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Windows of technological opportunity: do technological booms influence the relationship between firm size and innovativeness?

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Harald Degner

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Windows of Technological Opportunity[*]

Do Technological Booms Influence the Relationship between Firm Size and Innovativeness?

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Abstract

Many papers have been written about the effect of firm size on innovativeness, revealing a positive, a negative or a mixed impact. To this day, the so-called Schumpeterian hypothesis of the above-average innovativeness of large firms has been neither confirmed nor rejected, often because of insufficient data or a too-short observation period. Many studies concentrate only on a specific region or a specific sector, or they analyze a very short time period. Windows of technological opportunities, providing technological booms for both firms and sectors, have not yet been investigated. An analysis of Germany's chemical, metal and electronic-engineering sectors between 1877 and 1932 reveals that the sector-specific long-term relationship between firm size and innovativeness is negative, except during times of specific technological booms. In combination with firm-specific characteristics, this new aspect can contribute to a better understanding of the long-term relationship between firm size and innovativeness.

Introduction

Like their predecessors, today's policy makers are often challenged to create policy that provides an innovation-friendly environment. To create an environment that supports economic growth, it is necessary to know whether it is better to support entrepreneurship at smaller

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[*] For helpful comments, I thank Claude Diebolt, Tobias Alexander Jopp, Jochen Streb, Gerhard Wagenhals and an anonymous referee. I thank Jörg Baten and Jochen Streb for the provision of their patent-dataset.

firms or to rely on existing larger firms for innovation. If larger firms are seen to be more innovative, policy makers then face an important trade-off between competition policy and technological progress.

This leads to the main interest of this paper, namely the investigation of the relationship between firm size and innovativeness. This investigation, in turn, will help determine whether the above-mentioned trade-off actually exists.

Schumpeter (1912) describes organizational and technological changes—which Verspagen (2006) identifies as the most important drivers of economic growth—as a new combination of resources, mostly by new and often small firms. Hence, seeing competition und innovation policy as complementary, Schumpeter Mark I would deny the existence of a trade-off between them. Claiming that not the market form of perfect competition, but an oligopolistic or even monopolistic market structure, would provide ideal conditions for innovation, Schumpeter Mark II (1950) sees the relationship between competition and innovation policy as conflictual.

The disparity between these two Schumpeter Theories (provided by O'Sullivan (2006), for example) has provoked a large debate and a huge literature. Langlois (2007) shows that the Schumpeterian dichotomy cannot actually be found that clearly in Schumpeter's work. However, to this day, as the literature review will show, the so-called Schumpeterian hypothesis about the advantage of large firms in creating innovations has been neither confirmed nor rejected, often because of insufficient data or a too-short observation period.

This paper analyzes the patenting activity of both large and small German firms between 1877 and 1932. Technological booms, as a measure for windows of technological opportunities, have not yet been investigated in this context. Thus, a new model, which introduces technological booms as an important factor in understanding the relationship between firm size and innovativeness, will contribute to the debate over the Schumpeterian hypothesis.

Placing the Framework

Since Kamien and Schwartz's (1982) well-known review of older investigations of the relationship between firm size and innovativeness, many papers have been written on the subject. However, there are only a few investigations of the period between 1877 and 1932. Baten et al. (2007), using a dataset of 2400 firms in Baden, investigate various possible determinants of innovativeness around the year 1900. The authors claim that one of their main findings is the significant positive impact of firm size. Spoerer et al. (2007), analyzing the same dataset and focusing on 1906, find mixed effects by observing the sectors separately. At the firm level, the authors observe both the innovativeness per worker and the total number of workers. With an increasing number of workers, Spoerer et al. (2007) find an increasing innovativeness per worker for the textile and chemical industries and a decreasing one for the machine-construction and metal-processing industries.

Mixed results are found not only with respect to different sectors, but also among large and small firms. For example, Pavit et al. (1987) investigate the distribution of the size of firms that developed important innovations in Great Britain between 1945 and 1983. They reach two conclusions: First, the share of all innovations of firms with fewer than 1000 employees was significantly higher than their share of all research and development (R&D) expenditures. Second, firms with fewer than 1000 or more than 10,000 employees had an above-average share of innovations per employee.

A very interesting approach by Dhawan (2001), measuring the differences in productivity between large and small firms, relates the profitability of firms to their probability of surviving. In his model, small firms are more profitable but less likely to survive. Using a dataset containing information on American joint stock companies for the years between 1970 and 1989, the author confirms his theoretical implications about the higher profitability of smaller firms. In addition, Dhawan calculates that, during that period, the innovative activity of small firms was between two and four times riskier than that of larger firms. However, using only joint stock companies leads to an overemphasis on large and successful firms. The underrepresentation of small and less-well-known firms will be solved here by investigating the patent activity of all German firms, both large and small, between 1877 and 1932.

Analyzing a Bank of Korea dataset containing information about more than 1400 Korean firms for the years 1987 and 1988, Nahm (2001) separates the firms into scientific and non-scientific firms. The author bases his decision on the extent of firm-level R&D expenditures. His main finding is that the revenue's (Nahm´s measure for firm size) elasticity on R&D expenditures shows the strongest reaction in medium-sized firms. Nahm argues that a firm needs to be a specific minimum size before independent R&D is possible.

