# Innovation by start-up firms: The role of the board of directors for knowledge spillovers[⋆]

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**Abstract**

This paper investigates whether board directors interlocked with or employed by innovative firms affect start-up firms' propensity to be innovators themselves. Drawing upon a sample of more than 50,000 Swedish start-up firms, we find that board connections to incumbent innovators have a causal impact on the new firms' probability to apply for patents. The results are robust when controlling for industry, geography, firm age, as well as spillovers through worker and managerial mobility, external knowledge sourcing through patent disclosure, access to venture capital and board attributes.

*Keywords:* start-ups, board of directors, knowledge spillovers, innovation, instrumental variables estimation

## 1. Introduction

Research has shown that technological knowledge is a key resource for the competitive advantage of innovative firms (Agarwal, Echambadi, Franco and Sarkar, 2004; Kogut and Zander, 1992; Audretsch and Lehmann, 2006). In most technology fields, progress draws upon knowledge from a number of earlier discoveries and experiences (Dosi and Nelson, 2010). Therefore, new entrants to the market, due

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to their lack of experience, can encounter difficulties without external contact to established organizations or individuals (Dalziel, Gentry and Bowerman, 2011; Jones, Coviello and Tang, 2011). However, the capacity of start-ups to access and absorb external knowledge (Cohen and Levinthal, 1990) may be constrained by a limited endowment of initial knowledge and financial resources.

Building on the Schumpeterian view that incumbent organizations represent the origin of the innovation opportunities exploited by entrepreneurial start-up firms, scholars have investigated whether spin-offs may appropriate knowledge spillovers from their parents, fostering innovation and in turn productivity and growth (Acs et al., 2013; Eckhardt and Shane, 2003; Klepper and Sleeper, 2005; Klepper, 2010; Koellinger, 2008; Vaghely and Julien, 2010). Our paper takes a different perspective on knowledge spillovers and resource-constrained entrants by investigating the role of boards of directors for inter-firm links. We consider both inside and outside directors.[1]

So far, we know very little about the the ability of directors associated with innovative incumbents to support innovation in new firms. Prior works have almost completely neglected this role of board directors for innovative start-ups. Based on theoretical frameworks of knowledge spillovers, we address this gap by exploiting Swedish employer-employee panel data, formal intellectual property rights protections measures and appropriate identification strategies.

While the principal-agent relationship and corporate control are main objectives for the board of directors in large and listed corporations (Daily and Dalton, 1992; Kao, Hodgkinson and Jaafar, 2019; Shapiro, 2005; Solomon, Bendickson, Marvel, McDowell and Mahto, 2021), evidence from the literature shows that board members often serve as an extension to the management of small and young firms (Zahra and Filatotchev, 2004; Zhang, Baden-Fuller and Pool, 2011; Bizjak, Lemmon and Whitby, 2009; Brown, 2011; Shropshire, 2010). In this function, directors may assist the firm with higher information quality (Rutherford and Buchholtz, 2007), valuable

[1] Inside directors are employed by the start-up firm, while outside directors are not. Inside directors may serve on the board of external firms. Outside directors may be employed at other firms, serve on external boards (interlocked), or may not be linked to other firms.

strategic advice (Kor and Sundaramurthy, 2009) as well as first-hand knowledge, expertise and scarce information not easily acquired elsewhere (Balsmeier, Buchwald and Stiebale, 2014).

Knowledge spillovers, defined as the external benefit from knowledge transfer across organizational borders and networks when the creator is not fully compensated, have been studied from a broad range of perspectives and at different levels of aggregation. Although our paper is related to several theoretical views on spillovers from a variety of disciplines, the main guidance is the knowledge spillover theory of entrepreneurship (KSTE). This theory explains why start-ups are an efficient conduit in turning knowledge spillovers into innovation (Audretsch, Belitski and Caiazza, 2021), and how entrepreneurship is concerned with the start-up and growth of new enterprises (Audretsch and Lehmann, 2005). While KSTE mainly considers the one-way spillover process from an incumbent organization to entrepreneurial firms, our paper also rely on theoretical concepts allowing for two-way transmission of knowledge between firms. These include views on knowledge and strategic entrepreneurship (Agarwal, Audretsch and Sarkar, 2010) and the recombinant view of innovation (Weitzman, 1998). By shedding new light on the interplay between incumbent organizations and new entrants, as well as the concept of the bidirectional flow of knowledge between firms, our paper contributes to KSTE and related theories of knowledge spillover.

The study also draws on insights from previous empirical research on knowledge spillovers, innovation and board interlocks. Similar to Helmers, Patnam and Rau (2017), Balsmeier, Buchwald and Stiebale (2014), Balsmeier, Fleming and Manso (2017) and Srinivasan, Wuyts and Mallapragada (2018) we apply instrumental variable approaches to account for endogeneity in the empirical analysis. The method of constructing external instruments is inspired by Kor and Sundaramurthy (2009) and Lööf and Viklund-Ros (2020). We consider board educational diversity in accordance with Schubert and Tavassoli (2020), and the directors' academic education level as suggested by Audretsch, Lehmann and Warning (2005). Like Srinivasan, Wuyts and Mallapragada (2018), we identify directors serving on one as well as multiple boards.

This study has several specific empirical features that distinguish it from existing studies of innovative start-ups. First, we study genuine and privately owned start-ups ensures that there is no internal knowledge transfer between companies within the same ownership group. Second, we remove spin-outs from the sample and control for spillovers through migration of management and employees. Third, we use data that allows tracking and accounting for the background of all employers, all employees, and all directors of the new firms and their links to other companies across the entire economy. Forth,we consider both patent applications and trademarks as indicators of innovation.[2] Finally, we account for possible influence through venture capital and patent citations.

The empirical setting for the analysis is 11 annual Swedish cohorts of start-ups, defined as micro-firms with a maximum of 9 employees, founded between 2002 and 2012. In total, the sample contains 312,458 firm-year observations with detailed information on 54,801 new entrants to the market.

Beyond the availability of comprehensive, high-quality data on firms, their employees and their boards of directors, the justification for focusing on Sweden for this study is the country's position as one of the world's leading innovative economies. Global companies like the music-streaming service Spotify, the online-payment firm Klarna, and the gaming company King are all examples of successful Swedish start-ups.[3]

Applying a recursive correlated random effects probit model to account for possible endogeneity, the econometric results we show that board members are linked to innovative firms defined by their patent applications as well as trademark registrations.

The paper is structured as follows. Section 2 reviews the relevant theoretical and empirical literature and formulates the hypothesis to be tested. Section 3 presents our data, variables and descriptive statistics. The identification strategy and em-

[2] Our matching rate is above 99% for global patent applications registered by PATSTAT, and all trademark applications on the European market are identified in our study

[3] According to the European Innovation Scoreboard for 2020, Sweden held the first place in Europe followed by Finland, Denmark, and Belgium, see https://ec.europa.eu/growth/industry/policy/innovation/scoreboards_en retrieved on 21th June 2021.

pirical approach are described in Section 4. In Section 5, the empirical models are evaluated, which is followed by a section describing sensitivity tests. Section 7 concludes the paper.

