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Regional Knowledge and the Emergence of an Industry: Laser Systems Production in West Germany, 1975–2005

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Abstract

We analyze the emergence and spatial evolution of the German laser systems industry. Regional knowledge in the related field of laser sources, as well as the presence of universities with physics or engineering departments, is conducive to the emergence of laser systems suppliers. The regional presence of source producers is also positively related to entry into laser systems. One important mechanism behind regional entry is the diversification of upstream laser source producers into the downstream systems market. Entry into the materials processing submarket appears to be unrelated to academic knowledge in the region, but the presence of laser source producers and the regional stock of laser knowledge are still highly predictive in this submarket.

Keywords: Innovation, regional knowledge, laser technology, emerging industries, diversification.

JEL classification: L22, L69, R11, O52

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1. Introduction[1]

Radical product innovations often establish new markets and give rise to the emergence of new industries. They may also lead to the emergence of new *related* industries, for example, by providing the basis for the development of new applications in downstream markets. In this way, radical product innovations may not only give rise to changes in the national industry structure, but can also be a powerful source of growth in those regions where the early producers of the new industry (or industries) are located.

Over the past decades, numerous studies on the emergence and evolution of new industries have contributed to our knowledge about the factors that determine the economic development of nations as well as of regions (recent examples include Comin, Hobijn and Rovito, 2008; Comin and Hobijn, 2010, Klepper, 2010). However, much less is known about the evolution of related markets and industries that emerge on the basis of radical product innovations. In particular, the role of region-specific factors in such processes is not well understood. Where do such related industries arise first and what are the reasons for their early occurrence?

To help answer these questions, this paper analyzes the geographic development of the laser systems industry in West Germany during its formative years from 1975 to 2005. The laser is regarded as one of the most important scientific inventions of the 20th century (Bertolotti, 2005) and has found many applications. The evolution of this science-based

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[1] This paper is based on the project "Emergence and Evolution of a Spatial-Sectoral Systems of Innovation: Laser Technology in Germany, 1960 to Present" jointly conducted by the Friedrich Schiller University Jena, the University of Kassel, and the Technical University Bergakademie Freiberg. We are particularly indebted to our co-workers in this project, Helmuth Albrecht, Cornelia Fabian, and Matthias Geissler. Wolfgang Ziegler and Sebastian Schmidt provided invaluable help in preparing and processing the data. Financial support from the Volkswagen Foundation is gratefully acknowledged. We are grateful to Ljubica Nedelkoska for comments on an earlier version of this paper.

industry has attracted considerable attention from economists.[2] Their work has mostly focused on laser sources. In contrast, the related laser systems industry—which produces the devices and machines that put laser sources to useful applications in various submarkets such as materials processing, information transmission and storage, measurement technology, and health care, to name but a few—has been left largely unexplored.

We investigate the emergence of commercial laser systems suppliers in West Germany from a regional perspective. Our analysis reveals that the emergence of the laser systems industry was highly dependent on regional factors. The presence of laser source producers and of universities with departments of physics and/or engineering was closely related to the first entry of laser systems suppliers in a region, and the probability of entry into the laser systems industry increased with the regional stock of laser knowledge, as indicated by the number of laser-related patents. Furthermore, the analysis suggests that existing (upstream) laser source producers considerably shaped the geography of the (downstream) laser systems industry, mostly through their own diversification. The role of public research apparently varied across submarkets; in laser-based materials processing, this type of research was less important than it was in the fields of health care and measurement, which are more directly related to medical and scientific research.

In what follows, we first discuss the theoretical framework and hypotheses informing our empirical analysis (Section 2). Section 3 introduces the data and Section 4 provides an overview of previous work on the spatial diffusion of the laser industry. We then describe the geography of the laser systems industry in West Germany (Section 5) and

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[2] Sleeper (1998), Grupp (2000), Klepper and Sleeper (2005), Klepper and Thompson (2006), Buenstorf (2007), Buenstorf and Geissler (2010), and Fritsch and Medrano (2010).

analyze the determinants of the first regional occurrence of laser systems producers (Section 6). Section 7 concludes.

2. Theoretical framework

2.1 Space and the evolution of new industries

Understanding why new industries emerge and prosper in some regions but not in others is a core issue in economic geography. Ellison and Glaeser (1997) show that the vast majority of U.S. manufacturing industries are more concentrated than would be expected based on random processes alone. However, few industries are characterized by extreme levels of spatial concentration in the fashion of Silicon Valley or, historically, the U.S. automobile industry in Detroit. On the contrary, the spatial distribution of most industries can be characterized as “slight concentration” (Ellison and Glaeser, 1997). Similar results were obtained for Germany by Alecke et al. (2006).

The notion of agglomeration economies plays a big part in attempts to explain the spatial evolution of an industry. It is widely assumed that regional concentrations of economic actors and, particularly, spatial proximity to important sources of knowledge may play an important role. With respect to the emergence of innovative industries, empirical evidence suggests that knowledge spillovers tend to be geographically bounded, and that they exert a positive effect on innovation activities (Feldman, 1999). There are various potential sources of knowledge spillovers. Beginning with Marshall (1920), localized knowledge flows within industries have traditionally been highlighted as a source of localization economies (cf., e.g., Henderson et al., 1995). Jacobs (1969) and numerous subsequent studies argue that knowledge flows across industries may also provide important stimuli for innovation, providing benefits to producers located in urbanized regions that contain a wide variety of industrial activities (Glaeser et al., 1992).

Particularly in the case of science-based industries, universities and other public research organizations may generate important geographically mediated spillovers (Feldman, 1994) that can have pronounced effects on industrial location patterns. If knowledge tends to be sticky and regionally anchored, the presence of universities may be a valuable inducement for the co-location of firms in close proximity (Anselin, Varga, and Acs, 1997; Zucker, Darby, and Brewer, 1998). Empirical evidence indicates that the impact of university research on regional innovative output depends on the intensity and quality of this research (Fritsch and Slavtchev, 2007).

Klepper (2006) suggests that spin-off dynamics, rather than agglomeration economies, are the main force behind extreme spatial concentration of industries. In the U.S. automobile (Klepper, 2007, 2010), tire (Buenstorf and Klepper, 2009, 2010), and semiconductor industries (Klepper, 2010), entry often occurred in spatial proximity to successful firms, which frequently spawned similarly successful spin-offs in their regions. Because spin-offs tend to locate close to their geographic roots (i.e., in proximity to the founders' prior employers), industry clusters emerge around successful early producers, leading to concentration in the region. Several empirical studies identify the spin-off process as an important driver of spatial concentration in a variety of industries, including footwear (Sorenson and Audia, 2000), telecommunications (Dahl, Pedersen and Dalum, 2003), and fashion design (Wenting, 2008).

The importance of spin-off activities suggests that incumbent firms play a dual role in the spatial evolution of industries. First, their activities can give rise to traditional agglomeration (localization) economies, which generally improve the regional conditions for other producers and also facilitate entry of new producers. Second, they involuntarily educate potential entrepreneurs in their industry and may thus become a source of new (spin-off) firms. While both types of effects imply spillovers, these spillovers are less diffuse in the latter case and restricted to the incumbents' employees and their ventures. A very similar argument can be made for universities and other public research organizations. They may be sources of potentially powerful knowledge spillovers that benefit regional producers, *and* they can directly contribute to new entry via entrepreneurial activity by researchers and students.

Similar to industry incumbents and universities, existing firms in related industries can play two roles in the evolution of new industries. On the one hand, they may be a source of agglomeration economies. Localized knowledge spillovers may extend beyond narrowly defined markets, for example, because producers in multiple related industries all use a specific component or input. Geographic proximity to producers in closely (vertically or horizontally) related markets will then give rise to positive externalities. On the other hand, these preexisting firms in related industries can diversify into the target industry and in that way directly contribute to entry into that industry. Hence, similar to incumbent firms in the target industry (as sources of spin-offs) and universities (as sources of academic start-ups), firms in related industries may (as diversifiers) enlarge the pool of potential entrants in the region.

Klepper (2006) and Boschma and Wenting (2007) find the location of new entrants to be influenced by the spatial distribution of related industries. In the case of the emerging U.S. television receiver industry, the earliest (and most successful) entrants were prior radio producers that diversified into the new industry (Klepper and Simons, 2000). Therefore, the spatial distribution of television producers was greatly influenced by the location of radio firms so that the new industry concentrated in those regions where radio producers were already clustered (Klepper, 2006). In the case of the U.S. automobile industry, Klepper (2006) finds that an important related industry was carriages and wagons, and that regions with producers in this industry had more new entrants in the automobile industry. The importance of related industries is confirmed by the case of British automobile manufacturers, where the main center, Coventry, was already home to the country's bicycle industry (Boschma and Wenting, 2007). In this industry, the regional endowment of firms in related industries was particularly important in the years before spin-offs started by industry incumbents gained importance.