Acs and Audretsch (1991), in their study of American firms in 1982, find a significant negative impact of firm size (measured by the revenue squared). Hence, in their study, smaller firms were more innovative. In an earlier empirical study, Acs and Audretsch (1988) find a positive impact of the share of skilled workers on the innovativeness of large firms, measured by expenditures on R&D, and a negative one for unionized employees. Concerning the negative correlation between innovativeness and unionized employees, this indicator might measure the age of a firm that had passed its most innovative era. The authors attribute the inconsistencies in their results to insufficient data. Van Dijk et al. (1997) try to test Acs´ and Audretsch´s results by recalculating their model using a dataset on Dutch firms. The authors often find different results, especially about the different impact of the share of skilled workers. The authors find a positive impact for both large and small firms, whereas Acs and Audretsch find it only for large firms.

Pagano and Schivardi (2003), analyzing a dataset on European firms between 1994 and 1995, find a consistently positive impact of firm size. Working on innovations in 1950s Britain, Broadberry and Crafts (2001) argue strongly against the Schumpeterian hypothesis. The authors, as well as Geroski (1990), show that the negative effects (e.g., the missing competition) of large firms outweighed the positive effects of large firms (e.g., market power).
Smythe (2001) finds the exact opposite: His study, which observes a period much closer to my observation period of 1877-1932, shows that in American manufacturing firms from 1899-1909, a high level of industry concentration led to fast innovation. Smythe (2001, 263) interprets this result as support for the Schumpeterian hypothesis.

Nicholas (2003) provides a very important piece of cliometric literature dealing with the Schumpeterian hypothesis. The author analyzes 1920s American firms and finds a positive relationship between market power and innovativeness. Hence, this result provides additional support for the Schumpeterian hypothesis. Explaining this result in the context of Schumpeter's era, Nicholas (2003, 1054) presents, at least in part, the background for the investigations in my paper. He points out that his analysis of American firms in the 1920s—a period of fast technological progress—cannot simply be extrapolated without factoring in the historical setting.

The important question of how small firms, which often invest little in R&D, are able to develop innovations at all is answered, in part, by Acs et al. (1994)[1]. The authors argue that small firms can be innovative because they use the knowledge generated in the laboratories of larger firms and universities more efficiently. Following Winter (1984), the authors subdivide the total effect: Large firms more often use the knowledge produced in their own R&D departments, while small firms benefit much more from university research.

Working theoretically at the microeconomic level, Gifford (1992) mentions another interesting point with respect to the debate about the Schumpeterian hypothesis. The author assumes that the resources of both a firm and the firm's decision maker (e.g., time, analytical skills and financial resources) are limited. If a product becomes obsolete and, therefore, unprofitable, the firm has two alternatives. First, it can renew and improve the product; second, it can abandon the old product and try to develop a new one. Gifford interprets such adjustments forced from outside the firm (e.g., by competitors' imitations or by a change in customers' needs) as a part of Schumpeter's creative destruction. Only if the existing innovation's danger of being obsolete is low does the firm have the opportunity to grow because it does not have to spend resources on renewing old or developing new innovations.

With respect to the evolution of market forms, different from perfect competition, Bassanini and Dosi (2006) explain why it should be plausible that a specific technology could dominate the market and, therefore, a specific firm 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. The authors argue that monopolies or market-dominating firms, therefore, are much more likely than the coexistence of different technologies that different firms often develop.

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[1] In addition to this, Baten et al. (2007) mention that small firms benefit more from technical and commercial schools in their neighborhoods.

Also closely related to the evolution of market forms, Smythe (2010) develops the 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 they are too risky and too expensive for smaller firms. Working on the great merger movement in the American manufacturing sector (1895-1904), Smythe (2010) finds historical evidence and contributes to our understanding of firms' incentive to merge and the role innovations could play in this context.

There are many other examples of a positive, a negative or a mixed impact of firm size on innovativeness. To this day, the so-called Schumpeterian hypothesis has been neither confirmed nor rejected. Many studies concentrate only on a specific region or sector, or they analyze a very short time period. In contrast, this study focuses on a long-term analysis of the economic and technological development of German firms in all industrial sectors. To contribute to an understanding of the different results' coexistence, this paper introduces a new model.

Towards a New Testable Model

In analyzing the relationship between firm size and innovativeness, it is necessary to include other factors that may have an impact on innovativeness. The geographical closeness to educational institutions (universities and technical colleges) is an often-discussed factor in the literature. Two aspects are especially important: first, the opportunity of 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. Aghion shows that while primary and secondary education helps less-developed countries (LDC) catch up to the technological frontier, it is mainly through imitation; higher education, however, is necessary to the development of true innovations. With respect to R&D cooperation, Lööf and Broström (2008), based on 2114 observations of Swedish firms between 1998 and 2000, show that such cooperation has a positive impact on the innovativeness of producing firms. Anselin et al. (2000) also point out this interesting aspect of university research's spillover. Using the same database as Acs et al. (1994), the authors show that such technological transfers have a significant impact only on specific sectors (electronics and 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. Very interesting 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) come to the conclusion 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. A firm with better access to the capital market may be more innovative and, therefore, have better opportunities to secure financing for its planned projects. Through an increase in its capital stock, a joint stock company, for example, may find it easier than partnership firms to secure new capital. Hence, the question is how financial constraints influence the innovativeness of firms.

