector (increasing concentration), the dummy variable realizes the value zero. The information about the total number of the sector´s firms is taken from the statistical yearbook, published by the German statistical office.

To capture a firm's innovative experience, the variable $EXPER_{it}$ is used. This indicator measures the innovative experience—i.e., the technological knowledge of firm i in year t. As we saw in the literature review, technological knowledge, like real capital, can be accumulated over time but might also become obsolete. Taking these characteristics into account, we constructed firm-specific patent stocks accumulating the number of valuable patents of this firm over time. Following Labuske and Streb (2008), an annual depreciation rate of five percent is used which implies that the particular knowledge represented by a valuable patent was fully depreciated after 20 years.

To control for sector-specific effects for the six most important innovative sectors—chemicals, machine-construction, electrical-engineering, metal, instruments and mining—dummy variables ($SECTOR_{kt}$) are included in model one, providing an analysis over all sectors. For example, for all firms belonging to the electrical-engineering sector, the electrical-engineering dummy realizes the value one; otherwise, it realizes the value zero. Belonging to a highly innovative sector k—as in one of the four innovation waves discovered by Streb et al. (2006)—can overlay the impact of the different variables and, therefore, cause a bias in the results.

To control for time effects—e.g., general technological progress—it is necessary to include time dummies in the analysis, which are indicated by the variable $YEAR_t$.

Results

The following section presents the results of several panel analyses. In all six models outlined in Table 2, the dependent (endogenous) variable is the annual firm-specific innovativeness, measured by the number of new valuable patents per year.

Table 2: Total and Sector-Specific Panel Analysis of the Determinants of German Firms' Innovativeness (1877-1932)
(Dependent Variable: Annual Firm-Specific Innovativeness)

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Variables / **Sector**	**All**	**Chemicals**	**Electrical Engineering**	**Metal**	**Machine Construc-tion**	**Scientific Instruments**
SIZE (log)	-48,875*	-115,2823***	-19,8066*	4,4846	-1,1828	32,3397*
	(25,3012)	(33,3467)	(10,4414)	(5,7909)	(2,7075)	(17,2962)
SIZESQ (log)	3,3669*	7,9623***	1,3928*	-0,3456	0,0845	-2,2340*
	(1,7443)	(2,1879)	(0,7941)	(0,3890)	(0,2060)	(1,1985)
SIZECUB (log)	-0,0764*	-0,1817***	-0,0320	0,0087	-0,0020	0,0510*
	(0,0396)	(0,0472)	(0,0197)	(0,0086)	(0,0051)	(0,0276)
GENHC	-0,0587	-0,1526	0,0598	0,0350	-0,0140	0,1036
	(0,1045)	(0,3192)	(0,1165)	(0,0284)	(0,0299)	(0,1622)
TECHC	0,1765	0,1242	0,4487	-0,0229	0,0130	0,2995
	(0,1184)	(0,3093)	(0,3256)	(0,0650)	(0,0692)	(0,2411)
CAPMA	-1,3726**	-0,3138	-0,6886	-1,0958***	-1,1649***	-2,2423***
	(0,5564)	(1,4201)	(1,1898)	(0,3505)	(0,3529)	(0,4078)
URBAN	-0,4205	0,1376	-0,1956	-0,2206*	0,1748	-3,8468***
	(0,5252)	(1,4384)	(1,1203)	(0,1238)	(0,2243)	(1,2964)
INDIV	-0,1606	-0,6883	-0,1580	-0,3635***	0,0976	-0,9011**
	(0,1179)	(0,4337)	(0,6548)	(0,1057)	(0,1093)	(0,3516)

MACONC	-0,1666	-1,5397	-	0,3157*	-	-0,4241
	(0,1503)	(1,3380)	-	(0,1770)	-	(0,6379)
EXPER	0,1523***	0,1577***	0,1573***	0,1159***	0,1388***	0,1008***
	(0,0189)	(0,0387)	(0,0189)	(0,0152)	(0,0113)	(0,0342)
Constant	235,9475*	552,9623***	93,7786**	-17,6734	6,9895	-150,1948*
	(121,1455)	(167,15)	(44,5687)	(28,5592)	(11,7401)	(82,7355)
R2 (within)	0,5337	0,4575	0,7928	0,3569	0,2478	0,3509
R2 (between)	0,9151	0,9368	0,9460	0,9406	0,8362	0,1080
R2 (overall)	0,7493	0,7082	0,8775	0,6520	0,4801	0,1852
N	8871	1383	644	1586	3355	335
Hausman	0,0000	0,0000	1,0000	1,0000	0,2939	0,0000
Methode used	Fixed Effects	Fixed Effects	Random Effects	Random Effects	Random Effects	Fixed Effects
Prob > F	0,0000	0,0000	-	-	-	
Prob > Chi2	-	-		0,0000	0,0000	-

Method: Depending on the Hausman specification test result, fixed or random effects panel regressions are used.

