Innovation and growth in Germany over the past 150 years

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Abstract. This contribution starts from today's definitions of innovation indicators and traces their evolution back over the past 150 years. It is divided into a descriptive and an econometric part. The German innovation system has generally been very stable, even though it witnessed several political changes over the past century. This allows a comparison of the period 1850–1913 with 1951–1999. In the first period, the overall empirical results indicate a linear innovation relation between student numbers as well as public science expenditure, the number of patents granted, and economic demand. However, the second period suggests a different logic in the innovation process: demand drives total R&D expenditure, while patent output does not follow demand. The real domestic product does not seem to depend strongly on innovation activities.

JEL Classification: L16, L52, O11, O31, O47, N10

1 Introduction and structure of the contribution

If we want to understand our modern science and technology (S&T) system as an outcome of its evolution, we have to understand how it came about historically. This is an important task for historians of technology and economic historians, but not the prime concern of this paper. Rather, we want to understand what drives an innovation system over long periods, including external shocks which could be disruptive to the arrangement of driving factors. Can we provide evidence as to how such an innovation system reacted to earlier structural changes? Do we observe paradigm shifts or more persistent elements?

Germany is an ideal object of study as it has undergone many territorial and governance changes: it existed as a large array of individual states before 1871, was united in 1871 from Alsace-Lorraine (in the South-West) to East Prussia (in the North-East), reduced in 1918 after World War I and split into the GDR and West Germany from 1949 to 1990. You can hardly imagine more external shocks to an innovation system.

A suitable measurement concept is essential for such an endeavor. A practicable way to measure innovation and growth in the long term could be the elaboration of definitions and measurement methods historically, with the objective of recording the enormous changes characterizing innovation activities. However, our contribution takes the opposite point of departure: starting from today's definitions, an investigation of the comprehensive statistical material, including related indicators, is carried out, followed by an attempt to trace and complete these indicators back to before the foundation of the German Empire. This means that the presently achieved level of theory and methodology serves as a point of departure.

Consequently, this contribution tries to include a considerable number of quantitative variables in the form of *time series*. This analysis can be included in the field of *cliometrics*, the "new" kind of economic history, which is based on quantitative methods, including econometrics, aimed at reconstructing and interpreting the past (Bannock et al., 1998, p. 61). This method has been criticized by evolutionary economists (Freeman and Louçã, 2001, pp. 9; Walter, 1997, p. 75) since *indicators* cannot be *facts*; however, no fundamental difference exists between the description of facts and the interpretation, since every description already represents a certain interpretation which, moreover, depends on the definitions presently available (Lorenz, 1997, p. 32). This is aggravated by the fact that the theoretical constructs of innovation research are not clearly defined. Up to the present, rival and incompatible innovation theories still exist in several disciplines (Grupp, 1998). Linear models are widespread, presuming a sequential succession of innovation-oriented phases, the point of departure of which is an unpredictable serendipity in basic research or exogenous technical progress which falls like manna from heaven. It is evident that the definition of innovation, as it is used nowadays, cannot be considered as an anchor for the investigation period since 1850. Prior to the 1960s, innovation phenomena were described using other definitions: archives, libraries, and research institutions, as well as documents from management, personnel departments, or from production centers use terms that differ from those used according to present standards (like laboratory, try establishment, experimental factory).

According to today's view, the concept of a specific research process that leads to measurable innovation and that requires personnel and financial expenditure, is based on Bernal (1939), who distinguished the role of public research expenditure from that of civil research and – as things stood at the time – from that of the war industry. The first statistics on expenditure for "industrial research" by British companies are found in the annexes of his works. As reported by Freeman (1992, p. 3), the definitions used by Bernal during his lectures at the London School of Economics were brought to international committees (by Freeman himself, as well as by others). Here, in the 1960s, work was done on another standardization of definitions, which resulted in a first paper on the measurement of output of research and development (Freeman, 1969). Today, there is an established multidimensional array of innovation-related indicators (see, e.g. Grupp, 1998). Nevertheless, these still suffer from various respective shortcomings, so their combined use is recommended (loc. cit.).

Consequently, the empirical framework underlying this contribution will be determined using the current definitions and concepts. While these may have had other meanings in the past, this "*anachronism*" of long-lived indicators' definitions must be accepted (Lorenz, 1997, p. 364). The definitions found in the leading OECD manuals from the 1990s will be used. If a structural breakage is found in time series, this could point to sudden changes in the innovation system. Consequently, any structural breakages[1] located must always be interpreted and categorized in a qualitative way.

For Germany, the most relevant system shocks are those due to changing territory and thus population and governance. In this contribution, we consider, for example, the size of the Empire or the federal territory. Not only is the German Democratic Republic considered here, but also the Saarland, the Corridor, East Prussia, and others (refer also to Hoffmann, 1965, p. 2). On the basis of today's statistical procedures, we will introduce dummies for these shocks, so that the data series, a priori, do not have to be absolutely consistent with a territory. However, it must be pointed out that, in most cases, the omission of *smaller* districts (such as Alsace-Lorraine from 1871 to 1917) brings in its train less important errors of estimation than the *large variances* in the series of the whole territory of the German Reich (same paper, p. 3).

This contribution is divided into a description of the data (chapter 2) and an econometric part (Chapter 3), in an effort to analyze innovation and growth in Germany. The data chapter is extraordinarily long. The reason for this was mentioned above: this data base was reconstructed for the purpose of this analysis and is not documented elsewhere[2].