Analyzing East and West German firm-level data of the 1990s, Felder et al. (1995) find only a low negative influence of financial constraints on the innovative activity of firms. Freel (2007), however, finds that banks overestimate the risks in comparison to 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), the author concludes that small innovators are more credit-rationed than non-innovative small firms.

Studying Italian firms between 1992 and 2001, Angelin and Generale (2008) find that firms suffering from financial constraints are, on average, smaller than the others. The authors calculate that firms that had difficulty financing their last investment project (the authors' measure for 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, Angelin and Generale point out that financial constraints cannot be seen as the firm's growth driver. The authors argue that the existence of a developed capital market makes firms more independent from financial constraints (e.g., too little cash flow).

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, the access to a large market and spillover effects, possibly caused by cooperation between firms, show the importance of urbanization as an exogenous (explanatory) variable.

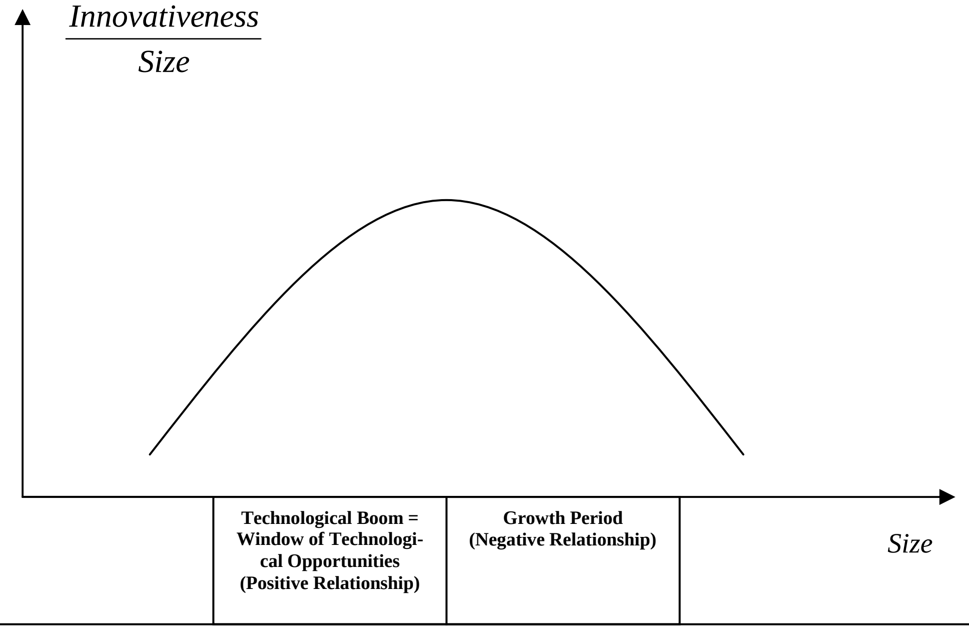
With respect to sector-specific effects, Malerba (2002) sees sectoral innovation systems as an important concept to explain innovations. The main elements in Malerba's theory are basic technologies, several types of interactions, institutions and learning processes. The author defines a sectoral innovation 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 of the abovementioned elements. The question of how firms or sectors react to technological or economic trends is highly related to that. In addition to economic cycles, technological cycles may also be an important determinant of firms' innovativeness. Identifying different technological waves, Streb et al. (2006) make an important contribution to this issue. Using a part of the database the present paper uses, the authors analyze the distribution of valuable patents in the German Empire between 1877 and 1918. They look at the different technological classes to which the German patent office allocated patents, and they construct an annual ranking of these classes. Hence, the class with the largest number of patents granted in a specific year ranks number one in this year. Doing this for every year between 1877 and 1918, Streb et al. (2006, 359) observe that the annual ranking was not constant. Hence, the bulk of patents were not always granted to the same technological class.

Streb et al. (2006) define a patent boom of a specific technological class as the period in which the respective technological class does not rank below its average rank between 1877 and 1818, and in one or more years of this period, does not rank below third in all technological classes. The authors identify four technological waves—in railway, chemicals (first, synthetic dyes, than fertilizer and medicine) and electrical engineering—that can be interpreted as periods of specific technological opportunities, such as the identified wave of synthetic dyes (1887-1896). At this point, it is very important to distinguish between windows of technological opportunity and patent or technological booms.

A window of technological opportunity can be seen, from a firm's point of view, as an exogenous occasion—such as the new field of organic chemistry. Such an exogenous occasion reflects the general possibility of exploring a new technological field.
A technological boom, however, is endogenous because it is shaped by the firm's activities. Since a new technological window is open, R&D activities in the respective field can lead to results. Because of firm's effort to protect this new knowledge, we can observe an increasing number of patents granted in this specific area. Hence, a technological boom is a period characterized by above-average patenting activity in a specific technological field, as Streb et al. (2006) discovered.

Thus, the technological boom is the measurable activity that firms create from the opportunity of an open technological window. Such technological windows are characterized both by the exploration of new technological opportunities and by patenting to save the results generated through R&D. As mentioned above, a technological window may make it easier for the firms in a particular sector to develop innovations as an extension of their R&D activities. Hence, in such a period, the relationship between firm size and innovativeness could be positive, as Figure 1 shows in a stylized form.