2.2 Hypotheses on the emergence of laser systems producers

To compete successfully, entrants in emerging industries need adequate competences and knowledge. Empirical evidence on industry evolution shows that prior activities in related application markets are a relevant source of competence for preexisting firms (Helfat and Lieberman, 2002). Likewise, entrepreneurial opportunities are often discovered and realized by individuals who have a background related to a specific application or user need (Shane, 2000; Klepper and Sleeper, 2005; Chatterjii, 2009). In the context of the laser systems industry, incumbent producers of traditional medical or materials processing systems (or their entrepreneurially inclined employees) may have realized early on that lasers could be used to develop new devices in their areas of specialty.

As potential entrants into the downstream market, incumbents in related application markets possess knowledge related to the application, but lack in-depth knowledge of the new upstream technology. If this knowledge is geographically sticky, as is to be expected, particularly for early stages of technology development when the degree of codification is relatively low, then proximity to upstream producers will facilitate acquisition of the necessary knowledge by potential entrants. Moreover, the recognition of opportunities for applying the upstream technology may be facilitated by the local presence of that industry—a conjecture that closely resembles Jacobs's (1969) argument about cross-fertilization of innovators in cities. In addition, upstream producers may diversify into the downstream market. Their situation is the opposite of that of entrants coming from related applications: that is, they know more about the new upstream technology, but less about the downstream application. To the extent that diversifiers locate their up- or downstream activities in close geographic proximity to their current location, this will lead to the co-location of both industries.

These considerations predict the following patterns for the laser systems industry:

H1: The geographic distribution of the laser systems industry closely resembles that of the laser sources industry and exhibits a similar degree of spatial concentration, particularly in its initial years.

H2: Commercial systems applications of laser research will first occur in regions where laser source producers are concentrated.

Like the upstream producers, universities and other public research organizations may generate and possess new scientific knowledge that is useful for producers in downstream markets. This knowledge may be of two kinds. First, it can relate to the upstream technology, in which case public research may be a substitute for the knowledge of upstream producers. Second, scientific knowledge can relate to specific applications, in which case public research would complement the knowledge of upstream producers. This type of knowledge should be most relevant in those submarkets where the applications are closely related to research activities. In the laser systems industry, this is primarily expected to be the case for medical and research applications and to a lesser degree for materials processing.

As noted above, a number of studies have found scientific knowledge to be sticky in space, which suggests that it has substantial elements of non-codified knowledge. In addition, university researchers may become entrepreneurs in the downstream industry. Prior research on academic entrepreneurship shows that academic start-ups mostly occur in spatial proximity to the spawning university (Audretsch and Stephan, 1996; Egeln, Gottschalk, and Rammer, 2004). Through its effects on both knowledge spillovers and academic entrepreneurship, we therefore expect regional scientific research on lasers to be directly related to the emergence and ongoing presence of laser systems producers. Furthermore, we expect the presence of universities and other public research organizations to exert a stronger effect on the geography of the downstream industries in those submarkets that are more directly science-based. Specifically, we predict the following empirical relationships:

H3: Commercial systems applications of laser research will first occur in regions where research in the field of laser technology is conducted.

H4: Laser research will exert a stronger influence in systems submarkets that are more directly related to science.

We have stressed the dual role (provision of knowledge spillovers and source of new entrants) that both upstream producers and public research may play in shaping the geography of a downstream industry. For upstream producers, we can disentangle these roles by excluding those firms that diversified downstream from the production of laser sources into laser systems, which effectively provides a purer measure of knowledge spillovers. We predict the following relationship for the laser systems industry:

H5: Commercial systems applications of laser research will first occur in regions where laser knowledge is concentrated, even when the entry of upstream firms that diversify downstream is disregarded. The effect of laser source producers on the laser systems industry should, however, be considerably smaller as compared to the full sample.

3. Data

The term “laser” is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. The term describes a wide range of devices for the amplification of coherent light by stimulated photon emission generated by pumping energy into an adequate medium. A laser device emits *coherent* light, both in a spatial and in a temporal sense. This coherent light can be generated from various media, for example, solid crystals or semiconductors.

The laser industry as a whole is characterized by a complex mix of products, components, applications, and submarkets. For the purpose of our analysis, we classify the producers into two main groups.

- The first group is comprised of the *commercial laser source manufacturers*. These are firms that produce and market laser sources, i.e., devices that generate the laser effect by using one of several materials that determine the type of laser: e.g., solid state (crystals), semiconductor, chemical dye, or gas. Laser sources are a key component for the downstream laser systems industry.
- The second group is the *laser systems producers*, i.e., those firms that do not produce laser sources themselves, but integrate them into devices and machines for various applications, such as for materials processing, optical measuring, research applications, and health care.

In practice, there is considerable overlap between the two groups since a number of firms produce both sources and systems. If a firm markets both sources and systems, it is listed in both groups, and characterized as a “source and systems” supplier. If systems producers also produce laser sources in-house but the sources are not marketed separately, we classify them as “only systems” suppliers.

Our information about laser source producers is derived from the dataset analyzed in Buenstorf (2007), which identifies all German laser source manufacturers and includes detailed information about the time of market entry as well as entrants’ pre-entry experience (e.g., diversifier, spin-off, academic start-up). The dataset was assembled from a variety of sources, including trade publications, trade fair catalogs, listings in laser buyer guides, and firm registers (for a detailed description, see Buenstorf, 2007). Based on this database, we identify 128 source producers with 135 establishments for the period 1964 to 2005 in West Germany.

With respect to laser systems producers, we employ the LASSSIE dataset on the German laser industry described in Buenstorf and Geissler (2010), which covers the full universe of firms in all segments and submarkets of the German laser industry.[3] This dataset provides information about the number of laser systems producers per region and year, and allows us to identify systems suppliers by considering all establishments listed at least once in one or more of four main product categories: laser systems for “materials processing,” “health care,” “measurement, analytics, and communication,”[4] and “others.”

Since firms may have multiple production locations in various regions, we perform the analysis on the level of establishments, which can be unambiguously assigned to regions. For West Germany, we identified 789 establishments listed as systems suppliers in the 1975–2000 period, i.e., firms involved in integrating laser sources into commercial applications in at least one the above-mentioned product categories.[5] Systems suppliers have entered 68 of the 74 West German planning regions.

We use laser-related patent applications to measure the generation and accumulation of laser-related knowledge at the regional level. Patent data were obtained from the DEPATISnet database (www.depatisnet.de) maintained by the German Patent and Trademark Office (DPMA). From this database we selected all patent applications with West German priority that were assigned to the technological field “devices using stimulated emission” (IPC H01S) as either the main or the secondary class. Hence, patents that are related to laser applications such as printing and measurement but not to the laser source itself were not considered. Because not all early patents are electronically coded, we also consulted

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[3] Part of this dataset is constructed from the firm listings in the catalogs of the biannual trade fair “Laser World of Photonics,” an international trade fair for laser and optical technologies, including laser systems, components, and applications. The catalogs list producers from the entire range of laser sources and systems. First organized in 1973, “Laser World of Photonics” has grown to be the world’s largest trade fair for industrial lasers, and it also attracts producers from a wide range of other systems applications, notably health care and life science applications (http://world-of-photonics.net). Another important source is the “LASER Branchenführer,” which is an industry register listing active firms in the laser market starting in the year 1991.

[4] This category also includes systems for materials testing and defense applications.

[5] To some extent, this number is biased upward by distributor and/or importer establishments that are also included in the firm listings.

secondary sources, such as the patent register of the Friedrich Schiller University Jena.[6] From the patent data we obtained information about the applicant organizations, the inventors residing in West Germany, and their home address at the time of application. Patent applications are assigned to the region where the inventor resides.

Information about university departments and institutes whose fields of activity and/or research were close to emerging laser technology was obtained from two main sources. First, from the *Vademecum* registers, which contain information on all academic institutions in West Germany. These are published at four-year intervals, and we employed the registers issued from 1961 to 1992. For the remaining years, 1993 to 2005, data were taken from the German University Statistics issued by the German Federal Statistical Office. For the purpose of this study, we classified academic institutions as relevant for laser technology if they had departments in physics (including general physics, theoretical physics, experimental physics, applied physics, technical physics, physical chemistry, and optics) or in certain areas of engineering (electrical engineering, high frequency technology, communication technology, and mechanical engineering).

The study is restricted to the West German regions for two reasons. First, before 1990, information on the inventor's residence is incomplete in East German patent applications. Second, the 1990 regime switch from a socialist planned economy to a market system in East Germany makes this part of the country difficult to compare directly with West German regions. We also exclude the Berlin region because its boundaries changed during the period under investigation.[7]

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[6] These sources are the *Bibliographische Mitteilungen der Universitätsbibliothek Jena, 1960–1971*. We used this source particularly for collecting patents for the period 1961 to 1969, as these are not consistently documented in DEPATISnet.