2 Basic data on the national innovation system in German states

In this chapter, the reconstructed data base on research and innovation in Germany is presented in full, explained by basic historical events and critically discussed because so many assumptions were required. Later on it will be argued that an econometric analysis is not meaningful between the wars (First and Second World War), but rather for 1850–1913 (first period) and 1951–1999 (second period). We indicate the two periods in the figures, but include the data regarding the period in between, which are not used in the analytical part, to facilitate an own judgement by the reader.

[1] Maddison (1982, p. 2 and 83) talks about "system shocks"; compare also Wagner (1984). Machlup (1957) found 25 variants in the economic literature of what "structural change" could mean. Gerschenkron (1943) points to the pervasive institutional powers that may overcome external shocks for decades.

[2] For German readers, see Grupp et al. (2002). A detailed English list of data sources is available from the authors on request.

2.1 Public expenditure for national science and technology

Traditionally, the development of science and technology is measured by the number of *scholars*. In this way, for example, Gascoigne (1992) submitted a historical demography of the scientific community between 1450 and 1900, by listing the nationality and age of all the scientists. According to this study, Italy was the leading scientific country at the beginning of modern times (in the late 15^{th} century), representing about half of all the scientists in the world. This remained almost unchanged during the entire Middle Ages, before that century; then exponential growth with a doubling period of approximately 50 years took place.

Detailed and complete statistics are available regarding the *scientific staff* in Germany since the foundation of the Empire, accessible via today's electronic means. Generally accessible statistical material about R&D personnel in Germany has only been recorded since the 1960s (in the framework of the Federal Research Report, which has been published since 1965).

Another traditional approach to the empirical definition of the importance of an innovation system is scientific expenditure (the sum of R&D funds and those for training, teaching, maintenance and the diffusion of knowledge). Whereas the evaluation of expenditure for pure educational and R&D institutions is rather simple, this is more complicated in the case of institutions engaged in *both* research *and* teaching. Quotas were adopted to cope with the individual fields of specialization, as well as with the individual types of universities. However, it is questionable whether these reflect the right proportions between the percentage of research and that of teaching at all *historical* points in time. In addition, not only is the historical consideration problematic, but also the consideration of the present time. Nevertheless, it is common statistical practice in all OECD countries to work with such quotas (Hetmeier, 1990; Irvine et al., 1990). Expenditures for training, maintenance, diffusion, marketing and other innovation-related activities are not included.

Pfetsch (1982) added up scientific expenditures between 1850 and 1975, so that rough estimates of the degree of R&D financing could be derived. However, these data records only include *public* expenditure, and so disregard the private sector. Consequently, industrial innovation indicators must be researched separately (see chapter 2.3). In order to avoid dealing with the difficulty of different currencies, the development of scientific expenditure can be best evaluated by the percentage of the *total expenditure* of public budgets.

Accordingly, scientific expenditure in the German regions prior to the foundation of the Empire was approximately 1% (see 1). Linked to the foundation of the Empire, this percentage reached more than 2%, but dropped to almost 1.7% between the 1880s and the First World War. This reduction should be interpreted with care, as the reduced share in total public budgets merely tells us that, in these times of pre-war rearmament and a booming economy, government outlays were ballooning (Ziegler, 2000).

The Republic of Weimar attained a doubling of scientific financing which, however, was lost again due to the world wide economic crisis. Recovering from hyperinflation, a second booming scientific phase was set off, along with "formidable creativity and experimentation enthusiasm" (Ambrosius, 2000). The Nazi arma-

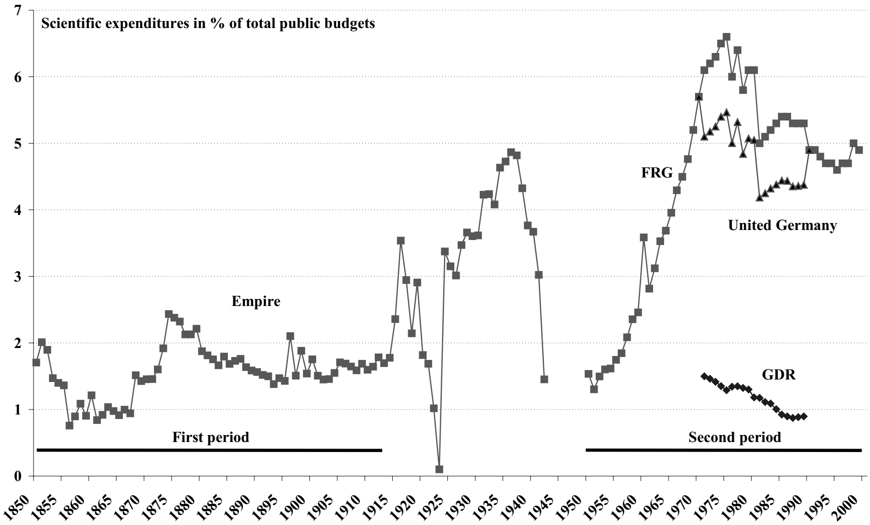

Fig. 1. Development of scientific expenditure in proportion to the total expenditure of public budgets
Source: Pfetsch (1982), Echterhoff-Severitt and Stegemann (1990), BMBF (2000).

ment research from circa 1935 onwards was financed with fiscal tricks and budget deficits. In West Germany, the support of science was pushed dramatically to reach a proportion of 6.5% of all public budgets by the 1970s (university expansion), but fell off to approximately 5.5% because of German re-unification. Finally, due to re-unification, the level dropped even further. These indications are based on the numbers of Empire or Federal institutions and those of regions and states. Surprisingly, the post-war-II expenditures start at around the same level as at the beginning of the last century (after World War I), which is at the same level as the endpoint of records in the Second World War period, and increases in a similar way after the war II as it did after World War I. This points to quite *stable* and *persistent* institutional structures underlying the financial totals.