Figure 1: Stylized Sector-Specific Relationship between Firm Size and Innovativeness



One might expect a negative relationship after such a specific technological boom, when technological opportunities are exhausted. Production and sale of the innovative products might be another argument for why the relationship between firm size and innovativeness could now be negative. The necessary extension of the firm's capacities (employees and facilities), as well as possible endeavors to enlarge market share, causes the firm's further growth. The decreasing number of innovations, due to exhausted technological opportunities, causes the curve's decline in Figure 1, indicating a negative relationship between firm size and innovativeness. As the abovementioned study by Gifford (1992) demonstrates, an exhaustion of technological opportunities can also be seen as a period in which existing innovations are not challenged by new innovations.

Technological booms can grasp not only different sectors simultaneously or time-lagged, but also individual sectors consecutively, as Streb et al. (2006) show for the German chemical industry. Immediately after the wave of synthetic dyes (1887-1896), a second technological boom grasped the same sector. This new window of technological opportunity, with its patent boom between 1897 and 1902, covered the fields of fertilizers and medications. External impacts of this kind, possibly influencing the firm's innovativeness, are not easy to measure and, therefore, not included in most of the studies about the relationship between firm size and innovativeness. Controlling for temporal effects—e.g., using dummy variables—would not capture the described effects. The existence of windows of technological opportunity, combined with the difficulty of controlling for them, could explain the often-inconclusive results in many studies about the relationship between firm size and innovativeness. Hence, the following sections will test the hypothesis that the relationship between firm size and innovativeness is negative, except during a window of technological opportunity. The negative relationship could also result from the above-average bureaucracy in large firms (Mensch, 1975) because subordinate managers probably have an incentive to prevent important innovations, as these improvements could devaluate their existing competencies.

The Data

Measuring the innovativeness of firms is not trivial. First, a firm may be seen as innovative because it improves its production methods or machines, or simply because it implements a new form of organization. Second, developing—rather than just implementing—something new can be interpreted as innovativeness, as well. This paper uses the second definition. Smith (2006, 152-153) divides the different ways to measure this into three main categories. The first category contains indicators around the 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 the second group of indicators. 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. Another, and probably the most important, advantage of patent data is the fact that they really measure the innovative output. Controlling for changes in the patent law, the usage 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 mostly free access to 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, for example, that patents in general probably reflect inventions rather than innovations. Using Freeman and Soete´s (1997) criterion to distinguish between inventions (the original knowledge) and innovations, an innovation is an economically successful invention. Hence, a patent protecting a novelty that finds success in the market and, therefore, generates monopoly profits or royalties can be seen as a valuable patent.

Analyzing the value of European patents, Gambardella et al. (2008) show a high positive skewness—e.g., the valuable patents are represented by the distribution's right tail. Following the abovementioned criterion of Freeman and Soete (1997), these patents are precisely the most interesting ones. 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. Concerning this, 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, containing 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, a dataset of 66,500 valuable patents was constructed from a basic population of 800,000 patents. This dataset contains information about the name and location of the patent holder, as well as the technological class of each patent. 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 1872, the year the German Empire was founded. It is important to say 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—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 are several possible ways to measure firm size: by its number of employees, by its revenue or by its capital stock. These three measures of firm size, 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, the revenue measures the sold goods' value. This shows that two indicators of firm size, employment and revenue, do not always have to point in the same direction. For example, banks can often create high revenues with relatively few employees, while mining firms generally employ many more people. Finally, the capital stock may capture, first, the firm's past success and, second, the confidence of the owners and investors. If a firm has been very successful, it might be easier to find investors to participate in an increase of capital stock. Hence, planned investments or even a takeover of other firms, financed by an

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[2] For more details, see Seckelmann (2006, 198).

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 determined by both the number of employees and 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 much 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, for example, 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 several hundred German firms.

Through the mentioned archival work, an exhaustive dataset was developed, providing additional information about the annual population per district and the annual number of students at both universities and technical colleges per district. All the data about university students are taken from Titze (1987). This author 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 by 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 the annual urbanization per district is taken from the statistical yearbook, published annually by the German statistical office.

Table1 provides some summary statistics.

Table 1: Summary Statistics

Variable	**Mean**	**Median**	**Std. Dev.**
New valuable patents per firm per year	1.01	0	6.958
Capital stock per firm per year	1,100,000	2,700,000	4,890,000
Employment per firm per year	4868.14	1418	12293.62
University students per 1000 habitants	1.223	0	1.697
Students at technical High Schools per 1000 habitants	0.378	0	0.704
Urbanization rate	0.459	0.394	0.281
N = 1418 firms * 56 years = 79,408			

It is important to mention that, about the employment, the lowest observed value is one and, about the capital stock, it is 5000 Marks. Hence, in the analysis, many small firms are included

The Model

The following section presents in detail the empirical model to test the hypothesis that, in general, the relationship between firm size and innovativeness is negative, except during a specific technological boom. The basic empirical model can be written as

$$\begin{gathered}\mathrm{INNOV}_{it} = \alpha_i + \beta_1\,\mathrm{SIZE}_{it} + \beta_2\,\mathrm{THUCAP}_{jt} + \beta_3\,\mathrm{GHUCAP}_{jt} + \beta_4\,\mathrm{ACAPMA}_{it} \\ + \beta_5\,\mathrm{URBAN}_{jt} + \beta_6\,\mathrm{SECTOR}_{kt} + \beta_7\,\mathrm{YEAR}_t + u_{it}.\end{gathered}$$