## 2. Background, theoretical framework and hypothesis

The impact of spillovers for economic development was first pointed out by Marshall (1890), who argued that the concentration of activity gives rise to beneficial externalities (Guiso and Schivardi, 2007). Since then, a large body of theoretical and empirical work from various research areas has developed models and studied both the role of knowledge spillovers and and the specific channels through which knowledge dissemination takes place.

Our paper builds on fundamentals in the theory of knowledge spillovers, such as imperfect appropriability (Cassiman and Veugelers, 2002), non-excludability and non-exhaustibility (Arrow, 1962; Grossman and Helpman, 1991; Romer, 1990), proximity Krugman (1991), the firm's ability to exploit external knowledge (Cohen and Levinthal, 1990), and the recombination view of knowledge creation (Saviotti et al., 1996).

The primary theoretical framework for the paper is the knowledge spillover theory of entrepreneurship (KSTE). The assumption that innovative start-ups play a key role for industrial dynamics if they are able to tap the stock of knowledge of the economy is a cornerstone of KSTE. This idea can be traced back to the MARK regimes described by Schumpeter (Breschi, Malerba and Orsenigo, 2000), where knowledge is generated in large corporations, while new firms may enlarge the existing knowledge base through spillovers. Particularly useful for our study on start-ups is that KSTE focuses on entrepreneurial behavior within the context of knowledge spillovers.

In concordance with predictions from the Schumpeterian view, the empirical literature on start-ups and other small businesses has linked successful performance to knowledge and experience from incumbent firms or organizations. This strand of research includes firm and university spin-offs (Agarwal, Echambadi, Franco and Sarkar, 2004; Audretsch and Stephan, 1996; Bercovitz and Feldman, 2006;

Colombelli, Grilli, Minola and Mrkajic, 2019; Klepper, 2001; Klepper and Sleeper, 2005), geographical and industrial clusters, relational networks, innovation systems and value chains (Breschi and Malerba, 2001; Feldman, 1994; Fritsch and Franke, 2004; Klepper, 2010; Rodríguez-Pose and Crescenzi, 2008). Our paper adds to this literature by examining the role of the board of directors for knowledge spillovers among innovative start-up firms. A vibrant stream of research on spillovers also focuses on technological opportunity and technological distance (Bloom, Schankerman and Van Reenen, 2013; Lychagin, Pinkse, Slade and Van Reenen, 2010; Marin and Sasidharan, 2010). Expanding our study in this way is important, as intra- or inter-industry spillovers may have an impact on board members' ability to connect knowledge across firms.

Audretsch and Stephan (1996, 1999) provide pioneering research on board directors as a possible link for knowledge transfer between established organizations and new ventures, and Audretsch and Lehmann (2005) reveal early empirical support for this perception. Their results indicate that IPO companies' access to knowledge at research-intensive universities increases with the academic degrees of the board members.

A major challenge when studying the impact of knowledge spillover through board members is to distinguish between correlation and causality (Adams, Hermalin and Weisbach, 2010; Cai, Dhaliwal, Kim and Pan, 2014; Hermalin and Weisbach, 2001). For instance, the particular ex ante strategy of a firm, typically not observable by the researcher, tends to influence the selection of board members and probably affects the impact of the selected directors. Recently, scholars have addressed this problem with various instrumental variables approaches when studying how board interlocks, a special form of organizational relationship, enable firms to acquire external knowledge and influence their technological development (Balsmeier, Buchwald and Stiebale, 2014; Li, 2019; Srinivasan, Wuyts and Mallapragada, 2018). We deal with self-selection problem by exploiting the panel nature of our data. The paper accounts for unobserved heterogeneity by using a correlated random effects model, which removes any firm fixed characteristics, controlling for the possibility that new entrants seeking an innovative advantage tend to recruit directors from innovative firms.

While spillovers can erode or destroy technological competencies for the firm investing in R&D, recent studies suggest that interlocks with other firms and possible leakages of knowledge may encourage the competitive advantage of the focal firm through inter-firm collaboration (Slater, Mohr and Sengupta, 2014; Chandy and Tellis, 2000). Thus, shared board directors may benefit both the original knowledge creators and the recipients. Given the proven significance of interlocks as conduits for knowledge spillovers among incumbent innovators in these studies, it is important to understand if inter-firm connections are also relevant for innovative start-ups, with their inherent challenges regarding lack of of experience, critical mass of knowledge and absorptive capacity.

In the spirit of Weitzman (1998) and the recombinant knowledge approach, Agarwal, Audretsch and Sarkar (2007) articulate the concept of creative construction where spillovers should be considered as a wider ecosystem complementing and cross-fertilizing existing ideas. Consistent with this concept, Yang, Phelps and Steensma (2010) discuss innovation in terms of recombination of existing knowledge or re-configuration of the ways in which knowledge elements are linked. Assuming that knowledge has been received from a spillover process, it can provide benefit also to the original creator as spillins, thereby enhancing its stock of knowledge. For instance, a spillover process from an incumbent innovator to a start-up firm through directors linked to both firms may create recombinatorial opportunities. In a reverse flow, the linked directors return information from the innovating start-up to the originating firm, adding to its knowledge pool in a continued recombinatorial process (Antonelli, Krafft and Quatraro, 2010; Saviotti, 2007).

What factors may affect the board's ability to convey knowledge between two companies? Empirical research on social networks has examined the importance of board composition and the directors' individual expertise for obtaining resources from firms' networks of external relationships. For instance, Ruigrok, Peck and Tacheva (2007) and Miller and del Carmen Triana (2009) report that diversity of the board is associated with positive cognitive effects such as creativity, innovation, new ideas and insights. Li (2019) uses data on historical records of board appointments and data on technological innovations from U.S. public companies and finds that more industrially diverse interlocks will have a greater impact on corporate technological innovation. Li (2019) also shows that interlocks with R&D-intensive firms are more important for technological exploration than board links to other firms. The educational background of the directors is another factor that may influence the efficiency of an interlocked board. Higher levels of education among board directors has been found to increase their willingness to use external information, develop networks, make use of consultants or develop more detailed accounting and monitoring in large firms (Lybaert, 1998; Bennett and Robson, 2004), but have been less frequently examined in start-up firms and other small businesses.

Based upon KSTE and the view that start-ups are an efficient conduit in effecting knowledge spillovers, while only a small fraction of these firms will ultimately prove to be innovative (Audretsch, Colombelli, Grilli, Minola and Rasmussen, 2020), we hypothesize that board members linked to innovative firms through employment or board membership positively affect a start-up firm's propensity to be innovative. To test this proposition, the paper accounts for board attributes as well as spillovers through worker and managerial mobility, external knowledge sourcing through patent disclosure, and access to venture capital. As the potential for spillovers may be dependent on the technological or geographical landscape, we use both as controls in the empirical analysis. We also include year, cohort, and firm age fixed effects in the the regression analysis.

