Chapter 13
Findings and Limitations

> *This neglect of other aspects of the system has been made easier by another feature of modern economic theory – the growing abstraction of the analysis, which does not seem to call for a detailed knowledge of the actual economic system or, at any rate, has managed to proceed without it.*
>
> (Ronald H. Coase 1991)

Abstract The question that naturally arises at this point is what have we learned so far and, maybe even more importantly, what have we yet to learn? This chapter addresses precisely these questions. In Sect. 13.1 we start with a brief discussion of some general issues and limitations. In doing so we focus primarily on general limitations related to the scope of data sources employed for the purpose of this study. In Sect. 13.2 we provide a summary of key findings for the analyses conducted in Parts III and IV. In the same breath, we also address theoretical and empirical issues that deserve particular attention in future studies.

13.1 General Issues and Limitations

Each empirical research project bears some inherent risks that cannot be excluded even by a conscious selection of the empirical setting. After careful and critical reflection we chose the German laser industry to put our theoretical considerations to the test. This proved to be a good decision for at least two reasons. Firstly, even though the majority of laser source manufacturing firms are micro and small enterprises, they demonstrate high cooperation and innovation activities. Secondly, the underlying technological developments that fuel technological change processes in the industry have, by no means, reached the end of the road. This study concentrates on laser source manufacturers (LSMs) that are at the very heart of the laser industry's value chain. The underlying assumption is straightforward; these

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firms are considered to be heavily involved in the development of laser sources. Cooperation activities between LSMs and laser-related public research organizations (PROs) were explicitly considered in this study. However, R&D cooperation between LSMs and up-stream firms (e.g. component suppliers) or down-stream firms (e.g. laser system producers) were beyond the scope of this study.

In general, the scope of this study is limited in several ways. Firstly, we chose a window of time between 1990 and 2010 to conduct our analyses. The reason for this is simple. There are considerable gaps in information on firm characteristics and cooperation activities in the period before 1990. In contrast, data availability for the time period after 1990 is much higher and firm histories can be more easily reconstructed based on these historical raw data sources. Because the laser industry database was still under construction in 2011, our window of observation was restricted to the time before 2011.

A second point relates to the R&D cooperation data sources used in this study. Data on publicly funded R&D cooperation projects was employed to construct annual innovation network layers between 1990 and 2010. As already highlighted throughout the study, the use of data on publicly funded research projects can cause selectivity problems. These problems are usually caused by some unobserved actor-specific characteristics which can lead to a systematic pre-selection of a sub-set of actors in a given population. Against this backdrop one could argue that the empirical findings in this study that higher innovativeness is related to cooperation-related determinants might simply be caused by the inherent superiority of those actors who were preselected because they were awarded more grants. These concerns seem to be of limited salience because the optical industry is considered to be one of the key technologies affecting the innovativeness and prosperity of the German economy as a whole (BMBF 2010). The very aim of German policy-makers was to increase the international competiveness of the industry as a whole (Fabian 2011). Since the early 1980s, German technology policy has strongly supported not only large but also small and micro-sized firms in the optical industry (ibid). In other words, funding decisions were primarily motivated by the aim to make German actors more competitive than their international rivals; spurring on domestic competition through highly selective merit-based funding decisions appears to have been of secondary importance. Basically the same arguments hold true with regard to European funding decisions. Scherngell and Barber (2009, p. 534) point out that one of the main EU Framework program objectives is to strengthen the scientific and technological bases of European industries and foster international competitiveness. Nonetheless, we believe that our current R&D cooperation database can and should be supplemented in several ways (cf. Chap. 14).

Thirdly, the use of patent data in constructing innovation indicators was frequently criticized in the literature. Other indicators such as survey-based innovation indicators are simply not available retrospectively over a period of more than two decades. Nonetheless, we agree that more appropriate proxies for measuring innovation output could be applied, especially for industries characterized by a high number of micro and small-sized firms. A promising way to gather additional information on innovation activities of LSMs and PROs may be the use of market-based innovation outcome measures. These and many other challenges constitute the next steps in our research agenda (cf. Chap. 14).

Finally, this study is restricted to the national level. An interesting observation throughout the data compilation procedure was the high involvement of international partners in CORDIS cooperation projects. In addition, we know from other studies that German laser source manufacturers have a strong position in international markets and they export their products to a large extent. Both observations substantiate the assumption that a national analysis provides some highly interesting results but may not go far enough.

Each of the areas addressed above provides interesting starting points for enriching our database and solidifying the empirical findings made so far.

13.2 Summary of Our Main Findings and Open Questions

In this section we briefly summarize the most salient descriptive findings (Part III) and address the insights of our four explanatory analyses (Part IV).