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, divided by the capital stock of the same year. It is important to say that the annual number of new patents, not the total number of patents, is used. Using the total number could result in a serious causality problem because important new patents confer a competitive advantage that results in firm growth over the next several years and, perhaps, even longer. For example, say that a firm was granted only one very important patent. If that patent conferred an advantage, the firm would end up investing in new capital, and the patent/capital ratio would fall while the size of the capital stock grew. Hence, this tends to imply a negative relationship between the total number of patents per million of capital stock and the size of firms' capital stocks. This example shows how important it is to use new patents instead of the total number of patents.

The size of firm i in the year t (SIZE_{it}), as the explaining (exogenous) variable—on which the analysis in this paper will focus—is measured by the capital stock in year t. To measure the local availability of human capital, two variables are used. The availability of general human capital (GHUCAP_{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 (THUCAP_{jt}) is constructed in the same way, only using the number of students at technical colleges instead of at universities. Concerning the human capital indices, it is, in fact, possible that the causality runs not only this way in some cases. The growth of educational institutions may have followed the technological developments that created a market for their services. In the present paper, these indicators probably can capture the general possibility of local cooperation between firms and educational or research institutions.

To measure a firm’s access to the capital market ($ACAPMA_{it}$), 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. To cover the abovementioned urbanization effects ($URBAN_{jt}$), the respective variable 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 control for sector-specific effects for the six most important innovative sectors—chemicals, machine construction, electronics, 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 machine-construction sector, the machine-construction dummy realizes the value one; otherwise, it realizes the value zero. Belonging to a highly innovative sector k—e. g., in one of the four innovation waves discovered by Streb et al. (2006)—can overlay the impact of firm size and, therefore, cause a bias in the results.

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 million of the capital stock.

Table 2: Total and Sector-Specific Panel Analysis of the Impact of Firm Size on German Firms’ Innovativeness (1877-1932)
(Dependant Variable: Annual Firm-Specific Innovativeness)

	Model 1	**Model 2**	**Model 3a**	**Model 3b**	**Model 4**	**Model 5**	**Model 6**
Sector Variables	**All**	**Chemicals**	**Electrical Engineering**		**Machine Construction**	**Metal**	**Instruments**
Constant	5.810 (10.171)	0.888* (0.454)	510.17** (203.21)	20.814 (86.531)	12.40*** (2.915)	8.997*** (1.198)	5.708*** (1.183)
$SIZE_{it}$ (log)	-0.322 (0.276)	-0.097*** (0.027)	-38.08*** (4.001)	-0.313 (4.795)	-0.843*** (0.179)	-0.381*** (0.073)	-0.006 (0.086)
$THUCAP_{jt}$	0.057 (0.526)	-0.044 (0.051)	-31.05** (13.35)	0.804 (8.536)	0.071 (0.327)	0.099 (0.205)	0.193 (0.149)

$GHUCAP_{jt}$	-0.097 (0.237)	0.006 (0.024)	-12.49** (5.107)	-0.153 (3.114)	-0.086 (0.1485)	0.040 (0.06)	-0.024 (0.052)
$ACAPMA_{it}$	-0.818 (1.642)	0.729*** (0.161)	-32.47 (26.88)	0.566 (34.36)	0.339 (1.148)	-3.606*** (0.372)	-5.462*** (0.371)
$URBAN_{jt}$	0.479 (1.919)	0.254 (0.166)	181.45*** (44.29)	0.039 (36.99)	1.906 (1.17)	-0.428 (0.486)	-1.882*** (0.485)
Machine Construction Dummy	0.700 (11.37)						
Chemicals Dummy	0.104 (14.37)						
Metal Dummy	0.245 (13.93)						
Electrical Engineering Dummy	59.76*** (18.26)						
Instruments Dummy	-0.018 (21.94)						
Mining Dummy	0.245 (36.63)						
R2 (within)	0.000	0.074	0.00	0.033	0.00	0.077	0.5483
R2 (between)	0,028	0.012	0.357	0.019	0.259	0.102	0.046
R2 (overall)	0.007	0.015	0.152	0.005	0.037	0.049	0.074
N	11,700	1786	734	734	4174	2080	439
Hausman	0.999	1.000			0.985	0.000	0.000
Method used	re	re	re	fe	re	fe	fe
Prob > F	-	-	-	0,999	-	0.000	0.000
Prob > Chi2	1.000	0.000	0.000	-	0.988	-	-

re: random-effects panel analysis, fe: fixed-effects panel analysis ***: significant on the 1% level, **: significant on the 5% level, *: significant on the 10% level, Std.-Errors in parenthesis, $^{+}$: because the result of the Hausman specification test is < 0, the results of both, fixed and random effects models are reported.

In Model 1, covering all sectors, none of the explaining variables shows a significant impact. Analyzing the most important sectors separately yields more-interesting results. Except for instruments, also showing a negative but insignificant coefficient, in all investigated sectors—chemicals, electrical engineering, machine construction and metal—firm size has a highly significant negative impact on innovativeness.