## 3. Data and variables

The firm-level data used in this study are constructed from several sources. We use the commercial database Serrano from the company Bisnode to identify 11 cohorts of start-ups in Sweden formed as micro-firms (9 or fewer employees) over the period 2002–2012. In total, our sample contains 312,458 firm-year observations on 54,801 new entrants. The sample is restricted to only include limited liability companies as those firms are required by law to have a board of directors. Our main sample also excludes firms that belong to business groups, firms created as spin-offs or spin-outs,[4] and new firms with only one employee throughout the sample period. Information on boards of directors is retrieved from the Swedish Companies Registration Office.

Using unique identification codes, we merge these two datasets with official register information provided by Statistics Sweden (SCB) on all firms in Sweden and all individuals linked to these firms: employer-employee (EE) data. The EE data include extensive statistics on both firms and individuals. We then match patent data from PATSTAT (EPO) and trademark data from the European Union Intellectual Property Office (EUIPO) with the EE data. From the PATSTAT (EPO) database we exploit information on patent applications and patent citations, while the EUIPO data provides information on the trademark protection obtained. We are able to identify more than 99% of the global patent applications by firms in Sweden, and 100% of their trademarks granted by EUIPO. Finally, we add venture capital data received from VentureXpert, Securities Data Company (SDC) Platinum to the constructed data set.

We classify incumbent firms as innovative in year $t$ if they applied for a patent in year $t$. This approach is also used for trademarks as an alternate proxy for innovation. According to our definition, a connection between a director on the board of the start-up firm and an innovative incumbent in a given year exists if the director serves on the board of the start-up in year $t$ and also is employed in or serves on the board of another firm defined as innovative in year $t$.

Table 1 defines the two categories of directors we consider in the analysis. The first category consists of inside and outside directors without any employment or interlocking connections with innovative firms. In the second category, inside and outside directors have formal associations with innovative incumbents through employment or membership of the board. Based on this classification, we construct a dummy variable $BCI_{i,t-1}$ that indicates whether any of the directors belongs to the second category. In order to account for spillovers from innovative incumbent firms through employer mobility, we include a control variable $IE10_{i,t-1}$ which in-

[4] We define start-ups as spin-offs or spin-outs if half or more of the employees were employed in the same parent firm in the year before firm formation.

dicates whether the share of employees in year $t-1$ whose last employment was with an innovative firm exceeds 10%. Furthermore, we include controls for number of directors on the board, firm size measured by log(total assets), firm age in years, the share of employees with three or more years of university education, and a regional variable indicating whether the focal firm is located in any of the three largest metro areas: Stockholm, Gothenburg or Malmö. Table 2 presents the dependent variables, $Patent_{i,t}$ and $Trademark_{i,t}$, the key explanatory variables constructed on basis of the classification of directors, $BCI_{i,t-1}$ and $BCT_{i,t-1}$, the instruments $New\ OBCI1_{i,t-2}$, $New\ OBCI2_{i,t-2}$, $New\ OBCT1_{i,t-2}$ and $New\ OBCT2_{i,t-2}$, and the covariates $Board\ size_{i,t-1}$, $log(Total\ assets)_{i,t-1}$, $Human\ capital_{i,t-1}$, $Metro_{i,t-1}$, $Firm\ age_{i,t-1}$, $IE10_{i,t-1}$ and year and industry fixed effects.

Table 3 reports the summary statistics for the sample of young firms during the first year of observation, which is four years after formation. The dependent variable is observed in year $t$ and the explanatory variables in year $t-1$. As could be expected, (see for instance Audretsch, Keilbach and Lehmann (2006); Audretsch, Colombelli, Grilli, Minola and Rasmussen (2020); Autio (1997); Baumol and Strom (2007) the proportion of new firms that apply for patents during their first years of existence is small. Only 0.2% of the new entrants apply for at least one patent in the fourth year after the firm was founded, and 0.1% registered at least one trademark. Human capital is represented by the fraction of employees with three years of university education or more. This corresponds to about a quarter of the employees in our data. Two out of five new companies is located in one of the three Swedish metropolitan areas: Stockholm, Gothenburg or Malmö.

In the empirical analysis, we observe companies from four years after foundation up to a maximum of 13 years. Thus, companies created in 2002 may be observed for 10 years while companies created in 2012 are observed only for one year. The total number of unique start-ups in our sample seeking patents is just above 200 and the number of unique new companies with trademarks is about 250. In total, we have 395 and 305 firm–year observations of patent application and registered trademark applications respectively. Summary statistics for the full panel of start-ups are provided in Table 4.

Table 1: Variable descriptions I: Categories of directors

| | |
|---|---|
| *Category 1:* | |
| $(i)_{i,t-1}$ | Inside director with no interlocking board |
| $(ii)_{i,t-1}$ | Inside director interlocked with board of one or more non-innovative firms |
| $(iii)_{i,t-1}$ | Outside director employed in a non-innovative firm and not interlocked with any board |
| $(iv)_{i,t-1}$ | Outside director employed in a non-innovative firm and interlocked with board of one or more non-innovative firms |
| $(v)_{i,t-1}$ | Outside director not employed in any firm and interlocked with board of one or more non-innovative firms |
| $(vi)_{i,t-1}$ | Outside director not employed in any firm and not interlocked with board of any firm. |
| *Category 2:* | |
| $(vii)_{i,t-1}$ | Inside director interlocked with the board of least one innovative firm |
| $(viii)_{i,t-1}$ | Outside director employed in an innovative firm and with no interlock |
| $(ix)_{i,t-1}$ | Outside director employed in a non-innovative firm and interlocked with the board of one or more innovative firms |
| $(x)_{i,t-1}$ | Outside director employed in an innovative firm and interlocked with the board of one or more non-innovative firms |
| $(xi)_{i,t-1}$ | Outside director employed in an innovative firm and interlocked with the board of one or more innovative firms |
| $(xii)_{i,t-1}$ | Outside director not employed in any firm and interlocked with the board of one or more innovative firms |