The financial support of *Research* and *Development* is typical for post-war Germany. Until 1945, the financing share for R&D only played a subordinate role in total scientific expenditure. Although the research share[3] was 20 to 30% during the first period after the foundation of the Empire, it dropped to less than 20% by the beginning of the First World War. In addition, it is important to note that a great deal of scientific expenditure by the Empire was used for defense tasks shortly after the foundation of the Reich. During the Weimar Republic and the Third Empire, the R&D share of the total of scientific expenditure continued to fluctuate around 20% (industrial research not included). A quick increase in the R&D share of scientific expenditure was the case when research in certain areas was admitted again in the young Federal Republic, after the signing of the Treaty of Paris in 1955: at times it reached 70% and has only declined due to the recent re-

[3] More precisely, "research share" means the "R&D share" of the total expenditure for science and technology.

unification. Regarding the R&D expenditure of the *German Democratic Republic*, note that the individual statistics were centrally maintained and are comprehensive. However, the conditions which were applied do not fully comply with those used by OECD countries and often show exaggerated values. Following re-unification, the relevant statistics were revised and adapted to Western standards. However, the conversion problem of the East German bank's Mark (M) persists. Due to the non-convertibility of this currency, the reliable purchasing-power parity values of OECD countries cannot be applied.

In order to be certain, we applied a pessimistic and an optimistic variation to show a range of uncertainty due to conversion. The first possibility of conversion is based on the purchasing-power parity (PPP) of so-called baskets of commodities. In the second model, the subsidies included in GDR commodity prices are taken into consideration and deducted (Anonymous, 1986, p. 259-268). In both estimations, the national R&D expenditures of the German Democratic Republic could not quite equal the West German level (per head of the population), but the general downward trends (in 1) resemble each other somehow. This may come as a surprise to those who point to the inefficiencies of the communist part of Germany, but, again, the underlying institutional structures remained basically the same as before the war, requiring similar amounts of public support. Again, this points to persistent basic structures in the national innovation system. In the econometric model, we did not add the East German expenditure to the ones of West Germany to avoid conversion problems.

2.2 Development of scientific activities

It is impossible to achieve an insight into the development of non-codified and thus "tacit" experienced knowledge of the scientific staff. For this reason, the historical development of an innovation system is often shown by personnel statistics, or by statistics showing monetary expenditures. However, only expenditure is measured by this method, instead of the fruit of scientific activities. Efficiency measurements are particularly impossible. Consequently, modern innovation statistics make regular use of yield measures; regarding scientific work, statistics of publications are a typical output indicator. Analysis of the degree of *publication* activities have been maintained for centuries. However, it must be noted that the publication media chosen by scientists may differ from one faculty to another, as well as over time (Wagner-Döbler and Berg, 1996, p. 289). Only during the 19^{th} century did scientific magazines achieve the same degree of significance as books, the dominating publication media until then. From 1900 onwards the availability of data improved world wide. The growth rates of periodicals were evaluated by Mabe and Amin (2001).

Analyzing the situation in *Germany*, the Science Citation Index (SCI), which has been available as an online version as early as 1974 (see below), has a printed version listing the publications from 1945 until 1974. Although no indications are found regarding the authors' nationalities or the institutes' locations, the listing of periodicals is classified by the countries editing and printing them. The repeatedly written announcement by the SCI that records would be completed back to 1900 was withdrawn[4], so there is no hope for the early publication of a *century's inventory*. Although the statistics of publications seems to be an interesting output indicator, it cannot establish the first period and thus cannot be used for estimating the econometric model. However, as we are analyzing structural issues such as persistence and paradigm shift, we can use this indicator for an assessment of the GDR research, which is difficult in monetary form (see above in section 2.1).

From 1974 to 1990, SCI publications from West and East Germany can be compared electronically. In the 1970s, the share of *East German* publications among all German publications was approximately 16 to 17%. However, if one compares East and West Germany, both the proportional shares of population and the proportion of R&D staff is almost 30%, so that scientific publications from the German Democratic Republic are less well-represented in the US-based database. The proportion of East German publications had constantly diminished, to reach 13% by the end of the 1980s; and there is no answer to the question as to whether the *representation* in the database was even worse or if the output efficiency of East German research activities continued declining until the end of this state[5].

Measured by its publication output, the *profile* of GDR research resembles that of the former Federal Republic. This *structural similarity* could be the reason for such a strong diminution of publication activities on an all-German level following re-unification. Integration did not concern differently specialized East and West research systems, but research systems with the same principal orientation, which led to the deplorable "re-allocation and consolidation" in East Germany. Independently from a political evaluation of the organization of GDR research institutes, this *structural persistence* must be pointed out; obviously 40 years of division were not sufficient for a differentiated development of the basic specialization patterns of research in both parts of Germany. To a great extent, and in the sense of *path dependency*, research is still based on the (common) preferences which existed prior to the division. This unique historical situation may be understood as an unintended experiment: basic patterns of scientific structure change only slowly, even in times of great political system change (Hinze and Grupp, 1995, p. 65).

2.3 Industrial research and development in Germany

Since the foundation of the Empire, the economic growth of industrial countries, and that of Europe in particular, has increasingly been based on the innovation energy of the *knowledge-based industry*. "This is undeniably true for the impulses of growth immediately released by these industries, starting with carbon chemistry and electrical technology" (Wengenroth, 1997). There is hardly a clearer and more distinct way to describe the effects of industrial research on the culture and efficiency of innovation.

It is still difficult to prove the companies' increasing R&D expenditure for such an undeniable success. In particular, no complete data records are available re-

[4] Personal communication Garfield, 14 October 2000.