[7] In the pre-unification years, Berlin, which was geographically located in the center of the former German Democratic Republic (GDR), consisted of a socialist Eastern part and a

The spatial framework of our analysis encompasses the 74 West German planning regions (*Raumordnungsregionen*). While districts (*Kreise*) frequently consist of only a core city without its surrounding area (or only part of it), planning regions generally cover both one or several core cities as well as the surrounding area.[8] They can therefore be regarded as functional units in the sense of travel-to-work areas and because they account for economic interactions between districts. Planning regions are slightly larger than what is usually defined as a labor market area.Using planning regions as spatial units of observation is particularly appropriate for our analysis since in a number of cases R&D facilities are located in a larger city, while the inventor's place of residence is in a surrounding district that belongs to the same planning region as the R&D facility.

4. Laser sources and systems industries: Composition, emergence, and spatial patterns

4.1 Composition of the laser sources and systems industries

The group of laser source producers includes several of the pioneer firms of the German laser industry, including Siemens and Impulsphysik, a Hamburg-based SME that in its early years produced laser sources for the German government (Albrecht, 1997, 114). A number of source producers subsequently diversified into the laser systems market, as commercial applications became increasingly feasible and successful. (Siemens is a case in point.) In our data, 71 establishments that started being laser source producers later diversified into the production of laser systems. They make up about 9 percent of the 789 laser systems manufacturers (Table 1). There are also 37 producers (4.7 percent of all firms in the laser

capitalist Western part. After unification, both parts of Berlin were aggregated in the official statistics.

[8] However, for historical reasons, the cities of Hamburg and Bremen/Bremerhaven are planning regions without surrounding districts. See German Federal Office for Building and Regional Planning (2003) for the definition of planning regions and districts.

systems industry) that began by supplying laser systems only but later started to produce laser sources as well. Forty-six of the systems suppliers (5.8 percent of all suppliers in the systems industry) appear to have started marketing laser systems and laser sources more or less simultaneously.[9] Overall, the establishments active in both markets—laser sources and systems—account for nearly 20 percent of all systems suppliers. Only 27 of the 135 laser source producers (20.0 percent) never entered the laser systems industry.

Table 1: Classification of laser system suppliers according to the mode of entry

	Laser systems		*Laser materials processing*	
	Number of establishments	Share of all establishments in laser systems (%)	Number of establishments	Share of all establishments in materials processing (%)
Source suppliers who diversified into laser systems	71	9.0	53	10.9
System suppliers who diversified into laser sources	37	4.7	30	6.2
Simultaneous entry into laser sources and systems	46	5.8	28	5.8
Pure system suppliers (not supplying laser sources)	635	80.5	374	77.1
Total	789	100	485	100

With regard to the four main submarkets, most of the systems suppliers have been listed as active in only one submarket (70 percent).[10]

[9] In these cases, we were unable to identify which market was entered first.

[10] Establishments supplying to two submarkets represent 19 percent of the total, to three submarkets 7 percent, and to all four only 4 percent.

By far the most important of these submarkets in West Germany is materials processing, in which 485 of the 789 (61.5 percent) listed establishments are active, followed by the submarkets of measurement, analytics, and communication (52 percent), health care, and the residual category “others” (15 percent each). Of the entrants in laser materials processing, 10.9 percent have diversified downstream from laser sources; the share of upstream diversifiers that first produced devices for laser-based materials processing and then also entered into laser sources is 6.2 percent. While 5.8 percent entered the market for laser sources and for laser materials processing at about the same time, more than 77 percent never produced laser sources.

Market estimates suggest that the laser systems market, measured in global sales in the year 2006, is about eight times larger than the market for laser sources (Optech, 2007). The global laser systems market is dominated by applications for information technology (47 percent of the total market), telecommunications (21 percent), and materials processing (13 percent), followed by microlithography (11 percent), measurement and research (4 percent), and health care (2 percent) (Optech, 2007). In Germany, materials processing is relatively more important than it is on the global scale (Heilmann, 2003).

Regarding the shares of different types of laser systems for materials processing, the global sales figures for 2008 show that laser macro-processing systems (e.g., for cutting and welding) dominate, with 77 percent of the market volume, compared to laser micro-processing systems with only 23 percent. Within the submarket of macro-processing systems, “high power cutting and welding” systems account for 51 percent, “market engraving” for 15 percent, and “low power macro, fine processing” for 12 percent of the sales volume (Optech, 2009).

4.2 Emergence of the laser source industry

Laser technology is often described as “science-based” in that (analytical) knowledge played a central role in its development (e.g., Bromberg, 1991;

Grupp, 2000; Bertolotti, 2005). Specifically, a refined theoretical understanding of laser processes was a key academic input needed for the development of the laser industry. It was one thing to generate a laser effect, which was initially a rather short flash of light; it was a completely different thing to make this light more durable and control it. In other words, to “tame” the laser it was necessary to know how it worked—and thus enters theory.

According to Grupp (2000), the laser industry experienced two main stages of development. The initial experimentation phase was unusually long and sluggish, lasting more than 20 years. It started when the first operating laser was developed in 1960 by Theodore Maiman at the laboratories of the Hughes Aircraft Company in the United States. In 1961/1962, the first patent applications were filed by the U.S. company Spectra Physics, the first firm to launch lasers on the market. These early commercial lasers were primarily for scientific research and military defense contracts. It became evident, however, that the technical concepts initially pursued were not marketable and/or that the corresponding equipment was not suitable for commercial applications. As a consequence, many producers exited the market in the 1970s. Grupp (2000) suggests that it was only around 1982 that the market for commercial laser products took off and the expansion phase of this technology began. At this stage, laser technology diversified further and began to be integrated into several commercial applications.

Entry into the U.S. laser source industry is investigated by Klepper and Sleeper (2005), who find that diversifiers accounted for 60 percent of the entrants, and spin-offs for 16 percent. With respect to the geography of the industry, there was no extreme concentration in one location; firms located throughout the United States. However, four areas had considerably more entries into the industry than others: northern California around Silicon Valley (which accounted for 15 percent of the entrants), southern California around Los Angeles (13 percent), metropolitan New York (7 percent), and Boston (7 percent).

Buenstorf (2007) analyzes the evolution of the German laser source industry from its inception in the early 1960s to 2003. Of the 143 entrants, 31 percent were industry diversifiers, 8 percent were laser distributors/importers that entered into laser manufacturing, 34 percent were corporate spin-offs, and 20 percent were academic start-ups (Buenstorf, 2007). Differences in pre-entry background affected the odds of survival in the market, with diversifiers and corporate spin-offs outperforming academic start-ups. This suggests that incumbents and individuals with industry experience were better positioned than academic start-ups as they possessed more adequate competences, for instance, knowledge about market opportunities and customer needs.

Buenstorf and Geissler (2010) observe entry into the German laser source industry in 46 out of the 97 German planning regions (including East Germany; 47 percent of all regions), with some concentration of entrants in the three largest German cities: Munich has been the leading region in terms of entrants (19 percent), followed by Berlin (14 percent), and Hamburg (6 percent). Most of the source producers tended to locate close to their geographic roots (i.e., the location of founders' or firms' prior presence; cf. Figueiredo et al., 2002; Dahl and Sorenson, 2009), with 80 percent of the entrants locating in the same region where they originated. Diversifiers from related industries occurred mainly in regions where there were many laser-related firms, academic start-ups mainly in the centers of laser research, and spin-offs mainly in locations with already existent laser source producers.

One important feature is that even in the presence of a strong spin-off process (spin-offs constituted one-third of all new entrants), the German laser source industry did not attain a pronounced level of spatial concentration. Buenstorf and Geissler (2010) speculate that this may in part be due to public research. Because universities conducting research in the field of laser technology were more evenly distributed in space than the laser source industry, both their knowledge spillovers as well as the entrepreneurial activities of their employees had de-agglomerating effects (Buenstorf and Geissler, 2010).

As outlined above, traditional agglomeration economies and spin-off processes may each play a role regarding concentrated entry into new industries. However, with regard to the laser *systems* industry, we do not know whether it follows a pattern of moderate concentration similar to that observed for the producers of laser sources, or what factors shape its geographical patterns. Was scientific knowledge and public research also relevant for commercial systems applications? Or did other factors have more weight, such as proximity to end users or to important industrial centers? Even more specifically, did the location patterns of the source producers influence the systems industry, leading to a pattern of co-location of the two industries?

In what follows we explore these issues by focusing on the extent to which regional knowledge in laser technology and research influenced the spatial distribution of the commercial laser systems industry.