The local—i.e., in the respective—district, availability of both general and technical human capital has an impact only on electrical-engineering firms. Such a negative impact of the two variables, possibly used as a proxy for external knowledge (i.e., not in the firm's research department), supports the abovementioned findings of Kafour and Buckley (2008) that especially large firms prefer to foster their own R&D activities.

The results concerning access to the capital market are very interesting. In Model 2, analyzing the chemical sector, access to the capital market has a highly significant positive impact on the chemical firm's innovativeness. Keeping in mind the expensive R&D departments in this capital-intensive sector, this result can be explained easily. While in the metal and instruments sectors, the impact of access to the capital market is significantly negative, it is insignificant in the electrical-engineering and machine-construction sectors. The significant negative impact for the metal and instruments sectors supports Freel's (2007) finding that non-innovative firms may find it easier to get their projects financed because investors often overestimate the risks in comparison to the future returns.

Urbanization as a measure for the local market has a highly significant (positive) impact only on electrical-engineering firms. A possible explanation is that those firms' products, especially telephony and telegraphy devices and electronic lighting installations, were often sold directly to private customers and, therefore, influenced the firms to locate in an urban area. The two most innovative firms in this sector, Siemens and AEG, were, in fact, located in Berlin, a highly urbanized area. Concerning the chemical, machine-construction and metal sectors, urbanization had no impact; these sectors' firms sold their products mainly to other firms and did not need to be located in a highly urbanized area. This effect seems to be even stronger concerning the instrument sector, showing a significant negative impact of urbanization.

To summarize the main results so far, the negative impact of firm size on innovativeness in all analyzed sectors can be identified, mostly highly significant.

Next, the idea of windows of technological opportunity, measurable by technological booms, will be investigated. As mentioned above, the hypothesis being tested is that the relationship between firm size and innovativeness is negative, except during technological booms, such as the chemical wave (1887-1902), the railway wave (1877-1886) and the wave of electrical engineering (1903-1918). The railway wave captured almost all the firms in the metal sector because steam boilers, metal processing and railroad tracks were necessary for railway installations (Streb et al., 2006, 360). To point out the innovative importance of these three sectors, it is helpful to notice that between 1877 and 1932, German firms developed 26,106 valuable patents. Firms in the chemical sector developed 6,209 valuable patents, firms in the metal sector 2,923, and firms in the electrical-engineering sector 4,860. Thus, those three sectors' firms were responsible for 53.59 percent of all valuable firm patents in the German Empire and the Weimar Republic during that period.

The following section will test the abovementioned hypothesis that, for the chemical, metal and electrical-engineering sectors, the coefficient of firm size is not constant over time. Chow breakpoint tests will be conducted, testing the null hypothesis that the estimated parameters of firm size, presented in Table 2, are stable over time.

Table 3 displays the results of the Chow breakpoint test, which tested for all three sectors the null hypothesis that the parameters are structurally stable over the entire period (1877-1932).

Table 3: Chow Test-Results for Intertemporal Stability

Sector	Parameter	F-Value	chi2-Value
Chemicals	$SIZE_{it}$	-	12.12***
Metal	$SIZE_{it}$	2.57*	-
Electrical Engineering	$SIZE_{it}$	-	0.03
Electrical Engineering	$SIZE_{it}$	0	-

***: significant on the 1% level, *: significant on the 10% level.

The evidence presented in Table 3 indicates that the null about intertemporal stability can be rejected at the one-percent level for the chemical sector and at the ten-percent level for the metal sector. Hence, revealing the existence of a structural shift in the firm-size parameters during technological booms—despite the insignificance for the electrical-engineering sector—provides strong statistical support for the hypothesis that the coefficient of firm size is not constant over time, especially not for every sector. This result might also support Nicholas´ (2003, 1054) supposition that the relationship between market power and innovation possibly vary temporally.

Given these results, for the two sectors in which a structural parameter-shift was detected (chemicals and metal), the relationship between firm size and innovativeness is re-analyzed separately, both inside and outside of a specific technological boom. The results are reported in Table 4.

Table 4: Sector-Specific Panel Analysis inside and outside the Windows of Technological Booms (1877-1932)
(Dependent Variable: Annual Firm-Specific Innovativeness)

Sector	**Chemicals**		**Metal**	
	Model 1	**Model 2**	**Model 3**	**Model 4**
Technological Boom	**Yes (1887-1902)**	**No (1877-1886, 1903-1932)**	**Yes (1877-1886)**	**No (1887-1932)**
Variables				
Constant	-0.707 (1.163)	0.629 (0.473)	-0.758 (0.880)	10.52*** (1.278)
SIZE_{it} (log)	0.064 (0.071)	-0.081** (0.028)	0.048 (0.057)	-0.40*** (0.079)
THUCAP_{jt}	-0.123 (0.076)	0.001 (0.064)	-a)	0.101 (0.212)
GHUCAP_{jt}	0.028 (0.066)	0.001 (0.025)	0.110 (0.181)	0.034 (0.064)
ACAPMA_{it}	-0.223 (0.471)	0.67*** (0.196)	-a)	-4.629*** (0.434)
URBAN_{jt}	0.433 (0.29)	0.022 (0.19)	0.106 (0.426)	-0.396 (0.508)
R2 (within)	0.057	0.063	0.109	0.091
R2 (between)	0.04	0.036	0.111	0.119
R2 (overall)	0.06	0.029	0.026	0.059
N	484	1302	152	1928
Hausman	0.997	0.695	0.000	0.000
Method used	re	re	fe	fe
Prob > F	-	-	0.2826	0.000
Prob > Chi2	0.132	0.000	-	-

re: random-effects panel analysis, fe: fixed-effects panel analysis, a): dropped because of multicollinearity, ***: significant on the 1% level, **: significant on the 5% level, Std.-Errors in parenthesis.