[5] Due to the delay in appearance of scientific publications following submission, no quantitative cutback in literature production by the researchers of German Democratic Republic institutes can be perceived until the end of 1990 (Weingart et al., 1991, p. 4).

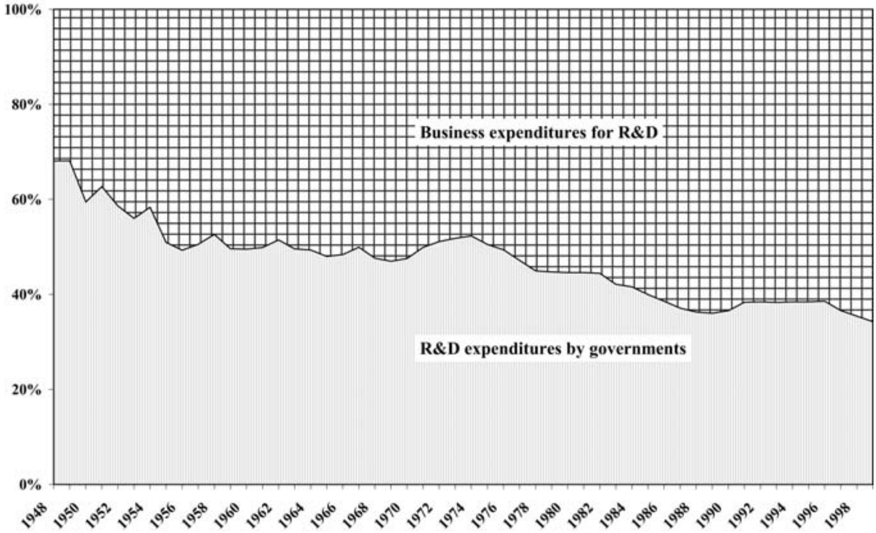

Fig. 2. Development of government and industrial R&D expenditure in relation to each other from 1948–2000

Source: BMBF (2000).

garding monetary expenditure or research personnel prior to the end of the Second World War, i.e. the data record established by Pfetsch (1982) regarding public scientific expenditure has no counterpart for industry. Today's statistics about R&D expenditure and personnel of the Federal Republic systematically start from the year 1962; certain presumptions allow the reconstruction of the corresponding indicators starting from 1948/49 (Fig. 2). According to this, industry has continuously increased its R&D budgets to a higher degree than government, the share of which is presently approximately 40%. R&D expenditure of the business sector will be included in the analytical model for the second period only. This is consistent with the assumption that these were small or negligible in the first period.

2.4 Development of technological activity in Germany

The observation of the development of innovation activity is important in itself in order to establish R&D results, mostly on a technological or application level. Adopted methods are statistics on *patent applications* (a figure representing successful innovation activity seen from the innovators' or applicants' subjective perspective) on the one hand, and, on the other hand, statistics on the number of *granted patents* (as a figure representing successful innovation activity, seen from the objective perspective of patent examiners). Statistics on patents make even more sense if one takes into consideration that only fragments of industrial R&D expenditure are known prior to the Second World War. Instead of inputs, industrial R&D activities can be measured by their patent outputs, and this even more precisely from a technological perspective than by monetary indicators. This also explains our interest in

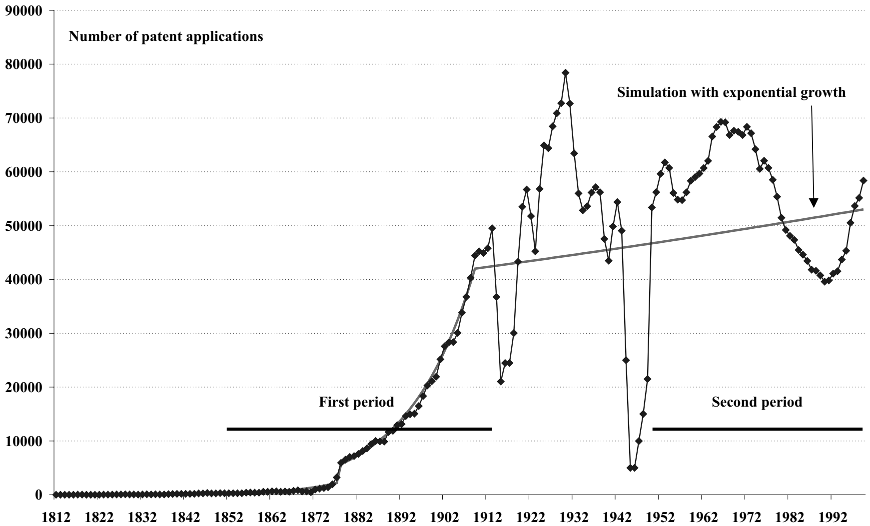

Fig. 3. Development of granted patents (from 1812 to 1877) and domestic patent applications from 1878 to the present.

Source: Federico (1964), German Office for Patents and Trademarks (several years).

both patent grants and patent applications: if no patent is granted after verification of the novelty, the inventive step and its commercial usefulness, for example due to a lack of novelty, the applying company nevertheless may have invested in R&D efforts – even if these led to an objectively already known result. Consequently, the "subjective" perspective of a successful invention is closely linked to the R&D performance which was in fact realized. Statistics on patent applications as a *proxy variable* for R&D expenditures may ignore whether the object of the invention was a world novelty or not. R&D expenditure also includes the costs of unsuccessful or belated inventions in comparison with competitors (imitations).