5. Emergence and geographical distribution of laser systems suppliers in West Germany

Where in West Germany did the laser systems industry first emerge? Starting in 1975, the first regional entries into laser systems are recorded in 14 of the 74 West German planning regions (19 percent). Entry concentrated mainly in the regions of Munich (34 percent), Frankfurt (16 percent), Darmstadt (9 percent), Hamburg (6 percent), and Karlsruhe (6 percent). At least one source producer was also located in almost half these regions (Figure 1). Figure 1 furthermore suggests that most of the first entries, if not in a region where a source producer was already active, were at least located in geographic proximity to regions with source producers.

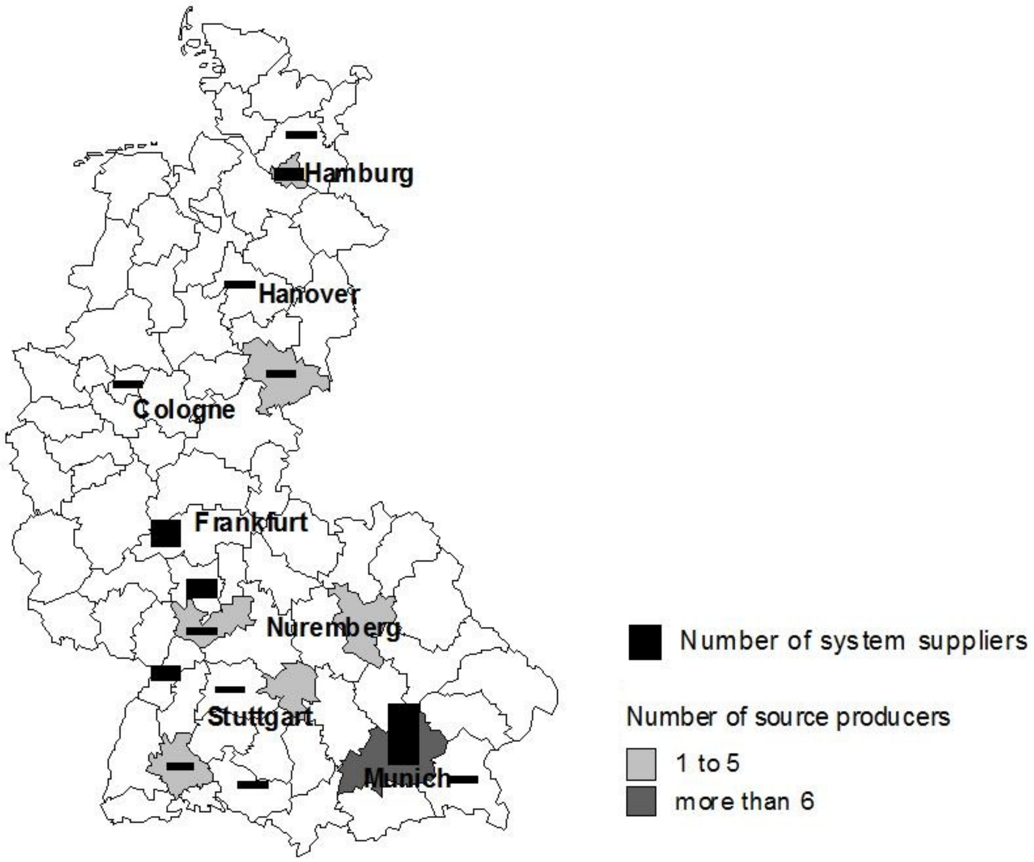

Figure 1: Regional distribution of laser systems suppliers and source producers in West Germany, 1975

In 1985, 22 percent of the regions were home to source producers and/or systems suppliers (Figure 2). As before, Munich had the highest share of all active suppliers (37 percent), followed by the regions of Frankfurt, Darmstadt, and Karlsruhe (8 percent each). From 1975 to 1985, seven regions experienced the first entry of systems producers. Three of these regions were already home to at least one source supplier.

The number of active firms peaked in the 1990s, specifically in 1999, at 273 establishments. In 1995, the systems producers were distributed over 42 of the 74 planning regions (57 percent). While Munich still had the highest concentration of both systems suppliers and source producers, its share of the total systems suppliers had fallen to 26 percent, followed by Darmstadt (9 percent), and Stuttgart (5 percent). Compared to 1985, there

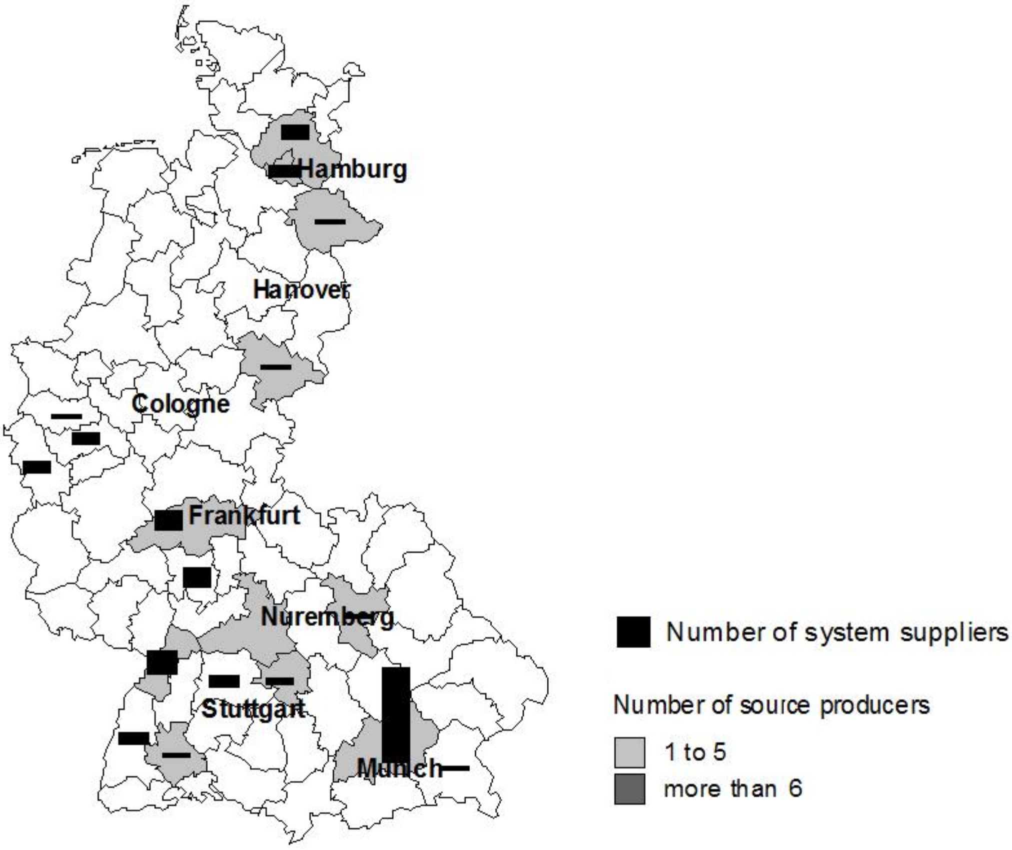

Figure 2: Regional distribution of laser systems suppliers and source producers in West Germany, 1985

is considerable variation in the regional ranking and a more even distribution of systems establishments. Forty-two percent of the regions with active systems suppliers had at least one source producer (Figure 3).

By 2005, systems suppliers could be found in 48 of the 74 planning regions (65 percent). Munich's leadership was reduced to 19 percent of all active firms. The second and third places remained stable, but now in reversed order, with Stuttgart (9 percent) ahead of Darmstadt (7 percent). Source producers and systems suppliers were co-located in 44 percent of all regions that had any laser-related establishment. The total number of listed active firms in this year was 180 (Figure 4).