Outside of such technological booms, analyzed in Models 2 and 4, firm size has a highly significant negative impact. That result is consistent with this paper's hypothesis. In Models 1 and 3, analyzing the chemical and metal waves, no significant impact of firm size on innovativeness can be observed. These results suggest that, in fact, the coefficients of firm size inside a specific technological boom significantly differ statistically from the coefficients outside this boom.

At this point, it is important to mention that the negative relationship outside the technological booms probably could result from a concentration process. If maturing industries tend to be more concentrated and less innovative, this could explain why the innovativeness of firms in the chemical and metal sectors appears to decrease as they become larger. To further test this result, Figure 2 shows the two sectors' annual number of patents granted, together with the number of firms developing them.

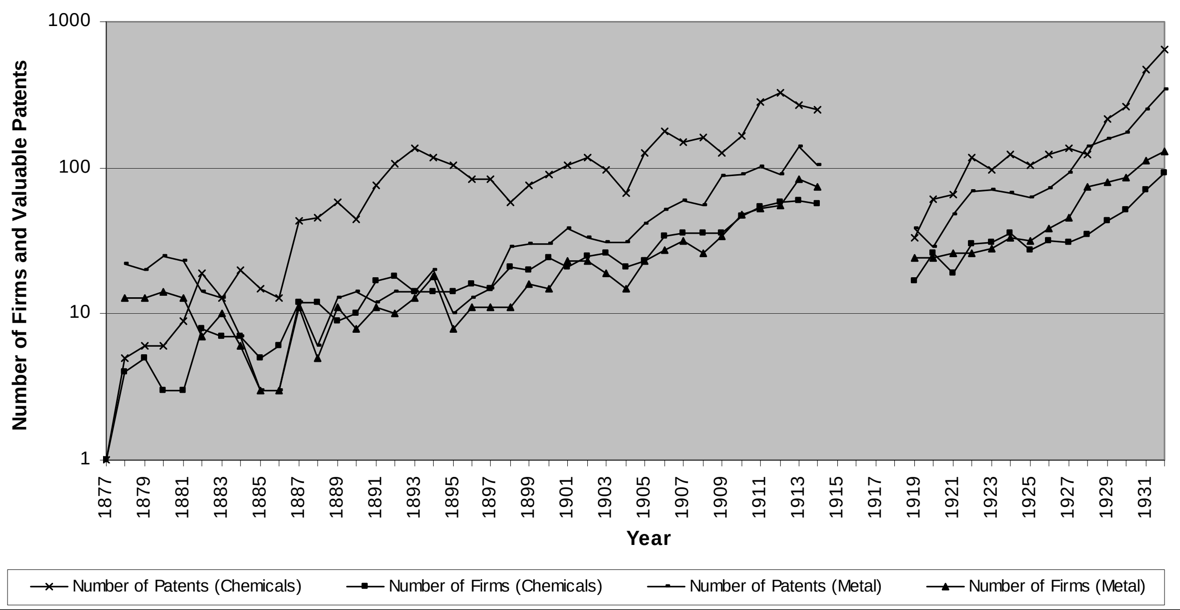


Figure 2: Innovative Firms and Number of Valuable Patents Granted in the German Chemical and Metal Sectors (1877-1932)

Source: Baten/Streb database.

Regarding Figure 2, the strong increasing number of innovative firms, as well as the fast-growing number of valuable patents granted, provides no evidence for the supposition that the negative relationship between these sectors' innovativeness and firm size result from a concentration process with a decreasing number of both firms and innovations.

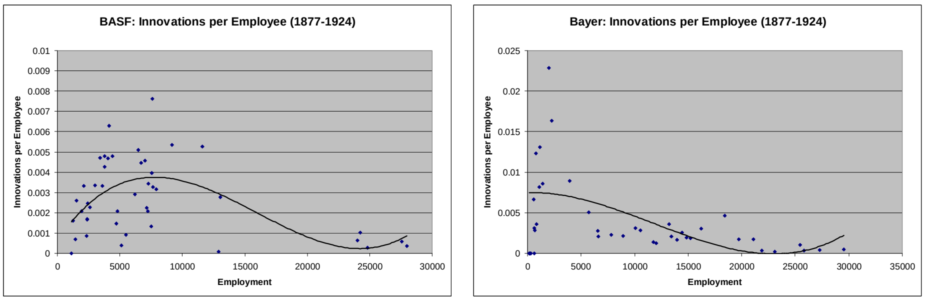
The following explores some possible reasons why the incontrovertible results outside a specific window of technological opportunity cannot be found inside such a window. Figure 3 shows the relationship between firm size and innovativeness of the two most innovative firms in both the chemical and metal sectors.