The descriptive exploration of industry data has revealed some interesting patterns. The initial descriptive analyses provide a comparison of industry dynamics and spatial distribution patterns for laser source manufacturers (LSMs), laser system providers (LSPs) and laser-related public research organizations (PROs). We start with a brief look at the overall industry dynamics and find that LSPs dominate in terms of numbers over the entire observation period. All in all, the period between 1990 and 2005 is characterized by a more-or-less stable growth trend with only some minor fluctuations in all three types of organizations. The last 5 years are characterized by a slight decrease in the number of LSMs and LSPs whereas the number of PROs continues to grow at a moderate rate. Next, we employed geographical Herfindahl-Hirschman Indices to track the geographical concentration patterns at the overall industry level. Concentration indices for both LSMs and LSPs start at a high level in 1990 and, after some minor fluctuations, level off at around 0.06 index points in 2010. Analyzing spatial patterns at the regional level reveals a concentration of laser-related organizations in four geographical regions: Munich, Thuringia, Berlin and Stuttgart. These geographical areas still constitute the centers of the German laser industry.

Our study concentrates on the full population of German laser source manufacturers between 1990 and 2010. A closer look at the entry and exit dynamics and the size distribution of LSMs provides some interesting insights. Data indicates the highest number of firm entries in 1995, 1999 and 2001. In contrast, the total number of firm exits peaked in 2000 with 11 LSMs leaving the industry. The overall trend indicates a 3.4-fold increase in firms over the course of just 15 years with a peak in 2005 followed by an overall decrease by 2010 with some minor fluctuations. The descriptive analysis of the firm size distribution over the entire observation period reveals interesting insights. At the beginning of our observation period, more than half of all firms are micro firms. Even though micro firms lose ground over time, the total number of micro firms in the sample remains comparably high. Small firms show the highest average growth rates, followed by medium, large and very large firms. A closer look at the size distribution of LSMs at the regional level shows a notable number of LSMs in 10 out of the 16 federal states. The majority of large and very large firms are located in Bavaria and Baden-Wurttemberg. In contrast, the situation in Berlin and North Rhine-Westphalia is characterized by a comparably high number of either micro firms or small firms. In Bremen, Saxony-Anhalt and Mecklenburg-Western Pomerania we found a very low presence of LSMs over the entire observation period.

Not only LSMs but also laser-related public research organizations (PROs) play an important role in this study. PROs are considered to be important sources of applied and basic scientific knowledge. The descriptive analysis of the composition of laser-related PROs in Germany reveals some interesting insights. Fraunhofer institutes make up the largest percentage of non-university research organizations in our sample at about 22 %. The proportion of technical universities, universities and universities of applied science was 10 %, 34 %, and 4 % respectively. About 20 % of the laser-related PROs were members of the Leibniz, Helmholtz or Max-Planck societies. Finally, about 10 % of the overall population of all laser-related PROs in Germany do not belong any of the four major German research societies. Accordingly applied research facilities seem to play a key role in the Germany laser industry.

Cooperation data for this study came from two sources: *Foerderkatalog* data and *CORDIS* data. From the first source, we identified 416 laser-related R&D cooperation projects and the second source produced R&D projects. The findings show that *CORDIS* projects are considerably larger than *Foerderkatalog* projects. The average size of *CORDIS* projects, measured by the number of partners involved, was 10.44 with a standard deviation of 8.02. In the case of *Foerderkatalog* projects, we found an involvement of 6.38 organizations per project with a standard deviation of 3.96. Both data sources were used to construct innovation networks on an annual basis. In general, our analysis of cooperation project involvement of LSMs and PROs at the national level shows an increasing proportion of organizations participating in publicly funded research projects over time. The average percentage of PROs participating in either *CORDIS* or *Foerderkatalog* R&D cooperation projects was 42.74 % and the maximum percentage of cooperation reached nearly 60 % in 2008. A look at the overall participation of LSMs in both types of publicly funded cooperation projects reveals a minimum participation of 24.05 % in 1990, a maximum participation of 47.24 % in 2008 and an average participation of 36.92 %.

In Chap. 8 we focused on an exploratory analysis of structural evolution of the industry's innovation network. We applied two strategies to gain a comprehensive picture of evolutionary network change processes in the German laser industry. On the one hand, we made use of exploratory social network analysis methods (De Nooy et al. 2005) to explore structural change patterns over time. We also conducted an in-depth analysis of large-scale properties by using more sophisticated network models (Barabasi and Albert 1999; Watts and Strogatz 1998; Borgatti and Everett 1999).