***: significant on the 1% level, **: significant on the 5% level, *: significant on the 10% level, Robust Std.-Errors in parentheses

Regarding model 1, covering all sectors, firm size has a significant negative impact. Considering the two non-linear terms of firm size, first, the significant positive coefficient of firm size squared shows that the relationship between firm size and innovativeness has a parabolic form with the open side upwards; second, the negative coefficient of the cubic firm size indicates that the curve, describing the impact of firm size, is again declining after the parabola's right arm, showing again a negative impact. This unusual pattern can also be detected for both the chemical and the electrical-engineering sectors. In model 6, giving the results for the scientific-instruments sector, the complete opposite can be identified. Firm size has a significant positive impact on the innovativeness of this sector's firms. The two non-linear terms reflect that this impact can change into a negative and back into a positive one.

Very interesting are the results for the two education-related variables GENHC and TECHC, measuring the possibility of local cooperation between firms and research institutions such as universities and technical colleges. In total, as well as for the five sectors separately, these variables are insignificant. This surprising result might support the hypothesis that German firms at that time relied more on the knowledge they generated in their own R&D facilities.[4]

With respect to the access to the capital market, which we measure as Aghion and Howitt (2005) by a joint stock company dummy, a highly significant negative impact can be observed. This result holds not only for all sectors together (model 1), but also for the metal, the machine-construction and the scientific-instruments sectors individually. The negative impact of this variable is contrary to Aghion's and Howitt's (2005) findings. In our study, joint stock companies were not more innovative but less innovative than other firms.

The degree of urbanization is mostly insignificant. Only in models 4 and 6, analysing the metal and the scientific instruments sector, does the respective coefficient show a significant negative impact.

The variable INDIV, measuring the regional diversification of innovative firms, shows a significant impact only for the metal and scientific-instruments sectors. Concerning the other analyzed sectors individually, as well as in model 1, which covers all sectors simultaneously, this variable seems to be insignificant. To give the correct interpretation of the negative coefficient found for the metal and scientific-instruments sectors, we have to remember the construction of this variable in detail. If innovative firms of only one sector dominate a specific region, the variable, constructed as Hirschman-Herfindal-Index, realizes the value one. The more innovative firms of other sectors there are in a region, the smaller are the values that the variable INDIV realizes. Hence, the negative coefficient for the two above-mentioned sectors provides the following interpretation: The less diversified a region is, the less innovative are the two sectors' firms located in that area. At least for the metal and the scientific-instruments sectors, this result supports Jacob's theory that regional diversification and not regional specialization creates an innovation-friendly environment.

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[4] Because Baten et al (2007) find a positive impact of local human capital availability for small firms only, the present dataset was subdivided into different size classes. The separate analysis of the 25%, the 50% and the 75% percentile does not confirm the results found by Baten et al (2007). Of course this does not restrain their findings because of the smaller geographical area and the shorter observation period in their analysis.

Probably one of the most important results is the sector-independent, robust positive impact of EXPER. For all analyzed sectors individually, as well as for all sectors simultaneously, the firm's innovative experience shows a highly significant positive impact on its current innovativeness. Hence, this variable is the only one showing a consistent and sector-independent impact. This result leads to the conclusion that the firm's past innovative activity determines its present capability to innovate. Because innovativeness is often not limited to one specific project, a positive influence of the firm's experience is plausible. It is possible that several minor innovations or other major innovations can follow one very important innovation. Hence, following an important patent, other patents may then be granted over time. This result is consistent with Burhop and Lübbers (2010), showing that the number of patents granted to a firm in year t-1 has a positive impact on the respective number of patents granted in year t.

Another reason for the result might be that the exploration of a new technological field does not reveal all the possibilities at the beginning—i.e., before the first patent is granted. Exploring and developing a new technology probably leads, step-by-step, to several ways of implementing the new knowledge. In addition, the firm's decision to invest in R&D—i.e., in scientific personal and facilities—can be seen as part of a larger strategy that extends beyond just one patent. Considering the expense of R&D, which is a long-term investment, from a firm's point of view, the innovative output must not end with the first patent granted.

To summarize the main results so far, except for the scientific-instruments sector, firm size has a negative, if significant, impact on the innovativeness of firms. The significance of the non-linear terms of firm size reflects that the relationship might not be constant. Degner (2011) presents a possible explanation for this changing relationship between firm size and innovativeness over time. The author shows a positive relationship during periods of specific technological booms, followed by periods of decreasing innovativeness due to exhausted technological opportunities in combination with the firm's further growth.