Table 2: Variable descriptions II

| | |
|---|---|
| **Dependent variables** | |
| $\text{Patent}_{i,t}$ | indicator (0/1): firm $i$ applied for one or more patents in year $t$. |
| $\text{Trademark}_{i,t}$ | indicator (0/1): firm $i$ registered one or more trademarks in year $t$. |
| **Key determinant** | |
| $\text{BCI}_{i,t-1}$ | equals 1 if any of the directors on the board are connected to an innovative (patent) firm (Category 2). |
| $\text{BCT}_{i,t-1}$ | equals 1 if any of the directors on the board are connected to an innovative (trademark) firm. |
| **Instruments** | |
| New $\text{OBCI1}_{i,t-2}$ | equals 1 if any of the outside directors were newly hired in a firm with patenting experience in year $(t-2)$ and were employed in a different firm without patenting experience in year $(t-3)$, 0 otherwise. |
| New $\text{OBCI2}_{i,t-2}$ | equals 1 if any of the outside directors were newly hired in a firm with patenting experience in year $(t-3)$ and were employed in a different firm without patenting experience in year $(t-4)$, 0 otherwise. |
| New $\text{OBCT1}_{i,t-2}$ | equals 1 if any of the outside directors were newly hired in a firm with trademark experience in year $(t-2)$ and were employed in a different firm without trademark experience in year $(t-3)$, 0 otherwise. |
| New $\text{OBCT2}_{i,t-2}$ | equals 1 if any of the outside directors were newly hired in a firm with trademark experience in year $(t-3)$ and were employed in a different firm without trademark experience in year $(t-4)$, 0 otherwise. |
| **Control variables** | |
| Board $\text{size}_{i,t-1}$ | number of directors on the focal firm's board. |
| $\log(\text{Total assets})_{i,t-1}$ | log of total assets, winsorized. |
| Human $\text{capital}_{i,t-1}$ | share of employees with three or more years of university education. |
| $\text{Metro}_{i,t-1}$ | indicator (0/1): focal firm is located in metro area (Stockholm, Gothenburg or Malmö). |
| Firm $\text{age}_{i,t-1}$ | firm age during the estimation sample, 2–10 years. |
| $\text{IE10}_{i,t-1}$ | equals 1 if the share of employees whose last employment was with an innovative firm $> 0.1$, 0 otherwise |
| Additional controls | year and industry fixed effects |

*3.1. Innovation measures*

In this subsection, we discuss the justification for our choice of dependent variables: patent applications and trademarks. It has been suggested that the protection of knowledge and technology as a competitive advantage is especially important for young companies. These often lack the control over their ownership and complementary assets for innovation which, in contrast, established and resourceful companies have (Teece, 1988).

A firm's knowledge or intellectual assets can be protected by patents, trademarks, copyright, secrecy, complexity, or first-mover advantage. Within this set of protection mechanisms, patents are the most studied mechanism in the literature (for a survey, see Hall, Helmers, Rogers and Sena, 2014). Patents offer a standardized and transparent measure of inventive activity (Popp, 2019). They contain information on the prior knowledge on which the patents are based, and identify individuals, firms and organizations. Patents provide a good indicator of R&D (Griliches, 1991), and they may also capture non-formal research investments. Moreover, patents are often a predictor of new product announcements (Artz, Norman, Hatfield and Cardinal, 2010), although with variation across firm sizes (Arundel, 2001) and industries (Mansfield, 1986). On the other hand, a well-known insight from this literature is that patents have drawbacks as indicators of innovation and are not always the most suitable measure of firms' intellectual assets. Therefore, we observe another instrument for protecting intellectual property, which recently has receives increased attention in research: the registration of trademarks.

Both patents and trademarks as formal appropriation mechanisms provide the owner with the exclusive right to use or sell the invention, and they are found to be both substitute and complementary modes of protection (Block, De Vries, Schumann and Sandner, 2014; Zhou, Sandner, Martinelli and Block, 2016; Veugelers and Schneider, 2018). A trademark is a word, symbol, or other expression used to distinguish a good or service produced by one firm from the goods or services of other firms (Landes and Posner, 1987). Trademark registration is relatively inexpensive and straightforward and may therefore suit resource-scarce innovative start-ups (for a recent survey, see Block, Fisch, Hahn and Sandner, 2015). Also, trademarks seem to have a similar effect as patents on firm value, productivity, and survival (Sandner, 2009; Crass, 2020).[5]

Especially for young companies, protection of intellectual property (IP) is not solely about reducing the risk of imitation, infringement and theft of their invention. IP rights may also have a signaling value to investors and can serve as collateral in financial markets. Being financially constrained, small firms may lack the resources needed to produce and commercialize the innovation (Hall and Lerner, 2010), and may lack access to financial markets. Patents and trademarks have also been found to facilitate licensing of the invention, improving the attraction of brands (Veugelers and Schneider, 2018), and enhancing reputation (Audretsch, Bönte and Mahagaonkar, 2012; Söderblom, Samuelsson, Wiklund and Sandberg, 2015; Colombelli, Grilli, Minola and Mrkajic, 2019).

The innovation literature contains a variety of other measures to compare companies' ability to generate new ideas besides patent applications and trademarks. However, most of them are not applicable to a study on start-ups. The firms in our sample are young and have a maximum of 9 employees in the year of their formation. First, while R&D is a common measure for studying investment in technological development, it is less relevant for young and small firms with mainly informal innovation activities. Second, the European Community Innovation Survey (CIS) has successfully introduced *innovation sales* as an innovation measure suitable for both manufacturing and service companies. However, among innovative start-ups, it is common that the market introduction of new products or services takes several years, which means they do not have any sales revenue from innovations. Third, using granted patents or citation-weighted patents instead of patent applications is not possible due to the long time lag. Fourth, total factor productivity is not a meaningful measure of innovation and technical change for new and small entrants on the market. Finally, we are not able to observe intellectual property protection mechanisms such as secrecy, complexity or first-mover advantage for the start-ups

[5]For more detailed discussions on the role of intellectual property rights as innovation indicators, see among others Verhoeven, Bakker and Veugelers (2016), Nagaoka, Motohashi and Goto (2010), Holgersson (2013), Morrar (2014), Gotsch and Hipp (2012) and Mendonça, Pereira and Godinho (2004).

in our sample.

## 4. Empirical models and identification strategy

Our empirical models analyze the influence of directors' external connections on firms' propensity to be innovative, using patent applications and granted trademarks as proxies. The first model estimates the probability that the focal firm applies for a patent in year $t$, conditional on the number of board directors of each of the twelve types described in Table 1. This model is estimated separately for each of those director types to gauge the importance of their characteristics on the firm's innovation.

For firm $i$ in industry $j$ and time $t$, the model is

$$Pr[Y_{i,t} = 1] = \Psi(\alpha P_{i,t-1} + X'_{i,t-1}\beta + \theta_j + \phi_k + \tau_t + e_{i,t}) \tag{1}$$

where $Y_{i,t}$ is an indicator of whether the focal firm applied for any patents during year $t$, $\Psi(\cdot)$ is the CDF of the normal distribution in the binomial probit model, and $P_{i,t-1}$ is the number of directors on the focal firm's board with connections ((i)-(xii)) to innovative firms as specified in Table 1. $X_{i,t-1}$ is a vector of firm-specific control variables including firm age, total assets, human capital, metro location, board size and the share of employees with work experience in innovative firms, while $\theta_j$, $\phi_k$ and $\tau_t$ denote industry, cohort and year fixed effects, respectively.

We then extend these descriptive analyses of directors' linkages to innovative firms with a second model that accounts for the potential endogeneity of the firm's choice of directors. It is likely that the owners of the firm actively seek "high quality" directors to be appointed to the board by screening characteristics of the potential directors' employers and networks. This implies that the presence of directors linked to innovative firms could be endogenous, as directors with that experience may be more willing to serve on the firm's board if it exhibits innovative behavior. Without appropriate instruments for mitigating endogeneity, one cannot establish a causal link between external knowledge via outside directors and firm performance.