The periods to be considered are fully included in the statistics of patents. In some German regions, patents were applied for as early as 1820, starting from the South due to the influence of the Napoleonic legislation. From July 1^{st}, 1877, a *patent act* for the German Empire standardized procedures. Thus, the creation of patent acts in Germany follows the scientific-technological innovation push of the 19^{th} century, at the end of which Germany was one of the leading industrial nations. In about the middle of the century, the local, largely secluded markets were dissolved, and the German economy was integrated into the quickly expanding world economy (Ziegler, 2000, p. 198 and North, 2000, p. 13).

Since 1879, *patent statistics* have been available using *machine readable* methods. The electronic data records since 1970 are more informative than those of former periods, leading to an increased importance and use of these patent data records by modern studies in science and technology. But if one makes the effort to chain together different patent data records for the appropriate historical sequences including written sources, assembled patent statistics can be established for the whole period (see Dominguez-Lacasa et al., 2003). Considering global patent activities in Germany (Figure 3), the strongest growth at a low level takes place from 1820 to the foundation of the German Empire. The total growth rate for German regions is shown to be constant with the setback due to the war of 1870/71. Following the introduction of the countrywide German patent act, the number of applications and grants rises rapidly within a few years, and continues growing at a constant rate, which, although at a considerably higher level, is lower compared with that of the period preceding 1870. This growth, which lasted for almost one century, is abruptly stopped by the First World War, the annual patent production being halved. From approximately 1920 to 2000, an eventful development pattern nevertheless shows growth close to zero. During almost one century, the number of annual patent applications is approximately 50,000 to 60,000. German patent productivity per person reaches one of the highest rates, in comparison with the United States, Japan, and the European Union. Diverging from this rough rule, growth is observed during the Weimar Republic phase until the beginning of the Third Reich, followed by a very deep setback during the Second World War, which is distinctly more serious than that of the First World War, and a return to the secular quota by approximately 1960. Another boom follows until 1975, when a deep recession takes place which is only overcome in the mid 1990s.

No investigation has yet discovered whether these growth cycles have *only* economic causes. The economic boom around the foundation of the Empire is well-known (Ziegler, 2000, p. 201; Stolper et al., 1964); the same is true for the serious recession following the oil crisis in 1973, straight after the "economic miracle". The question remains as to whether the reduction of innovation activities at the beginning of the Third Reich was only due to economic reasons or to a modified practice of patenting (for example, by the stronger observance of secrecy due to the early war economy, by expulsion or migration of Jewish scientists). Further, the question is asked as to why the growing R&D budgets granted after the Second World War did not lead to an increase in patent activities. Obviously, this decrease of patent efficiency was not exclusively driven by R&D inputs.

The analysis so far includes all patent documents of national and international actors on German territory. By *international actor* is understood that either the inventors' residence or the applying company is located abroad. From 1881 to 1913, the share of foreign patent grants was extremely high, showing an average of 35%: until 1933, Germany's reputation as the leading scientific country attracted many young scientists from abroad, especially Americans who came to the German Empire in order to benefit from practice-oriented education for their degrees, and possibly even to experience some years of active industrial research (Erker, 1990; Smith Jr., 1990). After the First World War and the efforts to achieve self-sufficiency in the 1930s, the share of foreigners was reduced by almost 10% but remained a significant figure in spite of all war speculations. Since the reconstruction of the German patent administration following the Second World War, the share of foreign patent grants has consistently increased, reaching more than 60% in this so-called globalization era. In the analytical part of this contribution, we use domestic patent applications only in order to avoid any influences from changing migration policies.

The basic framework conditions for GDR activities in view of industrial property rights are fixed in the *patent law* of 6 September 1950 (Albrecht et al., 1991,

p. 4). Nevertheless, GDR patent activities according to Western legislation are hard to ascertain during the first years. This is linked to the various forms of recognition of the GDR as an autonomous state by different nations. Some GDR inventors operated from Federal Republic addresses. Compared with Western conditions, certain deviations in the patent law conditions of the *former GDR* were ruled by the socialist spirit of ownership. Consequently, the national patent applications at the former GDR Authority of Invention and Patent Administration (AfEP) can hardly be compared with those submitted in the West (Hinze and Grupp, 1995, pp. 42). Therefore, another method was chosen for the analysis summarized in the next paragraph, which is based on GDR patent activities in West Germany. With the help of this method, all the particularities related to patent law specifications are circumvented, enabling comparison with Western countries. GDR inventors were mostly interested in the economic sector of the former Federal Republic, so that the foreign applications submitted for this target market can be referred to (independently of whether the application was submitted to the German Patent and Trademark Office, to the European Patent Office, or to the International Patent Authority WIPO designating the Federal Republic of Germany).

A comparison of the *specialization* of GDR patent portfolios with those of West Germany is very interesting. According to a division of the whole technology area into 28 subfields, the specialization profile was constant over time. In particular, the eastern regions' patent profile of the 1990s (including East Berlin) corresponds largely with that of the GDR of the 1980s (Schmoch and Sass, 2000). In addition, there is an amazing correlation with that of West Germany. In spite of completely different economic conditions (Stolper et al., 1964), large fields of technology show a *correspondence* between East and West Germany until re-unification (Grupp and Schmoch, 1992, pp. 118). This was also found for the area of basic research (publication statistics) and can be explained by path dependencies and *persistent* structures in both parts of Germany despite their different political regimes (chapter 2.2).

When Germany was re-unified in 1990, two almost identically specialized technology systems came together. It was not possible to integrate the strength of one side and the weakness of the other one. Instead, the fields characterized by strength were the same on both sides of the "iron curtain" and the weaker fields were equally neglected. Any particular incentives to growth and innovation in the unified country are rather unlikely and thus, again, the German innovation system turns out to be very stable. This is an encouragement to undertake an econometric comparison of 1850–1913 with 1951–1999.