We start by reporting the findings of the scale-free analysis. The German industry innovation network displays no perfect power law behavior. Nonetheless, the log-log plot for the degree distribution over the entire observation period reveals systematic differences between the real world and the random network. This indicates at least a pronounced tendency towards the emergence of scale-free properties. Our results are in line with the findings of Powell et al. (2005) for the US biotech industry. Next, we looked at the small-world properties of the innovation network. We employed graph theoretical concepts and measures, i.e. the "clustering coefficient ratio", the "path length ratio" and the "small-world Q" to test for the existence of the network's small-world nature. Data clearly reveals the emergence of small-world properties in the German laser industry innovation network. Robustness checks substantiate this finding. In addition, we found an increasing tendency towards a solidification of small-world properties over time. Last but not least, we checked for the existence of core-periphery patterns by using complementary indicators. Our findings give us good reason to assume that the German laser industry innovation network exhibited a pronounced core-periphery structure during three time periods – (I) 1994–1997, (II) 1999–2002 and (III) 2004–2008. At least two out of four indicators substantiate these findings in all three time periods.

In Part IV we conducted four empirical investigations. Each of the empirical studies addresses a quite narrowly defined problem and provides new empirical evidence for innovation networks in the German laser industry, a still widely unexplored topic in the literature.

The overall objective of the first empirical part (Chap. 9) was to contribute to an in-depth understanding of the causes and consequences of evolutionary network change processes at the micro-level. A natural starting point to throw some light on the evolution of networks is to look at a firm's initial cooperation event and the determinants that affect the timing of network entry processes. In particular, we included three types of determinants in our analysis: firm size, cooperation type, and geographical location. Estimation results from a non-parametric event history model indicate that micro firms enter the network later than small and large firms. An in-depth analysis of the size effects for medium-sized firms provides some unexpected yet quite interesting findings. These findings show that the choice of cooperation type makes no significant difference to a firm's timing in entering the network. Finally, the analysis of contextual determinants reveals that cluster membership can, but does not necessarily, affect a firm's timing to cooperate. It appears that firms in some regions (e.g. Thuringia) tend to cooperate earlier and to have a significantly higher propensity to cooperate than those in other regions (e.g. Bavaria).

From a theoretical perspective, a lot remains to be done. For instance, our conceptual framework still requires further refinement. Organizational, relational and contextual determinates have to be concretized and interdependencies between these three dimensions have to be addressed more explicitly. An interesting theoretical study presented by Hagedoorn (2006) moves in this direction. The proximity concept (cf. Sect. 2.3.3.2) provides another promising starting point for addressing the role of interdependencies between these dimensions for micro-level network change processes. Our theoretical framework raises awareness of the importance of network paths. We included a very specific type of network path dependency to account for a network entrant's cooperation behavior in the subsequent cooperation rounds. We refer to this idea as "cooperation imprinting". We believe that the sequential analysis of cooperation processes, against the backdrop of new cooperation options and revised strategies, is crucial in understanding structural network change. A refinement of this idea constitutes one of the next steps in our research agenda.

From an empirical point of view we are still at an early stage. This study concentrates exclusively on a firm's first cooperation event. Cooperation events between incumbents were not addressed. Consequently, the next steps in our research agenda are straightforward. Firstly, repeated cooperation events have to be included in our empirical analysis. An initial step in this direction has already been made (cf. Kudic et al. 2013). Regression results of a parametric event history model reveal that a firm's knowledge endowment (and cooperation experience) shortens the duration to first (and consecutive) cooperation events. The study conducted by Kudic et al. (2013) also shows that previous occupation of strategic network positions is closely related to the swift establishment of further R&D cooperation at later points in time. Secondly, we have to find a way to analyze the structural consequences of micro-level network change processes empirically. Not only the formation entry processes and the network formation phase, but also dissolution processes and network fragmentation tendencies, have to be explored more in detail.

The focus of the second empirical part (Chap. 10) is quite different but closely related to the issues addressed in the first study. The key objective was to analyze how firm innovativeness is related to individual cooperation events and the structure and dynamics of a firm's ego network. We applied panel data count models to accomplish this task. Estimation results, from a fixed effects model, are suggestive of direct innovation effects due to individual cooperation events, but only as long as structural ego network characteristics are ignored. These effects, however, partially diminish when individual cooperation events and ego network characteristics are looked at simultaneously. Innovation effects of ego network size, as well as ego network brokerage, remain stable whereas ego network density reveals some surprising results. It is also interesting to note that, because we include firm-level funding as a control variable in all models, our findings relativize the argument that a firm's innovative performance is affected more by public funding than by the cooperation activities themselves.