In this second model, we consider a binary indicator signaling the presence of one or more 'Category 2' directors, as defined in Table 1, on the board. To allow for the potential endogeneity of that measure, we construct two instruments using information on innovation characteristics of firms other than the focal firm. The first instrument variable $NewOBCI1_{i,t-2}$ equals 1 if any of the outside directors in year $t-2$ who were appointed to the focal firm's board in $t-3$ or earlier were newly hired in a firm with patenting experience in year $t-2$ and were employed in a different firm without patenting experience in year $t-3$, and equals 0 otherwise. Our second instrument, $NewOBCI2_{i,t-2}$, equals 1 if any of the outside directors in year $t-2$ who were appointed to the focal firm's board in $t-4$ or earlier were newly hired in a firm with patenting experience in year $t-3$ and were employed in a different firm without patenting experience in year $t-4$, and is 0 otherwise.

We assume that the owners of the focal firms cannot foresee that elected directors will change their place of work in the future, so that the instruments can be considered as predetermined. Furthermore, we conjecture that there is some stickiness in the composition of the board, so that current directors are more likely to be candidates and will be reelected in the following year. Changes in the external directors' employment can thus be argued to be exogenous to the focal firm.

For firm $i$ in industry $j$ and time $t$, the model is

$$Pr[Y_{i,t} = 1] = \Psi(\alpha BCI_{i,t-1} + X'_{i,t-1}\beta + \theta_j + \phi_k + \tau_t + e_{i,t}) \tag{2}$$

where $Y_{i,t}$ is an indicator of whether the focal firm applied for any patents during year $t$, and $BCI_{i,t-1}$ indicates whether any of the inside or outside directors on the focal firm's board have connections to innovative firms. $X_{i,t-1}$ is a vector of firm-specific control variables including firm age, total assets, human capital, metro location, board size and share of employees with work experience in innovative firms. The symbols $\theta_j$, $+\phi_k$ and $\tau_t$ denote industry, cohort and year fixed effects, respectively.

Equation (2) estimates the new firms' propensity to be innovative, proxied by patent applications. To handle potential endogeneity we specify a second equation:

$$BCI_{i,t-1} = X'_{i,t-1}\pi_0 + \pi_1 NewOBCI1_{i,t-2} + \pi_2 NewOBCI2_{i,t-2} + \lambda_j + \gamma_k + \delta_{t-1} + \nu_{i,t-1} \quad (3)$$

Equations (2) and (3) are estimated applying a recursive bivariate probit model. Following procedures suggested by Wooldridge (2005), Papke and Wooldridge (2008) and Semykina (2018), we also apply a correlated random effects (CRE) approach by adding firm-specific time averages of all time-varying covariates to Equations (2) and (3). We also include firm-specific averages of year dummies to both equations as recommended by Wooldridge (2019) in the context of unbalanced panels.

## 5. Results

In this section, we present the results of testing our hypotheses for the influence of the board of directors on innovation by recently formed firms. The main sample consists of 54,801 unique firms established as limited liability companies between 2002 and 2012 and their possible links, through employment or board membership, to all other limited liability companies in the Swedish economy.

Our first set of results is an exploratory analysis, testing the hypothesis that the characteristics of board members, defined by the 12 director types (Table 1), influences firms' innovation, proxied by patent applications. 'Category 1' directors lack links to any innovative firm through either employment or board membership, while 'Category 2' directors exhibit such links. This facilitates a detailed analysis of the relevance of directors' characteristics for firms' innovation. In this preliminary analysis, we do not account for possible endogeneity of directors' motives for joining the board, so that these results can only be interpreted as correlations. We then estimate an instrumental variables recursive bivariate probit model for patents and trademarks to analyze the potential causal effects from directors with links to innovative firms.

### 5.1. *Exploratory analysis of the influence of different categories of board members*

Most newly established Swedish firms have no link to external networks through their BoD. Among start-ups with BoD connections to other firms, the tie is usually to non-innovative firms. Only a small fraction of start-ups have inside or outside directors associated with innovative firms via employment or their boards.

In our initial analysis, using a binomial probit model, we examine how the likelihood of patent applications varies across new firms with the presence of directors of each of the 12 types described in Table 1. The estimates are conditional on firm characteristics, industry classification, labor mobility from innovative firms, geographical location, and time effects as specified by Equation (1).

Table 5 presents results for the 12 models corresponding to these director types. The left panel (Category 1) reports estimates for the presence of directors not linked to innovative firms. The right panel (Category 2) shows estimates for the directors who are employed in or are members of the board in innovative firms.

We obtain negative and partially significant estimates for directors belonging to Category 1 with the exception of sub-group (v): outside directors not employed in any firm and interlocked with the board of one or more non-innovative firms. Column (v) reveals a positive and significant association with patent applications. In contrast to the results for Category 1, coefficients for the director types in Category 2, capturing links to innovative firms, are all positive with the exception of subgroup (vii). Three of the five positive estimates are significantly different from zero.

We obtain positive and highly significant coefficients across all 12 models on board size, total assets, human capital, and employees whose last employment was with an innovative firm.

Our initial findings based on the exploratory results from these probit models suggest that a larger number of non-innovative directors reduces the probability of patent applications. We conduct a sensitivity test of this conclusion by including all 12 types of board members in a single regression. These results are reported in Table 11 in Appendix 2 and they are in line with the former results.

Table 6 presents the average marginal effects (AME) for the binomial probit models. The magnitude of the marginal estimates on the number of directors linked to innovative firms is about 0.002. This is equivalent to saying that an additional director interlocked with or employed by an innovative firm increases the likelihood of a focal firm to apply for a patent in the next period by 0.2 percentage points.

### *5.2. The importance of board members linked to innovative firms*

The binomial probit estimates presented above indicate the existence of knowledge spillovers between innovative firms and start-up firms through board members. The presence of directors connected to innovative firms is positively associated with start-up firms' likelihood to apply for a patent. However, the results may be biased by reverse causality: start-ups formed by innovative entrepreneurs are probably more likely to successfully recruit directors with links to other innovative companies.

To investigate whether board members linked to innovative firms through employment or board membership positively affect a start-up firm's propensity to be innovative, we need to ensure that the influence of board members is not affected by potential endogeneity. We address this concern by estimating the recursive bivariate probit model described by equations (2) and (3) in Table 7. The model includes external instruments for the binary variable $BCI_{t-1}$, which signals whether the focal firm has at least one director with a connection, through employment or other board appointments, to an innovative firm. The variable incorporates all six board compositions of Category 2 in Table 1. The instruments $New\ OBCI1_{t-2}$ and $New\ OBCI2_{t-2}$ are defined in Table 2. As the main objective of the paper is to examine the role of the BoD for knowledge spillovers, we do not include any instruments for the labor mobility variable, which also may capture diffusion of knowledge.