Despite the fact that Baten (2007) finds that small firms benefited from technical and commercial schools in their neighborhoods, the geographical proximity to research institutions cannot be seen as a significant driver of German firms' innovativeness.

As mentioned above, experience—i.e., the firm's past innovative activity—is the only variable to have a sector-independent positive impact on the innovativeness of German firms between 1877 and 1932. This result delivers interesting and important implications to be discussed in the following section.

Further Implications

As shown in the previous section, the innovative experience is an important determinant of firms' current innovativeness. The results show that the highly significant positive impact of this variable is sector-independent, but it can also be detected by analyzing all sectors simultaneously. This finding probably offers far-reaching implications. If the firm's innovative experience influences innovativeness sector-independently, the current capability to innovate at one specific point in time would not be distributed equally among firms, which, of course, have had different innovative experiences. Hence, the unequal capability to innovate should then result in a notable unequal distribution of valuable patents among firms. In the following, the distribution of valuable patents will be analyzed to determine whether such an unequal distribution actually existed in Germany between 1877 and 1932.

It is important to mention that the five analyzed sectors (chemicals, electrical-engineering, machine-construction, metal and scientific-instruments) were responsible for more than 85 percent of all valuable German firm patents between 1877 and 1932. To find out whether this unequal distribution of valuable patents between sectors can also be identified inside sectors, the five most innovative firms in the five sectors will be observed. These five firms' annual average shares of all valuable patents in their particular sectors are presented in Table 3.

Table 3: Annual Average Share of the five most Innovative Firms per Sector in all Valuable Firm Patents of the Respective Sector (1877-1932)

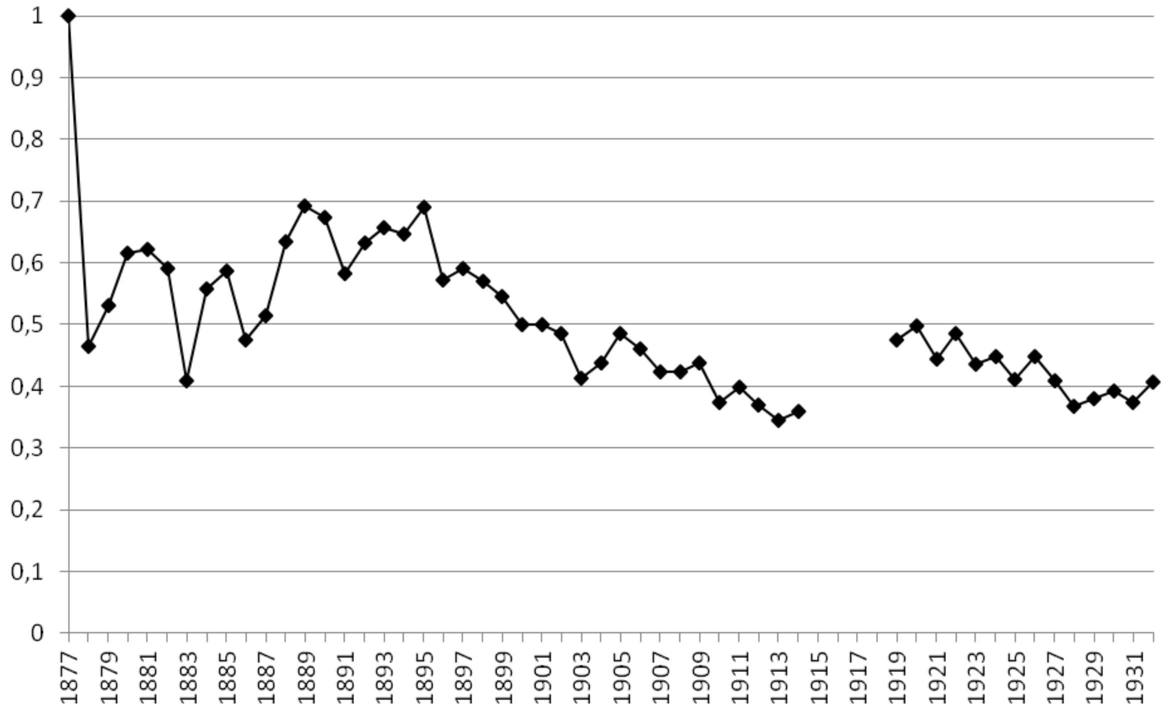
Sector	Annual Average Share
Machine-Construction	30.87%
Electrical-Engineering	82.02%
Metal	55.25%
Scientific-Instruments	75.99%
Chemicals	75.72%

Source: The Baten-Streb database

In Table 3, the very unequal distribution becomes plainly visible. The five most innovative firms in the electrical-engineering sector developed more than 82 percent of all valuable patents granted to this sector's firms. In the chemicals and scientific-instruments sectors, this share was larger than 75 percent, and in the metal sector larger than 55 percent. The relatively small share of 30.87 percent for the machine-construction sector still shows the remarkable inequality; five firms accounted for more than 30 percent of all valuable patents granted in this sector.