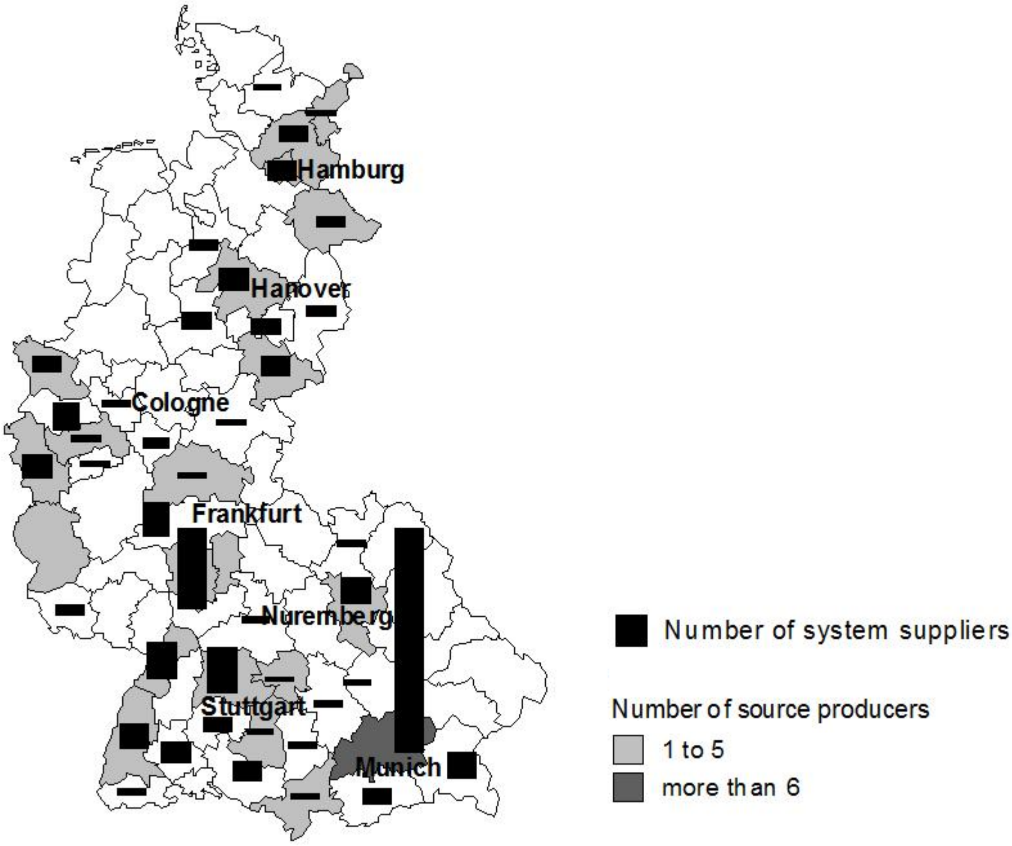

Figure 3: Regional distribution of laser systems suppliers and source producers in West Germany, 1995

To what extent did the laser source and systems industries co-evolve in space? Our first hypothesis predicts that the geographic distribution of the laser systems industry closely resembles that of the source producers, exhibiting a similar degree of spatial concentration, in particular in its initial years (H1). To test this conjecture, we estimated Spearman rank correlation coefficients for the two variables for the years shown in Figures 1 to 4. The estimated Spearman correlation coefficients range from 0.45 to 0.59, which suggests a positive and significant relationship between these two variables.[11]

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[11] Specifically, the rank correlation values are 0.45 for 1975, 0.68 for 1985, 0.51 for 1995, and 0.59 for 2005.

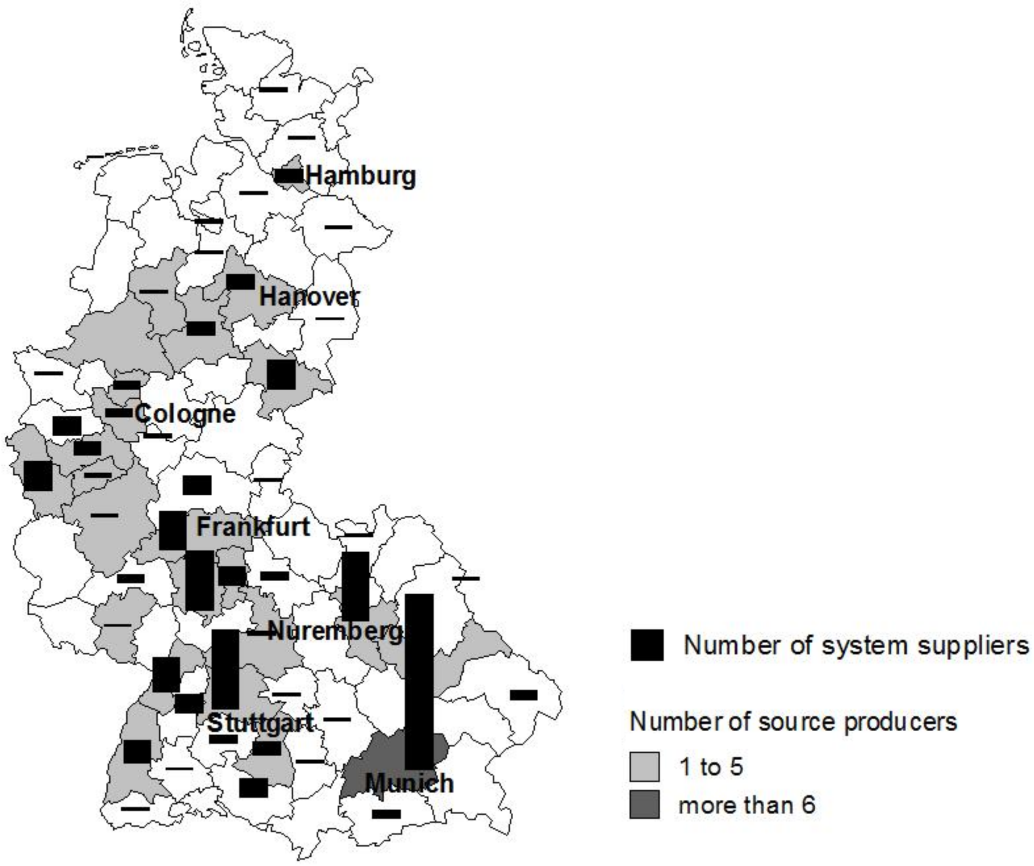

Figure 4: Regional distribution of laser systems suppliers and source producers in West Germany, 2005

Figure 5 plots the total percentage of West German regions with laser source or systems activities over time. In the late 1990s, nearly 80 percent of the regions had at least one laser systems producer and about 68 percent had at least one producer of laser applications in materials processing. The figure also shows that laser-related research at universities developed in parallel to industrial activity, which indicates the science-based character of these industries. In all years, most regions with active laser producers also had a university or public research institute active in the field of physics or in electrical engineering.

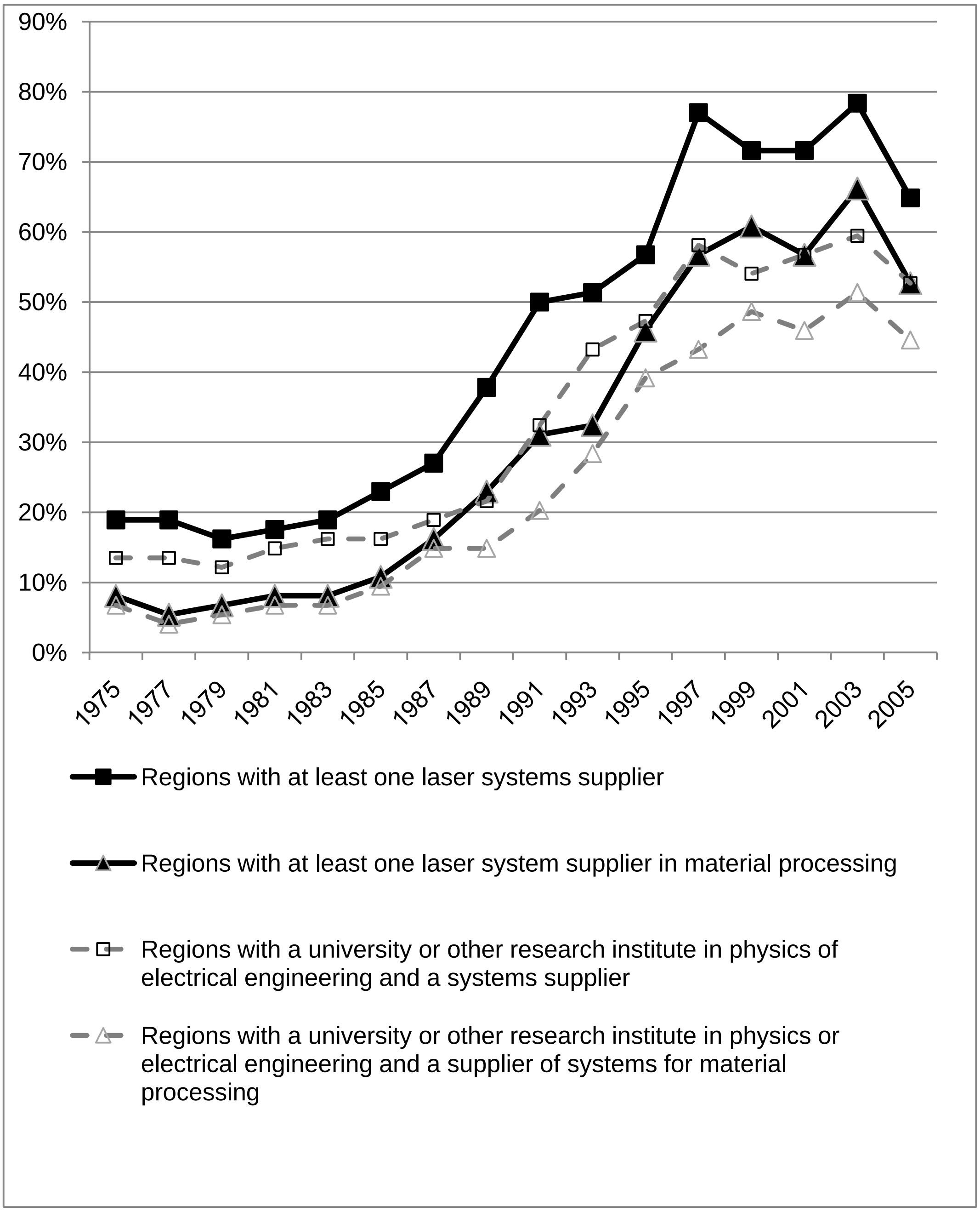

Figure 5: Regional diffusion of laser systems production as well as of universities or research institutes with a department in physics or electrical engineering, West Germany, 1975–2005

In summary, the evidence presented in this section supports Hypothesis 1, which stated that the geographic distribution of the laser systems industry is closely related to that of the laser sources industry and exhibits a similar degree of spatial concentration, particularly in its initial years. In the following section, we present some econometric results yielding further insights into the factors that helped shape the geographic distribution of the laser systems industry over time.