Table 7 reports estimates of recursive bivariate probit and correlated random effects (CRE) probit models, including firm-specific time averages of all time-varying variables to control for firm-specific time-invariant effects. As the CRE model also captures unobserved heterogeneity, conditional on the random effects, it may be considered as the preferred estimator. In both columns, we obtain positive and highly significant coefficients on the BoD spillover variable ($New\ BCI_{t-1}$). The magnitude of the estimates is almost identical in the two columns, and the two instruments ($New\ OBCI1_{t-2}$ and $New\ OBCI2_{t-2}$) are highly significant in both models.

Tests of instrument validity from a linear probability model presented in Appendix Table 17 show that we can reject both the null hypothesis of under-identification and of weak instruments. Also, we cannot reject the hypothesis testing the overidentifying restrictions. Taken together, the test results suggest that our instruments are valid.

Concerning the controls, there are some differences between the two models. The variables board size, total assets, human capital, and employees recruited from innovative firms are positive and highly significant in the pooled model, but not significant in the CRE model. An explanation for this is that the CRE model controls for the mean of all continuous covariates. This implies that the impact on patenting of human capital and labor migration as well as the size of the board is in accordance with the literature.

Average marginal effects for the recursive bivariate probit models are presented in Table 8. The point estimates suggest that firms with at least one director on the board with a connection to an innovative firm have a 0.5 percentage point higher probability of applying for a patent than firms with no connections to innovative firms through their board of directors.

Results from the instrumental variables model imply that we cannot reject the assumption that board members linked to innovative firms through employment or board membership positively affect a start-up firm's propensity to apply for patents.

While patents are broadly recognized as a proxy for innovation, we also test whether trademarks may be an alternative innovation indicator for analysing knowledge transfer via board members. When substituting $\mathit{Trademark\ application}_t$ for $\mathit{Patent\ application}_t$ (hence $BCT_{t-1}$ for $BCI_{t-1}$) we also construct new instruments, $New\,OBCT1_{t-2}$ and $New\,OBCT2_{t-2}$, following the same procedure as for $New\,OBCI1_{t-2}$ and $New\,OBCI2_{t-2}$, for trademarks rather than patent applications. Here, we find no evidence for knowledge spillovers from incumbent innovative firms to the start-up firms, as reported in Table 9 and 10.

The first equation in the recursive model shows that the two external instruments ($New\,OBCT1_{t-2}$ and $New\,OBCT2_{t-2}$) are highly significant in both models. However, the point estimate for boards linked to firms with trademarks is not significantly different from zero in either the pooled model (column 1) nor in the CRE model (column 2). The sensitivity test below extends this analysis by examining the links between trademarks and patents.

## 6. Sensitivity analysis

In this section, comprehensive sensitivity analyses of the estimates reported in the results section are performed. We investigate the effect of the board members' characteristics, the impact of patent citations, educational background, the importance of venture capital, different restrictions on firm size, and other definitions for start-up firms. We also study alternative models and extensions of the estimation sample in Appendix 2, evaluating whether the restrictions imposed to define that sample are driving the results.

Our first robustness test concerns the results for the two categories of directors reported in Table 5. Estimating separate equations for the different characteristics of board members, we find that directors not linked to any external innovative firm may negatively influence the focal firm's propensity to apply for a patent. This result is confirmed in Appendix Table 11, where all variations of the board members' characteristics are estimated in one equation rather than 12 different equations.

In the second sensitivity test we consider the board members' educational background and educational diversity as indirect drivers of innovation. For this analysis we introduce two new variables. The first, board human capital (BHC), measures the fraction of directors with three or more years of university education. The second is the *Blau index* (Blau, 1977) capturing the diversity of the board members' educational background (BEB). The results are presented in Appendix Table 12. We find positive and highly significant coefficients for human capital and diversity in the first stage regression, while the diversity estimates are not significant in the second stage. Human capital is positive and highly significant in the pooled model, and insignificant in the preferred CRE model. The results suggest that the level of education and educational diversity of the board of directors are indirect drivers of innovation by influencing whether any of the directors on the board is connected to an innovative firm.

The third sensitivity test applies instrumental variables techniques to focus on the results presented in Table 7. A concern with the reported patent estimates is that we retain the companies that have applied for patents in a given year in our sample. These companies may be more likely than other firms to apply for patents in subsequent years. As we are not modeling this potential autocorrelation at the firm level, we evaluate its importance by restricting the sample to only include firms which have not applied for a patent in prior years. A firm will be excluded from the sample after its first patent application. Appendix Table 13 reports recursive bivariate probit estimates from this reduced sample. The results show that the magnitude of the BoD indicators' coefficient estimates are somewhat lower in both the pooled and CRE model compared to Table 7. However, they are still positive and highly significant.

Extensive research within various strands of management, entrepreneurship and finance provides evidence on the importance of venture capital (VC) for innovative small businesses. To investigate whether our results may be driven by access to VC rather than knowledge spillovers from board members, we compare two model specifications in Appendix Table 14. The first column presents results including a binary variable indicating whether the focal firm received any VC in year $t-1$. The second column shows estimates from our main model excluding those firms that received venture capital in year $t-1$. Comparing the two columns reveals that the results for the two approaches are almost identical. This suggests that our results are not driven by omitting VC as a control variable.

Appendix Table 15 exploits citation information in the PATSTAT data to address the issue that innovative start-ups may have gained knowledge through spillovers from companies other than the companies to which the board members are affiliated. The table estimates our main model using a modified innovation measure. The dependent variable is set to 1 if the firm applies for a patent without citing any other patents, and zero otherwise. The results show that the causal impact from directors on the board connected to innovative firms on the focal firm's propensity to apply for patents remains, with the key estimate positive and highly significant.

Our results presented in Table 9 suggest that there is no spillover effect on start-up firms' trademarks from incumbents with trademarks (and no patent applications), while Appendix Table 16 broadens the analysis by examining the relationship between incumbents with registered trademark protection and start-ups seeking patent protection. This table shows that the instruments are positive and highly significant in the first stage of the recursive pooled and CRE models. The spillover measure reported in the second stage is positive and significant at the 1% level in both the pooled and CRE estimates. This provides evidence that there are knowledge spillovers not only from established patenting firms to future innovators but also from trademark companies to start-ups seeking patent protection. We do not conduct any further sensitivity tests of this result, but note that it is a new finding in the management and entrepreneurship literature that deserves further research.

Our next sensitivity tests consider the instruments. Appendix Table 17 presents IV linear probability model estimates to evaluate the validity of the instruments we have constructed. Two sets of results are reported. The first two columns report first and second stage estimates for the pooled model, while columns 3 and 4 reveal the corresponding estimates for the CRE approach. The instruments and the board variable are positive and highly significant in both models. Beyond this crucial result, our main interest is to test the validity of the instruments. The Kleibergen–Paap tests of both underidentification and weak instruments[6] and the Hansen $J$ test of overidentifying restrictions provide satisfactory results.