However, we still face some theoretical and methodological challenges. The structural configuration of an ego network can be analyzed from various theoretical perspectives. Not only the size, brokerage and density of the ego network but also additional structural features have to be explicitly considered in future research. For instance, various dimensions of node-level structural heterogeneity of ego networks (i.e. nationality, financial power, organizational form etc.) have to be integrated into the analysis. Additionally, a fine-grained differentiation between different types of collaboration (i.e. funded vs. non-funded collaborations, various types of strategic alliances etc.) can significantly improve our understanding in this research area. There are also some methodological limitations. For instance, the use of more sophisticated indicators of a firm's ego network structure is needed to account for additional ego network characteristics that go beyond the scope of this analysis. To accomplish these tasks, our laser industry database has to be refined and completed in several ways.

The third empirical investigation (Chap. 11) addresses the relationship between large-scale network properties and innovation outcomes at the micro-level. More precisely, we analyzed how small-world properties affect firm innovativeness in a longitudinal empirical setting. The estimation results for the network's average path lengths are as expected. Thus, a short average path length at the overall network level is positively related to a firm-level innovative performance at later points in time. Our results for the clustering coefficient are in line with our theoretical expectations. We found a positive relatedness between clustering at the overall network level and firm innovativeness. Finally, estimation results provide empirical evidence for a positive relatedness between a network's small-world nature and a firm's subsequent innovativeness. This result is in sharp contrast to the findings of Fleming et al. (2007, p. 949) but in line with previous findings by Schilling and Phelps (2007).

Both theoretical and methodological limitations are closely related to graph theoretical concepts. Firstly, concerns were expressed that bipartite networks significantly exaggerate the network's true level of clustering and understate the true path length (Uzzi and Spiro 2005, p. 453). We checked for this issue by conducting several consistency checks. Consequently, we have to address the bipartite nature of the networks more explicitly. Not only a network's small world nature but also an in-depth analysis of other types of large-scale network characteristics, such as core-periphery patterns, provide promising opportunities for further research.

Secondly, we did not specify an empirical model that incorporates path-length, clustering and small-world indicators simultaneously. The reason for this is straightforward. In this study we were particularly interested in investigating the relatedness between three distinct structural patterns at the overall network level and firm-level innovativeness. A more integrated estimation approach would be the next logical step towards an in-depth understanding of how systemic parameters affect the innovativeness of the actors involved.

The last of four analytical parts (Chap. 12) explicitly addresses the proximity concept and analyzes the extent to which firm innovativeness is positively or negatively related to various proximity dimensions. More precisely, we investigated the relatedness between firm innovativeness and distinct and/or combined network positioning effects, and geographical co-location effects. Firstly, we found strong empirical evidence for the relevance of distinct network proximity effects on the innovative performance of German laser source manufacturers. In other words, a firm's degree centrality turned out to be positively related to its innovative performance at later points in time. Against our initial expectations, estimation results for co-location between laser source manufacturers turned out to be negatively correlated with firm-level innovation outcomes. Findings on combined geographical proximity and network proximity confirm our theoretical expectations that combined proximity effects are not independent.

From a theoretical point of view, we are at the onset. The proximity concept proposed by Boschma (2005) opens up rich opportunities to study the relatedness between network proximity and other proximity dimensions. For instance, Nooteboom (2008) heightened our awareness for the importance of cognitive proximity in this context. Another interesting theoretical perspective could be the integration of the isolation concept (cf. Ehrenfeld et al. 2014). Hall and Wylie (2014, p. 358) argue that isolation only rarely appears as a stringent analytical concept in the literature on economics and innovation. It is usually used in a descriptive or metaphoric way without being clearly defined (ibid). They make the point that isolation is a pervasive element of all kinds of social and economic systems which can be exogenous but also self-imposed (Hall and Wylie 2014, p. 373). The consequences of isolation for technological innovation are not yet fully understood. However, it is important to note that isolation in a geographical, social or cognitive sense is not necessarily negatively related to innovativeness (ibid). Instead isolation can provide a unique environment and induces innovation processes that otherwise would not have happened (Hall and Wylie 2014, p. 374).

Like any empirical investigation, this analysis also has its methodological limitations. For instance, we used the localized density measure according to Sorenson and Audia (2000) to quantify two types of geographical proximity dimensions: geographical proximity between an LSM and other LSMs and geographical proximity between an LSM and other PROs. This approach is limited in several ways. It ignores, for instance, the effects of geographical proximity in the exploitation of inter-industry knowledge spillovers. Further research could include indicators capturing the effects of a firm's geographical embeddedness in diversified industrial agglomerations and in urban areas.

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