6. Econometric analysis

In analyzing the spatial diffusion of the laser systems industry, we investigate what determined the arrival of the first producer in that industry in a region. The analysis is first performed for the systems industry as a whole (Section 6.1), and then for one specific submarket: systems for materials processing (Section 6.2). Finally, we consider to what extent the results hold if the analysis excludes diversifiers and focuses on “pure” knowledge spillovers. To this end, we restrict the sample of establishments to those classified as being “only systems” suppliers (Section 6.3).

6.1 Regional knowledge and the emergence of the first laser systems suppliers

To analyze time-to-first laser systems producer in a region, conventional OLS regression techniques are inappropriate for two reasons. First, duration data are never negative and are generally censored because the length of the observation period is limited. Second, the distribution of the residuals of time-to-event observations in a linear regression tends not to follow the normal distribution required for hypothesis testing (Cleves, Gould, and Gutierrez, 2004). A proper methodology for our purposes is a hazard model in which the hazard function defines the probability that a region i experiences an event at time t conditional on a vector of covariates. In choosing the appropriate hazard model, a semi-parametric approach has the advantage of not making direct assumptions about the distribution of the time-to-event variable, but only with respect to the covariates of interest (Cleves, Gould, and Gutierrez, 2004).

The standard approach is a Cox proportional hazard model, which is specified as:

$$h_i(t, X_{it}, Z_i) = h_o(t)\ exp(g(t)[\textstyle\sum^{p}_{k=1} \beta_k X_{it}] + \theta_l Z_i)\ , \qquad (1)$$

where $h_i(t,X,Z)$ represents the likelihood that region *i* at time *t* experiences the event under consideration. Time is measured in years, starting with 1975 (= 0), the earliest year our data register laser systems producers entering the market.[12] Years are counted given the available observations, which start in 1975 with two-year interval information from the laser trade fairs, and then from 1991 in yearly intervals when industry registers are available. We thus have 23 years of observation points from 1975 to 2005. We define the event as the first laser systems producer (= 1) listed in the region; otherwise, the observation takes the value of zero. The baseline hazard function is by denoted $h_o(t)$, X_{it} represents the set of time-varying variables, and Z_i is the time-invariate variable.

The Cox model implies that the event of interest may occur at any particular moment on a continuous timeline, ignoring the problem of interval censoring (Allison, 1982). Although the underlying process of industry emergence can be considered as taking place in continuous time, our data do not provide the exact dates of entry, that is, observations are available only in discrete one- or two-year intervals. In this context, a complementary log-log model seems a more appropriate alternative because it allows the discrete representation of data generated in continuous time. Similar to the Cox model, it makes the proportional hazard assumption and has the desired semi-parametric characteristics. In short, the complementary log-log model is the discrete-time representation of a continuous time proportional hazard model (Allison, 1982; Jenkins, 2005). Therefore, we mainly focus on the results from this model and compare them to those from a Cox regression.

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[12] However, some pioneer firms may have entered with laser systems prototypes well before 1975. Therefore, the timing just captures the earliest "listed" systems producers, not necessarily all the first entries.

The hazard function of the complementary log-log has the form:

$$h_i(t,X,Z) = 1 - exp(-exp[c(j) + \beta' X_{it} + \theta' Z_i]) , \qquad (2)$$

where $h_i(t,X,Z)$ represents the likelihood that region i experiences the event under consideration at time t, $c(j)$ is the baseline hazard, and X_{it} and Z_i represent the independent variables.

The following variables are included in the model:

- *Cumulated laser source patents in the region (from non-source/systems suppliers):* This variable is a proxy for the regional stock of knowledge in laser technology. As discussed previously, patent applications are regionalized according to the residences of the inventor(s). To have an exogenous regressor, we classify patents according to the type of assignee as follows: patents applications filed by establishments that are “source and system” suppliers (52 percent), “only system” suppliers (7 percent), “only source” suppliers (1 percent), and, finally, those patents from assignees that are “other: neither source nor systems suppliers” (41 percent). Only patents in the latter category are considered in the econometric analysis. Their assignees are mainly firms (45 percent) that did not enter the laser sources or systems markets but used laser technology in their own products or processes. The remaining patent applications are registered to public research institutions such as the Max Planck and Fraunhofer Societies (22 percent), individuals (20 percent), co-patents (6 percent), contract research firms/others (5 percent), and universities (2 percent).

- *Source producer:* This is a dummy variable denoting the presence of active laser source producers in the region (1 = yes; 0 = no).

- *Population density:* We include population density of the region to control for its size and the number of potential researchers.

- *University:* This is a dummy variable that denotes the presence of at least one university with a department in the areas of physics, engineering, or both in region *i* at time *t* (yes = 1, no = 0).

- *Distance to Munich*: This time-invariant variable measures the average distance in kilometers to Munich for every region. This variable is included in the analysis given the high concentration shares of both systems and source producers in Munich, especially in the early stage of the industry.

- *Distance to adjacent source producer:* This variable measures for every region and year the minimum distance (in kilometers) to the next adjacent source producer, i.e., a producer not located in the region.

- *Distance to adjacent university:* This measures for every region and every year the minimum distance (in kilometers) to the next adjacent university, i.e., a university outside the region.

- *Patents from non-source/systems suppliers in adjacent regions (t-1):* To control for spatial autocorrelation, we include the patents from neither source nor systems suppliers in adjacent regions, lagged by one time period.

Finally, we include time dummies for five-year intervals, assuming that the hazard is constant over a longer interval than just one year. This assumption is necessary because otherwise the hazard cannot be estimated for time periods with no events. Descriptive statistics and correlations between variables are presented in the Appendix, Tables A1 and A2.

Columns 1–4 in Table 2 show the results from the complementary log-log model, and Columns 5 and 6 depict the results from the Cox regressions. The first column presents the results of our baseline specification, in which population density and interaction variables are not

Table 2: Regional knowledge and time-to-first laser systems supplier, 1975–2005

Variables	*Complementary log-log regressions*				*Cox regressions*	
	(1)	(2)	(3)	(4)	(5)	(6)
Cumulated number of patents (from not source/systems suppliers)	0.057** (0.023)	0.090* (0.053)	0.050** (0.024)	0.080 (0.049)	0.035** (0.016)	0.038** (0.018)
Source producer (dummy)	2.230***	2.647***	2.146***	2.082***	1.791***	1.731***
	(0.372)	(0.587)	(0.381)	(0.388)	(0.298)	(0.310)
University (dummy)	0.739***	0.884***	0.653**	0.592**	0.682***	0.601**
	(0.257)	(0.282)	(0.282)	(0.278)	(0.219)	(0.239)
Population density			0.001**	0.001**		0.001***
			(0.000)	(0.000)		(0.000)
Distance to Munich (km)	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Minimum distance to adjacent source supplier	0.001 (0.004)	0.000 (0.004)	0.000 (0.004)	-0.001 (0.004)	-0.002 (0.003)	-0.005 (0.003)
Minimum distance to adjacent university	-0.016** (0.007)	-0.017** (0.008)	-0.010 (0.007)	-0.011 (0.008)	-0.017*** (0.006)	-0.015** (0.006)
Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.012 (0.031)	0.023 (0.033)	0.010 (0.030)	0.012 (0.031)	0.028 (0.030)	0.030 (0.029)
Time dummies	Yes	Yes	Yes	Yes	No	No
Interaction terms:						
Cumulated patents * time dummies	No	Yes	No	Yes	No	No
Source producer * time dummies	No	Yes	No	No	No	No
Population density * time dummies	No	No	No	Yes	No	No
Number of observations	713	713	713	713	713	713
Log likelihood	-185.9	-180.0	-183.7	-178.0	-224.1	-217.7

Clustered robust standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

included. The regional presence of source producers and of a university with a physics/engineering department, together with the cumulated patents in the region, is positive and significantly related to the regional hazard of entry into laser systems production. From the several distance measures, only “distance to adjacent university” has the expected negative significance. In the second column, including interaction terms between “cumulated patents” and “source producer” with the time interval dummies does not significantly alter the previous results. With the exception of the “distance to adjacent university” variable, the results also remain robust to the inclusion of the “population density” variable in the third column, which, as expected, is positively related to regional entry into systems production. However, with the inclusion of interaction terms in Column 4, the “cumulated patents” variable becomes statistically insignificant, which suggests that the variation in time of the stock of knowledge and of population density may be counterbalancing the effect of the patent measure.