3 Statistical explanation of technical progress and welfare growth in Germany

In this section, we implement an econometric analysis using the economic and innovation indicators discussed in the previous sections. Our goal is to improve our understanding of the processes of innovation and growth. We compare the behavior of the variables in two periods, (1850–1913) and (1951–1999), by paying special attention to the effect of human capital, technology advances and expenditure in scientific activities to improve the standard of living. Within the scope of this contribution, we cannot go into the details of econometric analysis[6]

3.1 Variables and methodology

Our main goal is to identify the causal relationships underlying the innovation process on a macroeconomic level. Our approach is not to *define a priori* any variable as *endogenous*. This is because, with regard to econometrics, one criticism in the literature is that "there has been remarkably little attention paid to the problem of the endogeneity of the different variables used as regressors in modelling and testing growth theories" (Durlauf, 2001, p. 66). Instead, applying the state-of-the-art definitions of S&T indicators, we implement VAR tests and use the suggested causal relations to test a SURE (seemingly unrelated regression equations) model[7].

Model openness in empirical growth analysis is associated with a serious issue, the choice of variables (Durlauf, op. cit.). Therefore, new procedures that can assess the sensitivity of the estimates are required (e.g. impulse response functions, see below). In doing so, we add to the indicators that were the subject of analysis in the previous section, the usual variables for output that were not discussed above. Instead of the well-known human-capital variables such as schooling etc., which have proven to be neither very robust nor convincing (Weber, 1998, p. 49), we use the student numbers in higher education (for historical data sources see Titze et al., 1987). We have to admit that there seems to be no single privileged way to conduct empirical growth analysis, but to a certain degree this requires assumptions that cannot be falsified within the econometric procedure (Brock and Durlauf, 2001, p. 265).

The proxy specification is as follows (all are per capita and taken as logarithms):

- Human capital in Germany: the number of students in higher education (universities and technical schools) as a share of total population (variable LSTUDPK);
- Technology advances in Germany: domestic patents granted at the German Patent Office (LPATDPK);
- Government (and industry) participation in the innovation process: public (and private) expenditure in R&D activities in real terms (LEXPRPK);[8]
- Economic demand: Net National Product (in the first period) and Gross Domestic Product (in the second period) at constant market prices (1913 and 1991) per capita (LNSPRPK or LBIPRPK, resp.).

For each period, the first step checks the time series for the existence of unit roots. To address the causality issue, we then run the Granger causality tests

[6] See the full paper on econometric methodology by Jungmittag et al. (2004).

[7] See Zellner (1962, 1963); Zellner and Huang (1962), as well as Greene (2000, pp. 614–36) for a textbook presentation.

[8] To obtain public and private expenditure in R&D in real terms, we applied the price deflator of the Net National Product (in the first period) to the public science expenditure and that of the Gross Domestic Product (in the second period) to the public and private R&D expenditure at current prices.

(Granger, 1969) based on unrestricted vector autoregression models (VAR)[9]. These models normally contain some nuisance parameters which are eliminated in the third step by identifying an admissible restricted VAR model. This model serves as a starting point to identify a SURE model the equations of which only include in each case the significant variables and takes into account the contemporaneous correlations between the error terms of the individual equations.

3.2 Stationarity and causality in the first period (1850–1913)

To test for stationarity, we implement Augmented Dickey Fuller Unit Root Tests (ADF), which adequately take into account temporary additive and innovative outliers as well as structural breaks[10]. From the results it is clear that, in the first period (1855–1913), all variables are trend stationary[11]. This implies that we can model the variables as they are and that possible spurious correlations can be avoided by including deterministic trends. Yet, we need structural break dummies for the economic boom starting in 1872 (D72L) and ending around 1878 (D78L, D79L, D7278, resp.), this period also being relevant for the start-up of the national patent practice following the first national patent law. Student numbers dropped from 1870 (D70L) to 1871 (D71L) for a short period and increased strongly in 1895 (D95L).

To test for Granger causality in the first period (1850–1913), an unrestricted vector autoregression model (VAR) was first estimated. The many significant results are not reported here (compare Jungmittag et al., 2004). In order better to understand the dynamics of the model, we calculated the generalized impulse response function following Pesaran and Shin (1998). Impulse response functions measure the temporal profile of the impact of a shock at a certain point in time for the future values of the variables. From these sometimes seemingly contradictory profiles, we concluded that the model can be formulated more parsimoniously and therefore, in the next step, switched over to a restricted VAR model with one exogenous variable, namely the share of students which is not influenced by the other variables. The results, again not reported here, indicate that the model can be simplified even more and that more explicit parameters can be obtained. Therefore, in the final step, we further reduced the number of variables from the equations in a SURE model still

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[9] To analyze the empirical relationship between two stationary variables, the Granger test verifies whether past values of one can help to predict current values of the other. There are different types of Granger-causality analyses (see Hamilton, 1994, p. 302–9). Since we have several variables, bivariate tests may give rise to confusing results. For instance, there might be an effect of public expenses on output that in fact is due to human capital. This effect might be erroneously allocated to public expenses if the variable human capital is not included in the equation. Accordingly (and even though we are now not primarily interested in the dynamic properties of the innovation process) we decide to test for causality in a multivariate context, estimating a Vector Autoregressive Model (VAR). In this case the equations include lags of all variables under consideration.

[10] To this end, the tests proposed by Cati et al. (1999) (taking into account outliers), Perron (1989); Perron and Vogelsang (1993); Lumsdaine and Papell (1997) as well as Ben-David et al. (2003) (taking into account structural breaks) are applied. All estimations and statistic tests are carried out with Microfit 4.1.

[11] For details, see Jungmittag et al. (2004). Values from 1850 to 1854 were taken to calculate lagged first differences.