Finally, we test the sensitivity of our results by altering our definition of start-ups, starting with the entire population of independent firms as sample *A1*. Relative to our estimation sample, this represents an increase by almost 60% from about 312,000 firm-year observations to 490,515 firm-years. In sample *A2*, we exclude firms that have spun out of an incumbent firm. This sample is 28% larger than our estimation sample. Sample *A3* adds a restriction on the number of employees during firm formation, excluding all firms with 10 or more employees when formed, and is thereby 17% larger than the estimation sample. Sample *A4* imposes the further restriction of dropping firms with only one employee over the sample period, and is the sample used for the estimation results reported above. The characteristics of these four samples are described in Appendix 2, Table 18.

[6] See Baum, Schaffer and Stillman (2007) for details of these tests.

In order to assess the impact of these restrictions, we apply the recursive bivariate probit model on all four samples and compare the results in Appendix 2, Table 19. The reported marginal estimates show that the causal impact from board members affiliated with innovative firms on the likelihood of patent applications is positive and highly significant regardless of sample definition.

The main finding from our results reported in Sections 5 and 6 is that start-ups with directors linked to innovative incumbents have a larger propensity to apply for patents than do other start-ups. This is true regardless of whether the incumbents are defined as innovative based on patent applications or trademark protection. Although previous research (Block, De Vries, Schumann and Sandner, 2014; Veugelers and Schneider, 2018; Crass, 2020) suggests that trademark registrations may be an attractive method to protect intellectual property for resource-scarce innovative start-ups, we do not find any evidence that they are affected by knowledge spillovers. This is a plausible finding considering that patents are a more comprehensive and advanced intellectual property protection mechanism and knowledge is a more crucial factor for acquiring patents compared to trademarks.

A challenging research issue is to explore restrictions for the directors' ability to transfer knowledge from current innovators to future innovators. In this paper we have considered the importance of their level of education and diversity of education. Both have indirect impacts on the propensity to apply for patents through the first equation in the recursive bivariate probit model, whereas these estimates are not statistically significant in the second (innovation) equation. Other possible restrictions for efficient spillovers include exhaustion of technological opportunities, technological distance and the concept that the ruling technological paradigms may hamper the efficiency of knowledge diffusion (Olsson and Frey, 2002). One obvious limitation of the strength of spillovers is a lack of absorptive capacity, which we account for by considering previous innovation experience, human capital, firm age, and firm size. We also allow firms to receive knowledge through patent citations, venture capital engagement, or through recruitment of employees from innovative firms rather than directors' linked spillovers. As the potential for spillovers may be dependent on the technological or geographical landscape, we include both as controls in the regression analysis. Another possible limitation of the directors' ability to transfer knowledge is if the spillover jeopardizes rather than enhances return on R&D investments in the incumbent firm by its use in the start-up firm. This effect, as well as the quality of innovations linked to incumbent firms is not considered in our study, as they require a longer time-frame of observations than available in our data.

## 7. Conclusions

Building on the idea that incumbent organizations represent the origin of the innovation opportunities exploited by entrepreneurial firms, prior studies have examined knowledge spillovers through firm and university spin-offs, geographical and industrial clusters, relational networks, innovation system and value chains. This paper takes a different perspective by investigating whether board directors interlocked with or employed by innovative firms affect start-up firms' propensity to be innovators themselves. To the best of our knowledge, this is the first paper that systematically studies the importance of board of directors as knowledge conduits for innovative start-ups.

Our basic framework is the knowledge spillover theory of entrepreneurship (KSTE) that explains why start-ups are an efficient conduit in turning knowledge spillovers into innovation, and how entrepreneurship is concerned with the start-up and growth of new enterprises. While the KSTE view predominately considers the one-way spillover process from incumbent organizations to entrepreneurial firms, our paper also relies on theoretical concepts of a two-way, mutually beneficial spillover between firms. Board directors linked to both innovative start-up and innovative incumbents raise the possibility of a bidirectional flow of knowledge between firms. Identifying the importance of this spillover channel our paper shed new light on the interplay between incumbent organizations and new entrants, and contributes to KSTE and related theories of knowledge spillover.

Drawing upon a sample that contains 300,000 firm-year observations on almost 55,000 Swedish start-up firms, we show that board connections to incumbent innovators have a causal impact on the new firms' probability to be innovative. The results, based on a recursive correlated random effects probit model are robust when controlling for industry and geography, as well as spillovers via worker and managerial mobility, external knowledge sourcing through patent disclosure, access to venture capital and board attributes. We believe that our findings relevant for other knowledge based economies with board members in start-up firms linked to a network of firms through interlocks or employment.

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## Tables

Table 3: Summary statistics. Four years after firm formation.

| Variable | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|
| Patent application$_t$ | 0.002 | 0.042 | 0 | 1 |
| Trademark registration$_t$ | 0.001 | 0.031 | 0 | 1 |
| | | | | |
| BCI$_{t-1}$ | 0.02 | 0.141 | 0 | 1 |
| BCT$_{t-1}$ | 0.025 | 0.156 | 0 | 1 |
| NewOBCI1$_{t-2}$ | 0.001 | 0.03 | 0 | 1 |
| NewOBCI2$_{t-2}$ | 0.001 | 0.026 | 0 | 1 |
| NewOBCT1$_{t-2}$ | 0.002 | 0.042 | 0 | 1 |
| NewOBCT2$_{t-2}$ | 0.001 | 0.031 | 0 | 1 |
| Board size$_{t-1}$ | 1.55 | 1.035 | 1 | 19 |
| Log(total assets)$_{t-1}$ | 14.2 | 1.046 | 9.11 | 21.4 |
| Human Capital$_{t-1}$ | 0.194 | 0.327 | 0 | 1 |
| Metro | 0.409 | 0.492 | 0 | 1 |
| IE10$_{t-1}$ | 0.064 | 0.244 | 0 | 1 |
| BHC$_{t-1}$ | 0.174 | 0.353 | 0 | 1 |
| BEB diversity$_{t-1}$ | 0.12 | 0.225 | 0 | 1 |
| N | | 54801 | | |