To show that the distribution of valuable patents in Germany was highly skewed, the above-mentioned 25 innovative firms (five per sector) will be compared to the total number of valuable German patents granted to all sectors' firms. These 25 firms' share of all valuable patents is given in Figure 1.

Figure 1: Annual Share of the five most Innovative Firms of the five most Innovative Sectors in all Valuable German Firm Patents (1877-1932)



Source: The Baten-Streb database

On average, 50.47 percent of all valuable firm patents were granted to only 25 firms. During the observation period, this share was never below 34.46 percent. Hence, this finding provides strong evidence that the innovativeness of German firms was highly unequally distributed. Such skewness, identified in innovation history based on patent statistics, can also be observed in the field of international trade. Analyzing the 2003 export data at the firm level, Mayer and Ottaviano (2008) show that the largest ten percent of all exporting firms in a country are responsible for 80 percent of its total exports. Interpreting both innovativeness and export ratio as important components of economic success, the very unequal distribution seems to be an even more remarkable phenomenon.

Experience and Skewed Distribution of Innovations among Economic Actors

Our empirical observations suggest that the very unequal distribution of innovations across firms can be explained as the result of a path-dependent process.

Consider the sudden discovery of a new technological field like, for example, the possibility to manufacture synthetic dyes on basis of coal tar in the 1850s. This new technological opportunity[5] might motivate many start-up firms to engage in R&D. In this first round of R&D competition, no firm has a comparative advantage with respect to innovative experience in this new technological field. That is why the chances to innovate successfully are equally distributed across the firms. Despite this equality, however, not every firm's R&D project will finally lead to a success given the unavoidable uncertainty of any innovation process. Instead, only a small fraction of firms will discover an innovation that can be patented and successfully sold at the market. With respect to their future capability to innovate these successful firms profited from their innovation at least in two important ways. First, they accumulate experience resulting in an increase in the human capital of their scientific personnel. Second, due to the monopoly power provided by the patent granted, these firms can increase their profits which can be reinvested, at least partly, into the extension and improvement of their R&D departments.

Because of these effects, the successful and the non-successful firms of the first round of R&D competition will not meet on equal terms in the second round. The successful firms can use their innovative experience to increase the probability that a particular R&D project will lead to an innovation, and they can also increase the number of different R&D projects given their enlarged R&D departments. As a result, chances are high, that most of the successful firms of the first round of R&D competition will gain a comparatively high number of valuable innovations in the second round while most of the formerly unsuccessful firms remain

[5] See Streb et al (2006) and Degner (2010).

unsuccessful. Consequently, the differences in firm-specific innovative experiences widen and then influence significantly the outcome of the following rounds of R&D competition in favor of the early innovators. In the longer term, only a small number of firms will dominate innovation activities due to their high accumulated innovative experience the other firms cannot longer catch up to.

This path-dependent process is in accordance with the Polya urn models in which the random outcomes of the first drawings lead to highly deterministic outcomes of later drawings.

Conclusion

Analyzing all long-lived German firm patents between 1877 and 1932, this paper allows several interesting conclusions with regard to the important period of the Second Industrial Revolution. In addition, these conclusions also have broader implications.

Investigating the determinants of German firms' innovativeness, firm size, in general, has a negative impact despite a changing impact over time that can be shown with the non-linear terms of firm size.

Further interesting results are, first, that joint stock companies seem to be less innovative and, second, that cooperation resulting from geographical proximity to research institutions probably did not play a significant role for German firms. A firm's innovative experience, however, has, sector-independent, a highly significant positive impact.

Given this result, shouldn't the valuable patents be very unequally distributed among the acting firms? In answering this question, an extremely skewed distribution of innovations was observed. On average, only 25 firms developed more than 50 percent of all valuable German firms' patents between 1877 and 1932.

To find a reason for this remarkable result, this paper argues that having developed successful innovations in the past strongly increases the respective firm´s capability to develop more innovations in the future. Hence, such path-dependent upward spirals can help to understand, why innovations are very unequal distributed among economic actors.

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