Table 1. Domestic patents granted as dependent variable 1855–1913

Regressor	Coefficient	Joint significance	Sum of coefficients	Long-term coefficients
Constant	-12.6984			
	(0.000)			
LNSPRPK(-1)	-1.3104			
	(0.007)			
LNSPRPK(-2)	0.4511			
	(0.447)		0.8764	1.2665
LNSPRPK(-3)	0.5672	(0.000)	(0.000)	(0.000)
	(0.343)			
LNSPRPK(-4)	1.1685			
	(0.016)			
LPATDPK(-1)	0.3080			
	(0.001)			
LEXPRPK(-5)	0.2101			0.3036
	(0.046)			(0.025)
D71L	-0.4375			
	(0.004)			
D72L	0.7917			
	(0.000)			
D78L	0.3259			
	(0.003)			
	$R^2_{\mathrm{adj.}}$ = 0.9846	DW = 1.7395		

Notes: Levels of significance in brackets.

ensuring that the common significance of variables with all their lags was given. As a result, it was found that the public expenditure on science is mainly influenced by per-capita income in the long term (statistical coefficients not reported here). Also highly significant is the share of students in the total population (lagged by two years). The lagged patent grants (by one to three years) are individually and jointly highly significant, but because of opposing signs, neither the short-term nor the long-term effect is statistically different from zero. Thus, public involvement in science is mainly influenced by increasing demand (or standard of living of the population) and the intellectual potential or human capital available.

Table 1 shows the corresponding relations for patent activity. Again, the highly significant positive influence of per-capita income is visible: in the long run, patent grants per-capita increase by 1.3% if per-capita income grows by 1%. Interestingly, public science expenditure also exerts a highly significant influence on patent granting with a lag of five years.

On the other hand, net domestic product per-capita is significantly influenced by patent grants and student numbers (joint significance). However, if one differentiates between short-term and long-term impacts, the patent variable remains positive but slightly below the weak significance level of 10%. The influence of student enrolment remains negative (see Table 2).

Table 2. Net domestic product as dependent variable 1855–1913

Regressor	Coefficient	Joint significance	Sum of coefficients	Long-term coefficient
Constant	2.3332			
	(0.005)			
LNSPRPK(-1)	0.2708			
	(0.025)			
LNSPRPK(-2)	0.1581			
	(0.224)			
LNSPRPK(-3)	-0.2432			
	(0.038)			
LPATDPK(-2)	-0.0400			
	(0.066)		0.0201	0.0247
LPATDPK(-3)	0.0601	(0.016)	(0.122)	(0.123)
	(0.007)			
LSTUDPK(-1)	-0.1533			
	(0.170)			
LSTUDPK(-2)	0.0105			
	(0.917)		-0.3120	-0.3832
LSTUDPK(-3)	0.1441	(0.000)	(0.000)	(0.000)
	(0.179)			
LSTUDPK(-4)	-0.3133			
	(0.002)			
T	0.0176			
	(0.000)			
D7278	0.0843			
	(0.000)			
	$R^2_{\text{adj.}}$ = 0.9901	DW = 1.9001		

Notes: Levels of significance in brackets.

Altogether these results confirm the linear relationship between innovation activity, both on the side of inputs and outputs and increasing demand as a consequence of growing per-capita income in the period from 1855 to 1913. Additionally, public science expenditure increased innovation output considerably, although this was in a competitive relation to human capital.

3.3 Stationarity and causality in the second period (1951–1999)

The starting point for analyzing the second period between 1951 and 1999 was once again the assessment of structural breaks. For all time series, the structural breaks were definite, namely one around the year 1972 (oil price crisis) and the other for the "new" unification of Germany in 1991. These structural breaks, unlike the first period, did not only cause shifts in the levels of the variables involved, but also affected the trends themselves. This is particularly true for student enrolment and thus the expansion of the academic system after 1972. We use D72L and D91L to

Table 3. Public and private R&D expenditure as dependent variable 1956–1999

Regressor	Coefficient	Significance level	Long-term coefficient	Significance level
Constant	-1.5173	0.000		
LBIPRPK(-1)	0.3669	0.034	0.8490	0.000
LEXPRPK(-1)	0.5679	0.000		
T	0.0304	0.000		
D72L	0.3534	0.000		
D72L*T	-0.0213	0.000		
D91L	-0.1857	0.000		
	$R^2_{\mathrm{adj.}}$ = 0.9987	DW = 1.7970		

Table 4. Student numbers per population as dependent variable 1956–1999

Regressor	Coefficient	Significance level	Long-term coefficient	Significance level
Constant	-4.1225	0.000		
LPATDPK(-1)	-0.0855	0.001	-0.1473	0.000
LSTUDPK(-1)	0.4199	0.000		
T	0.0264	0.000		
D72L	0.2493	0.000		
D91L	0.8681	0.000		
D91L*T	-0.0256	0.000		
	$R^2_{\mathrm{adj.}}$ = 0.9984	DW = 1.3986		

denote the break in levels, and D72L*T and D91L*T to denote the trend changes. In the second period investigated, the time series for science expenditure and students are definitely trend stationary[12], whereas patent data seem to be ambivalent and only the gross domestic product is not stationary. However, in order to arrive at a comparable analysis to the first period, we analyze the variables as they are.

Again, the unrestricted VAR model and an analysis of the impulse response functions show that the full model can be simplified and accumulated considerably (in particular using the results of the restricted VAR model; see Jungmittag et al., 2004, for details). By reducing the non-significant variables from the equations in the SURE model, we arrive at the following relations for total R&D expenditure (Table 3). Exactly the same as in the first period in the 19^{th} century, R&D expenditure is mostly driven by per-capita income in post-war Germany. But in this period, there is no positive influence of human capital, which may be due to the fact that private R&D expenditure is included here as well. So it is interesting to learn more about the explanation of student enrolments per capita (Table 4).