The horizontal axis shows the size of the firm, measured by the number of employees and not by time. Because firms grew during the observation period, this axis can be seen roughly as a time axis. The vertical axis shows the innovativeness per employee, calculated as the number of valuable patents divided by the number of employees. Cubic functions are calculated to fit the underlying dots as well as possible. Such functions provide the opportunity to visualize the different patterns as they are shown in Figure 3.

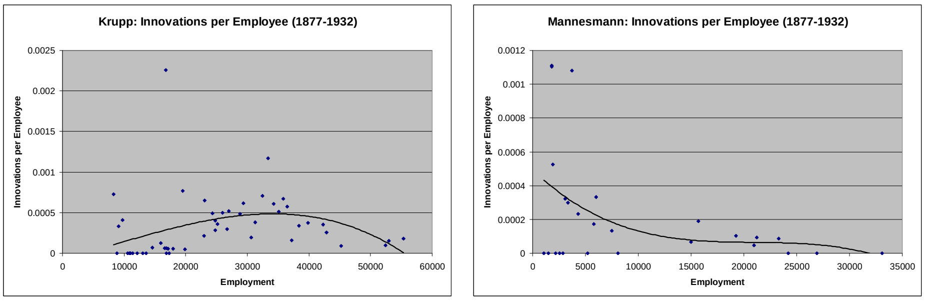
Figure 3: Innovativeness and Growth

The two most Innovative German Firms in the Chemical and Metal Sectors (1877-1932)

Chemicals:



Metal:



Source: see text

Observing, for example, BASF, the early development of innovations in the newly-founded firm caused an increase in innovativeness per employee. Under Heinrich Caro (1834-1910), BASF started industrial research in its new R&D department, concentrating on synthetic dyes. According to v. Hippel (2002, 36), this was the beginning of BASF's independent R&D activities. To produce and sell the innovative products, BASF needed a lot of workers. In addition, the growing size of the firm’s administration required additional employees; thus, average employment grew, while innovativeness, measured by innovations per employee, decreased.

Observing the competitor, Bayer, an interesting difference can be identified. As in the case of BASF, Bayer’s exploration of new synthetic dyes ended before World War I. During the technological boom (1887-1902), the relationship between firm size and innovativeness at BASF seems to be positive. In comparison, for the same period, Bayer shows a negative relationship. These two examples (the two most innovative German firms in the chemical sector) show that not every firm can benefit from a specific window of technological opportunity in the same way. The exact trend of a firm’s curve, describing the relationship between firm size and innovativeness, depends on, among other things, the firm’s R&D strategy.

In Figure 3, Krupp, the most innovative firm in the metal sector, shows a positive relationship between firm size and innovativeness during the metal and railway wave (1877-1886)[3], while Mannesmann, also a highly innovative firm in this sector, shows a negative relationship, illustrated by the decreasing curve. Krupp’s continued upswing of the curve beyond the specific technological boom was caused by the fact that Krupp’s main businesses were railroad and defense. Because of this, Krupp, perhaps more than others, was able to benefit from World War I. During the war, its revenues increased from 478 million to 1.5 billion Marks.[4]

As in the chemical industry, the two most innovative firms in the metal sector appear to have differing relationships between firm size and innovativeness during a specific technological boom. The reason for this difference may be twofold: The two firms had different R&D strategies, and not every firm can benefit equally from a specific window of technological opportunity. Exploring new technological opportunities, some firms become the technological leaders, while others react slowly or not at all. Even if the time frame of a technological window can be precisely identified, the firms’ unequal reactions make it difficult to identify a clear trend. Even at the sector level, it is ex ante hard to make out the exact time when, and to what extent, a firm tries to foster its innovativeness. The long-term relationship between firm size and innovativeness might be described as a recurring lying S-curve, shaped by innovation and growth periods following each other (Degner 2009). However, the frequency and the amplitude are not always equal. Failing to take into account technological waves and the changing

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[3] Indentified by Streb et al. (2006, 360).

[4] See Gall (2000, 342).

relationship between firm size and innovativeness at the firm level could be the cause of often-inconclusive results.

Conclusion

Using a newly-developed dataset, which contains every long-lived patent granted in Germany between 1877 and 1932, this paper analyzes the relationship between firm size and innovativeness. Although the literature has taken many variables into account, to this day, the relationship between firm size and innovativeness is still not clear. This lack of clarity might be caused by specific windows of technological opportunity with their technological waves, thus complicating the identification of a relationship, especially a linear one.

In an attempt to explain the inconclusive results in the literature, this paper introduced the hypothesis that the relationship between firm size and innovativeness is negative, except during a specific technological wave. Analyzing three very important German sectors—chemicals, metal and electrical engineering—Chow-breakpoint tests reveal the existence of structural shifts in the firm-size parameters for the chemical and the metal sectors. Re-analyzing these two sectors, a highly significant negative impact was found outside a specific window of technological opportunity. Investigating the relationship inside the respective technological boom, no significant impact was observed. This could be caused by both the firms' different R&D strategies and the fact that not every firm in a sector can equally benefit from a technological boom. The concept of the technological boom as a window of technological opportunity, in combination with firm-specific characteristics, might contribute to a better understanding of the long-term relationship between firm size and innovativeness.

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