To further test the robustness of these results, we perform a similar analysis by employing Cox regressions; in Column 5 without population density and in Column 6 including it. In each model, the stock of cumulated knowledge in the region is statistically significant and positively related to the hazard of having a systems supplier. For the remaining variables, we obtain results similar to those found previously.

Overall, the results support Hypothesis 2, according to which commercial systems applications will first occur in regions where source producers are located. They also support the prediction that commercial systems applications will first occur in regions where laser research is conducted (Hypothesis 3) and in regions with a more substantial stock of cumulated laser knowledge (Hypothesis 4). Both the presence of relevant universities and research output in the form of patents significantly increase the hazard of experiencing the event.

6.2 Regional knowledge and the emergence of the first suppliers of laser systems in materials processing

As noted in Section 4.1, materials processing systems are the most relevant submarket of the German laser systems industry, with about 61 percent of all establishments listed as suppliers in this submarket and German firms among the global leaders (Heilmann, 2003). Nearly 23 percent of all systems suppliers in this submarket produce sources and systems; the remaining 77 percent are pure system suppliers (Table 1).

We consider two types of knowledge related to laser technology. One is application-oriented knowledge possessed by source producers and possibly codified in the source patents; the second is knowledge from universities with departments in the relevant disciplines, particularly physics and electrical engineering. Hypothesis 4 conjectures that laser research will exert a stronger influence in application submarkets that are more directly related to science. We expect that academic knowledge will tend to be less relevant for materials processing applications compared to the systems industry as a whole (which also includes measuring technology and medical applications). We therefore conjecture that in contrast to the above findings for the entire systems industry, in the materials processing submarket the presence of universities with relevant departments will not be systematically related to the hazard of experiencing the first systems entry in the region.

The results of re-estimating the above hazard rate models for the materials processing submarket are presented in Table 3. As before, we first employ the complementary log-log model (Columns 1–4), and compare these results with those from a Cox regression (Columns 5 and 6).[13] Descriptive statistics and variable correlations are presented in Tables A3 and A4 in the Appendix. Similar to the analysis for the overall systems industry, in each model and in each specification the presence of a source producer, the cumulated number of patents, and population density are positively and highly significantly related with the hazard of first entry into systems for materials processing. The main difference from the above analyses is that the presence of a university with laser-related research activities is no longer significant. This finding supports the expectation that in less science-based sectors, other types of knowledge may have more weight in determining entry. As both the regional

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[13] The time dummies used are six-year intervals because of the longer periods of disrupted entry.

Table 3: Regional knowledge and time-to-first supplier in laser materials processing, 1975–2005

Variables	*Complementary log-log regressions*				*Cox regressions*	
	(1)	(2)	(3)	(4)	(5)	(6)
Cumulated number of patents (from not source/systems suppliers)	0.089*** (0.021)	0.175*** (0.061)	0.083*** (0.022)	0.170*** (0.060)	0.064*** (0.016)	0.058*** (0.017)
Source producer (dummy)	1.159*** (0.327)	2.059** (0.878)	1.139*** (0.320)	1.260*** (0.339)	1.036*** (0.303)	1.015*** (0.296)
University (dummy)	0.121 (0.324)	0.279 (0.338)	-0.109 (0.329)	-0.061 (0.343)	0.255 (0.309)	0.093 (0.318)
Population density	-	-	0.001*** (0.000)	0.002*** (0.001)	-	0.001*** (0.000)
Distance to Munich (km)	-0.001 (0.001)	-0.001 (0.001)	-0.001 (0.001)	-0.001* (0.001)	-0.001 (0.001)	-0.001 (0.001)
Minimum distance to adjacent source supplier	0.007* (0.004)	0.003 (0.004)	0.006* (0.004)	0.003 (0.004)	0.004 (0.004)	0.004 (0.004)
Minimum distance to adjacent university	-0.006 (0.008)	-0.006 (0.009)	0.004 (0.009)	0.000 (0.010)	-0.009 (0.007)	-0.002 (0.008)
Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.032 (0.031)	0.042 (0.031)	0.034 (0.032)	0.032 (0.031)	0.047* (0.028)	0.046 (0.028)
Time dummies	Yes	Yes	Yes	Yes	No	No
Interaction terms:						
Cumulated patents * time dummies	No	Yes	No	Yes	No	No
Source producer * time dummies	No	Yes	No	No	No	No
Population density * time dummies	No	No	No	Yes	No	No
Number of observations	993	979	993	993	993	993
Log likelihood	-193.4	-183.4	-190.2	-181.3	-211.6	-209.6

Clustered robust standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

presence of source producers and regional patenting activities are related to the entry of systems suppliers, codifiable knowledge about laser source technology seems to be one (but not the only) relevant type of knowledge.

Again, the distance variables contribute little to understanding the location decisions of systems suppliers, as none of them yields robust results in any specification. The distance to adjacent source suppliers is marginally significant (albeit with a sign opposite that expected) in one model but becomes insignificant when interaction terms are included and in the Cox models. Also the “distance to Munich” variable is marginally significant in only one of the specifications.

6.3 Regional entry excluding diversifiers

We previously argued that upstream producers (source producers) and public research may play important roles in the geography of the downstream emerging industry (systems suppliers). These effects may be achieved via knowledge spillovers and/or by entry of diversifying source producers and academic start-ups. In this section, we disentangle the possible effects of preexisting source producers by excluding entries of diversifying source producers. Hypothesis 5 conjectured that even when the source producers that diversified downstream into the laser systems industries are excluded, the commercial systems applications of laser research will still tend to first occur in regions where laser knowledge is concentrated. However, we expect the effect of the laser source producers on the laser systems industry to be considerably smaller than in the full sample.

Estimations based on the reduced sample (Table 4) show that the stock of laser knowledge in the region is positive and highly significant, whereas the effect of “source producer” is statistically significant in only one of the models. Also, the “university” variable remains highly significant. One main difference from the full-sample estimations (Table 2) is that the “distance to Munich” variable is now statistically significant in four of the six models. These results indicate that the regional knowledge base has a positive effect on entry into the systems industry, whereas this is not the case for the presence of source producers. Put differently, it appears that source providers were primarily relevant for the downstream systems industry in their role as diversifiers and less so as a source of knowledge spillovers.

Table 4: Time-to-first laser systems supplier excluding diversifying source producers from the regional entry event, 1975–2005

Variables	*Complementary log-log regressions*				*Cox regressions*	
	(1)	(2)	(3)	(4)	(5)	(6)
Cumulated patents (from not source or systems suppliers)	0.071*** (0.024)	0.110** (0.049)	0.062*** (0.024)	0.100** (0.043)	0.055*** (0.018)	0.047*** (0.017)
Source producer (dummy)	0.425 (0.437)	1.590*** (0.584)	0.326 (0.433)	0.349 (0.446)	0.355 (0.387)	0.258 (0.389)
University (dummy)	0.614** (0.251)	0.785*** (0.282)	0.535* (0.278)	0.538** (0.256)	0.625*** (0.229)	0.564** (0.256)
Population density	-	-	0.001*** (0.000)	0.001*** (0.000)	-	0.001** (0.000)
Distance to Munich (km)	-0.001* (0.001)	-0.001 (0.001)	-0.002** (0.001)	-0.001* (0.001)	-0.001 (0.001)	-0.001* (0.001)
Minimum distance to adjacent source supplier	0.004 (0.003)	0.001 (0.004)	0.003 (0.003)	0.002 (0.003)	0.001 (0.003)	0.000 (0.003)
Minimum distance to adjacent university	-0.013** (0.007)	-0.012 (0.008)	-0.006 (0.007)	-0.008 (0.008)	-0.014** (0.006)	-0.008 (0.006)
Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.009 (0.030)	0.024 (0.031)	0.005 (0.030)	0.006 (0.030)	0.029 (0.033)	0.025 (0.033)
Time dummies	Yes	Yes	Yes	Yes	No	No
Interaction terms:						
Cumulated patents * time dummies	No	Yes	No	Yes	No	No
Source producer * time dummies	No	Yes	No	No	No	No
Population density * time dummies	No	No	No	Yes	No	No
Number of observations	770	757	770	770	770	770
Log Likelihood	-204.1	-189.9	-200.5	-192.2	-229.3	-227.0