The relative number of students in the population is explained by a highly significant negative influence of per-capita patent grants. This points to the fact

[12] Here, values from 1951 to 1955 were taken to calculate lagged first differences. For details of the ADF tests see Jungmittag et al. (2004).

Table 5. Domestic patents granted as dependent variable 1956–1999

Regressor	Coefficient	Significance level	Long-term coefficient	Significance level
Constant	18.5941	0.007		
LBIPRPK(-1)	-3.0050	0.001	-3.9870	0.002
LPATDPK(-1)	0.2463	0.058		
LEXPRPK(-1)	0.8250	0.010	1.0945	0.016
D72L	-0.6515	0.002		
D72L*T	0.0373	0.000		
D91L	-0.2468	0.018		
	$R^2_{adj.}$ = 0.6910	DW = 2.1815		

Table 6. Gross domestic product as dependent variable 1956–1999

Regressor	Coefficient	Significance level	Long-term coefficient	Significance level
Constant	4.2277	0.000		
LBIPRPK(-1)	0.5714	0.000		
LPATDPK(-1)	0.0250	0.204	0.0584	0.191
T	0.0180	0.000		
D72L	0.1969	0.002		
D72L*T	-0.0097	0.001		
D91L	-0.0609	0.000		
	$R^2_{\mathrm{adj.}}$ = 0.9963	DW = 1.7691		

that there is still a competitive situation between public and private resources of national innovation processes.

For the explanation of relative patent numbers in the short term, the negative influence of per-capita income is surprising (Table 5). However, considering our analysis of the impulse response function for the non-restricted VAR model, one can expect that a small positive effect will occur for longer time periods. In addition, there is a very strong positive influence of gross national R&D expenditure. In the long run, we can assume that there is a one-to-one relation between the increase in gross national R&D expenditure and patent grants. Finally, we look at the gross national product in Table 6. It is confirmed that all the innovation-related variables do not explain gross domestic product. This is also true for the long-term impact of patent grants.

Finally, our results for the second period point to the strong influence of demand on innovation performance, or, in other words, an increasing standard of living boosts innovation activities. What is quite different from the 19^{th} century is the fact that patent grants now depend on both public and private R&D expenditure and are no longer influenced by demand. This certainly reflects the continuing importance of public contributions to innovation in this period and also the intertwining of science (mostly supported by public sources) and technology (mostly supported by the private company sector) rather than a linear (sequential) relation, as was the case in the 19^{th} century. A different picture emerges, however, if the more traditional variables of capital and labor are added to the model (see Jungmittag et al., 1999).

4 Discussion and conclusions

The view into historical innovation reveals many interesting perspectives: Most astonishingly, the German innovation system was very *stable*, although it witnessed several political system changes in the past century. The total amount of government spending on science and innovation followed similar quantitative tracks after its formation in the 19^{th} century, the First World War and the Second World War. However, considerable differences are observed when regarding the strong role of enterprises on innovation after the Second World War which was – in pecuniary terms – not as visible before. In terms of the basic sectoral structures in science and technology, the strong and the weak sides were almost the same, whatever regime and territorial boundaries existed. This *persistence* of the innovation system points to a *resistant innovation culture* in and around Germany, which may not be influenced much by external shocks or incentives be it in monetary or institutional form. Even the isolation of the former GDR and its subjection under the communist regime could not change much. This sustainable culture imprint can only be analyzed and detected in historical time series.

The industrial research system in Germany was one of the first in the world to be formed and developed. Other countries followed that pattern more or less closely. The suggested range of indicators on a national level gives a detailed impression of both the extent and the contents of innovation activities during more than the past hundred years. The empirical base is now broadened to a large extent, so that there is no longer a serious *empirical gap*.

As the German innovation system has turned out to be stable even though it witnessed several political system changes in the past century, an econometric comparison of 1850–1913 with 1951–1999 is allowed. The econometric analysis is performed in three steps in order to arrive at an appropriate, and at the same time parsimonious, model. In the first step, the statistical characteristics of the single time series are clarified, with a special attention to structural breaks. In the second step, an unrestricted VAR model is estimated, while in the final step some nuisance parameters are eliminated (SURE model). In the first period, the period of the formation of a liberal, unified and large market with ongoing "scientification" of technology, the overall empirical results point to a linear relation. Per-capita income as a variable for economic demand, as well as student numbers (as a share of total population), explain public science expenditure. These – lagged by five years – explain, together with per-capita income, the number of patents granted and thus the growth of the technological potential in Germany. The net domestic product (per capita) is positively, but not significantly, influenced by patent numbers in a competitive situation with human capital (student numbers have a negative influence). Overall, in the early period, the results point to a strong influence of growing demand on innovation activities.

Yet, for the second period in the post-war twentieth century, a different logic in the innovation process is suggested: Now, the total R&D expenditure (public and private) are driven by per-capita income, while patent output does not follow demand but only R&D expenditure. The real domestic product seems not to depend on innovation activities; there seems to be only a very weak but positive influence of patent numbers among all possible variables. A different picture arises, however, if the more traditional variables of capital and labor are added to the model (see Jungmittag et al., 1999).

The future research agenda should include more such long studies of innovation systems. The basic findings for Germany should be compared to other countries that possibly suffered less from territorial and political changes. The data used in this article should exist in other countries as well and may be brought to the surface. Also, we need more sectoral studies in order to work out typologies of innovation development over long periods. Altogether the results achieved so far should encourage more such research based on the evolutionary understanding of long-term development.

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