Clustered robust standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

This situation is even more pronounced in the materials processing submarket. Again eliminating diversifiers from the laser sources industry (Table 5), the presence of source producers is statistically insignificant except in one of the models, while the local presence of universities remains insignificant in all models. Interestingly, the effect of regional patent stock remains positive and highly significant, suggesting, as with

Table 5: Time-to-first supplier in laser materials processing (excluding "source and system" suppliers from the regional entry event), 1975-2005

Variables	*Complementary log-log regressions*				*Cox regressions*	
	(1)	(2)	(3)	(4)	(5)	(6)
Cumulated patents (from not source/systems suppliers)	0.084*** (0.019)	0.126** (0.063)	0.078*** (0.018)	0.128*** (0.044)	0.068*** (0.015)	0.070*** (0.023)
Source producer (dummy)	0.539 (0.375)	2.225** (0.942)	0.557 (0.359)	0.573 (0.370)	0.483 (0.351)	0.482 (0.353)
University (dummy)	0.176 (0.321)	0.316 (0.343)	-0.046 (0.342)	-0.042 (0.342)	0.236 (0.297)	0.054 (0.313)
Population density	-	-	0.002*** (0.000)	0.002*** (0.001)	-	0.002*** (0.000)
Distance to Munich (km)	-0.001 (0.001)	-0.001 (0.001)	-0.001* (0.001)	-0.001* (0.001)	-0.001 (0.001)	-0.001* (0.001)
Minimum distance to adjacent source supplier	0.002 (0.005)	-0.001 (0.005)	0.002 (0.004)	-0.001 (0.005)	0.001 (0.004)	-0.002 (0.005)
Minimum distance to adjacent university	-0.004 (0.009)	-0.007 (0.009)	0.009 (0.009)	0.004 (0.009)	-0.006 (0.008)	-0.001 (0.009)
Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.013 (0.030)	0.019 (0.029)	0.012 (0.030)	0.010 (0.030)	0.023 (0.028)	0.017 (0.029)
Time dummies	Yes	Yes	Yes	Yes	No	No
Interaction terms:						
Cumulated patents * time dummies	No	Yes	No	Yes	No	No
Source producer * time dummies	No	Yes	No	No	No	No
Population density * time dummies	No	No	No	Yes	No	No
Number of observations	1040	1028	1040	1040	1040	1040
Log likelihood	-200.2	-192.7	-195.8	-192.3	-210.8	-205.3

Clustered robust standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

the systems industry as a whole, that the regional stock of codified knowledge is relevant for start-ups. Overall, these findings support Hypothesis 5, which conjectured that the effect of the regional presence of source producers on entry into systems will be much smaller if diversifying source producers are disregarded.

7. Conclusions

Radical product innovations such as the laser provide the foundation of entire new industries. Where these industries locate is highly relevant for the development of national as well as regional economies. Yet in spite of decades of theoretical and empirical advances in industrial dynamics, regional economics, and economic geography, our understanding of the spatial evolution of new industries remains sketchy.

In this paper, we exploited a new dataset encompassing the full set of active firms in the broadly defined German laser industry over a 30-year period. Our data enable us to distinguish upstream laser source producers from downstream suppliers of laser systems, i.e., commercial applications of laser beams. Based on this distinction, we focused on the effects that preexisting producers in upstream industries and the regional stock of knowledge related to these industries, as well as relevant university research, have on the location decisions of new entrants in downstream markets. Consistent with our conjectures, we found that regions with preexisting laser source producers, relevant university research, and larger stocks of laser source patents were more likely to experience the entry of laser systems suppliers. These findings are robust across a variety of model specifications, whereas purely spatial variables, such as distance to the early center of laser research (Munich) and knowledge in adjacent regions, add little to the explanation of observed geographic patterns. The results suggest that early-mover advantages in high-tech sectors can create pronounced path dependency that extends beyond narrowly defined markets, further adding to regional imbalances in economic development.

Moreover, our results show that a considerable part of this path dependency and knowledge transfer across specific markets operates through diversification of preexisting firms. It is striking that only 27 out of 135 laser source producers in West Germany *did not diversify* downstream into the laser systems industry. Apparently, the diversifying firms were able to internalize a substantial share of the external benefits generated from their activities in the upstream market. At the same time, diversification may have helped laser source producers to survive a shakeout of the laser source industry, which has been observed at least in the US industry (but less so in Germany). Hence, a natural extension of our present analysis would be to study the diversification behavior of laser source producers in more detail.

Our analysis found university research plays a powerful role in entry into laser systems industries. This suggests that the evolution of present-day high-tech industries is not detached from their regional environment. Accordingly, adopting an innovation systems perspective seems to be appropriate in studying these industries with regard to both their geography and their market structure. We view our paper as one step down this path of system-oriented research in industry evolution. Many more steps will be necessary, however, to obtain a fuller picture.

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Appendix

Table A1: Descriptive statistics—variables in the analysis for laser systems producers

Variables	*Mean*	*Median*	*Minimum*	*Maximum*	*Standard Deviation*	*Number of Observations*
First regional entry into laser systems	0.095	0.000	0.000	1.000	0.294	713
Cumulated patents (from not source/systems suppliers)	9.494	2.333	0.000	221.326	24.918	1,702
Source producer (dummy)	0.292	0.000	0.000	1.000	0.455	1,702
University (dummy)	0.626	1.000	0.000	1.000	0.484	1,702
Population density	329.304	193.330	72.180	2308.706	370.225	1,702
Distance to Munich (km)	432.034	428.531	0.000	892.560	228.438	1,702
Minimum distance to adjacent source supplier	93.422	86.049	29.981	297.617	39.247	1,702
Minimum distance to adjacent university	71.811	71.850	29.981	203.285	17.950	1,702
Patents from adjacent regions (from not source/systems suppliers) (t-1)	2.665	1.500	0.000	28.917	3.617	1,702

Table A2: Correlations between variables in the analysis for laser systems producers

	Variables	1	2	3	4	5	6	7	8
1	First regional entry into laser systems	1.000							
2	Cumulated patents (from not source/systems suppliers)	0.180*	1.000						
3	Source producer (dummy)	0.302*	0.376*	1.000					
4	University (dummy)	0.127*	0.246*	0.264*	1.000				
5	Population density	0.110*	0.153*	0.258*	0.297*	1.000			
6	Distance to Munich (km)	-0.084*	-0.210*	-0.032	-0.005	0.249*	1.000		
7	Minimum distance to adjacent source supplier	-0.007	-0.049*	-0.108*	-0.012	-0.130*	0.054*	1.000	
8	Minimum distance to adjacent university	0.003	0.012	0.007	0.057*	-0.281*	-0.291*	0.341*	1.000
9	Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.086*	-0.006	0.056*	-0.066*	-0.096*	-0.405*	-0.167*	0.041

*Statistically significant at the 5 percent level.

Table A3: Descriptive statistics—variables in the analysis for producers in materials processing

Variables	Mean	Median	Minimum	Maximum	Standard Deviation	Number of Observations
First regional entry into laser systems for materials processing	0.062	0.000	0.000	1.000	0.242	993
Cumulated patents (from not source/systems suppliers)	9.494	2.333	0.000	221.326	24.918	1,702
Source producer (dummy)	0.292	0.000	0.000	1.000	0.455	1,702
University (dummy)	0.626	1.000	0.000	1.000	0.484	1,702
Population density	329.304	193.330	72.180	2308.706	370.225	1,702
Distance to Munich (km)	432.034	428.531	0.000	892.560	228.438	1,702
Minimum distance to adjacent source supplier	93.422	86.049	29.982	297.617	39.247	1,702
Minimum distance to adjacent university	71.811	71.850	29.982	203.285	17.950	1,702
Patents from adjacent regions (from not source/systems suppliers) (t-1)	2.665	1.500	0.000	28.917	3.617	1,702

Table A4: Correlations between variables in the analysis for producers in materials processing

	Variables	1	2	3	4	5	6	7	8
1	First regional entry into laser systems for materials processing	1.000							
2	Cumulated number of patents (from not source/systems suppliers)	0.214*	1.000						
3	Source producer (dummy)	0.181*	0.376*	1.000					
4	University (dummy)	0.078*	0.246*	0.264*	1.000				
5	Population density	0.079*	0.153*	0.258*	0.297*	1.000			
6	Distance to Munich (km)	-0.054	-0.210*	-0.032	-0.005	0.249*	1.000		
7	Minimum distance to adjacent source supplier	-0.042	-0.049*	-0.108*	-0.012	-0.130*	0.054*	1.000	
8	Minimum distance to adjacent university	0.001	0.012	0.007	0.057*	-0.281*	-0.291*	0.341*	1.000
9	Patents from adjacent regions (from not source/systems suppliers) (t-1)	0.086*	-0.006	0.056*	-0.066*	-0.096*	-0.405*	-0.167*	0.041

*Statistically significant at the 5 percent level.