Table 4: Summary statistics for full panel

| Variable | Mean | Std. Dev. | Min. | Max. |
|---|---|---|---|---|
| *Dependent variables* | | | | |
| Patent application$_t$ | 0.001 | 0.036 | 0 | 1 |
| Trademark registration$_t$ | 0.001 | 0.031 | 0 | 1 |
| | | | | |
| *Board variables* | | | | |
| BCI$_{t-1}$ | 0.016 | 0.124 | 0 | 1 |
| BCT$_{t-1}$ | 0.021 | 0.144 | 0 | 1 |
| | | | | |
| *Instruments* | | | | |
| NewOBCI1$_{t-2}$ | 0.001 | 0.027 | 0 | 1 |
| NewOBCI2$_{t-2}$ | 0.001 | 0.026 | 0 | 1 |
| NewOBCT1$_{t-2}$ | 0.001 | 0.035 | 0 | 1 |
| NewOBCT2$_{t-2}$ | 0.001 | 0.031 | 0 | 1 |
| | | | | |
| *Control variables* | | | | |
| Board size$_{t-1}$ | 1.514 | 0.996 | 1 | 20 |
| Log(total assets)$_{t-1}$ | 14.40 | 1.102 | 6.91 | 21.4 |
| Human Capital$_{t-1}$ | 0.185 | 0.318 | 0 | 1 |
| Metro | 0.398 | 0.489 | 0 | 1 |
| IE10 | 0.068 | 0.252 | 0 | 1 |
| BHC$_{t-1}$ | 0.164 | 0.347 | 0 | 1 |
| BEB diversity$_{t-1}$ | 0.113 | 0.219 | 0 | 1 |
| *Year* | | | | |
| 2006 | 0.101 | 0.302 | 0 | 1 |
| 2007 | 0.103 | 0.305 | 0 | 1 |
| 2008 | 0.104 | 0.306 | 0 | 1 |
| 2009 | 0.105 | 0.307 | 0 | 1 |
| 2010 | 0.106 | 0.308 | 0 | 1 |
| 2011 | 0.108 | 0.311 | 0 | 1 |
| 2012 | 0.105 | 0.307 | 0 | 1 |
| 2013 | 0.099 | 0.299 | 0 | 1 |
| 2014 | 0.094 | 0.292 | 0 | 1 |
| 2015 | 0.073 | 0.26 | 0 | 1 |
| *Firm age* | | | | |
| 4 | 0.175 | 0.38 | 0 | 1 |
| 5 | 0.155 | 0.362 | 0 | 1 |
| 6 | 0.137 | 0.344 | 0 | 1 |
| 7 | 0.121 | 0.326 | 0 | 1 |
| 8 | 0.105 | 0.306 | 0 | 1 |
| 9 | 0.087 | 0.282 | 0 | 1 |
| 10 | 0.073 | 0.26 | 0 | 1 |
| 11 | 0.061 | 0.24 | 0 | 1 |
| 12 | 0.051 | 0.219 | 0 | 1 |
| 13 | 0.035 | 0.183 | 0 | 1 |
| N | | 312458 | | |

Table 5: Patent application$_t$ - Probit estimates

| | Patent application$_t$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Category 1 | | | | | | Category 2 | | | | | |
| | (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) | (xii) |
| (i)-(xii) | -0.093*** | -0.055 | -0.187*** | -0.002 | 0.137*** | -0.210*** | 0.291 | -0.025 | 0.474*** | 0.161 | 0.713*** | 0.633*** |
| | (0.031) | (0.040) | (0.043) | (0.027) | (0.047) | (0.069) | (0.189) | (0.109) | (0.048) | (0.111) | (0.100) | (0.122) |
| Log(total assets)$_{t-1}$ | 0.213*** | 0.228*** | 0.213*** | 0.224*** | 0.220*** | 0.222*** | 0.222*** | 0.224*** | 0.205*** | 0.223*** | 0.218*** | 0.220*** |
| | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) | (0.024) | (0.025) | (0.024) | (0.024) | (0.024) |
| IE10$_{t-1}$ | 0.500*** | 0.498*** | 0.490*** | 0.497*** | 0.500*** | 0.494*** | 0.495*** | 0.498*** | 0.469*** | 0.496*** | 0.470*** | 0.492*** |
| | (0.052) | (0.051) | (0.052) | (0.052) | (0.051) | (0.052) | (0.051) | (0.051) | (0.053) | (0.052) | (0.053) | (0.052) |
| Constant | -6.751*** | -6.924*** | -6.562*** | -6.847*** | -6.790*** | -6.773*** | -6.809*** | -6.845*** | -6.476*** | -6.834*** | -6.705*** | -6.716*** |
| | (0.608) | (0.599) | (0.593) | (0.599) | (0.601) | (0.595) | (0.596) | (0.597) | (0.604) | (0.599) | (0.591) | (0.592) |
| Observations | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 |

Notes: For definitions of categories (i)-(xii) see Table 1. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects. Clustered standard errors in parentheses, $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table 6: Patent application$_t$ - Probit AME[a]

| | Patent application$_t$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Category 1 | | | | | | Category 2 | | | | | |
| | (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) | (xii) |
| (i)-(xii) | -0.000*** | -0.000 | -0.001*** | -0.000 | 0.000*** | -0.001*** | 0.001 | -0.000 | 0.002*** | 0.001 | 0.002*** | 0.002*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.001) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| Log(total assets)$_{t-1}$ | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** | 0.001*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| IE10$_{t-1}$ | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** | 0.002*** |
| | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) | (0.000) |
| Observations | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 | 312458 |

Notes: For definitions of categories (i)-(xii) see Table 1. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a]Average marginal effects.

Table 7: Patent application$_t$ - Recursive bivariate probit estimates

| | Pooled | CRE[a] |
|---|---|---|
| BCI$_{t-1}$ | 1.300*** | 1.335*** |
| | (0.174) | (0.168) |
| Board size$_{t-1}$ | 0.192*** | 0.080 |
| | (0.042) | (0.105) |
| Board size$^2_{t-2}$ | -0.019*** | -0.014 |
| | (0.004) | (0.009) |
| Log(total assets)$_{t-1}$ | 0.202*** | 0.083 |
| | (0.024) | (0.066) |
| Human Capital$_{t-1}$ | 0.389*** | -0.140 |
| | (0.078) | (0.172) |
| Metro | 0.046 | 0.046 |
| | (0.062) | (0.063) |
| IE10$_{t-1}$ | 0.421*** | -0.014 |
| | (0.054) | (0.070) |
| Constant | -6.914*** | -7.062*** |
| | (0.649) | (1.221) |
| | | BCI$_{t-1}$ |
| NewOBCI $_{t-2}$ | 2.475*** | 2.460*** |
| | (0.115) | (0.116) |
| NewOBCI2 $_{t-2}$ | 1.922*** | 1.922*** |
| | (0.110) | (0.109) |
| Board size$_{t-1}$ | 0.485*** | 0.440*** |
| | (0.018) | (0.032) |
| Board size$^2_{t-2}$ | -0.021*** | -0.022*** |
| | (0.002) | (0.002) |
| Log(total assets)$_{t-1}$ | 0.075*** | 0.006 |
| | (0.012) | (0.026) |
| Human Capital$_{t-1}$ | 0.507*** | 0.078 |
| | (0.039) | (0.077) |
| Metro | 0.087*** | 0.084*** |
| | (0.027) | (0.027) |
| IE10$_{t-1}$ | 0.323*** | -0.183*** |
| | (0.035) | (0.046) |
| Constant | -4.317*** | -4.604*** |
| | (0.293) | (0.530) |
| $\rho$ | -0.274** | -0.310*** |
| | (0.086 ) | (0.034) |
| Observations | 312458 | 312458 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include year-, cohort-, industry- and firm age fixed effects Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 8: Patent application$_t$ - Recursive bivariate probit AME[a]

| | Pooled | CRE[b] |
|---|---|---|
| $BCI_{t-1}$ | 0.0053*** | 0.0055*** |
| | (0.0012) | (0.0012) |
| Board size$_{t-1}$ | 0.0003*** | -0.0000 |
| | (0.0001) | (0.0002) |
| Log(total assets)$_{t-1}$ | 0.0008*** | 0.0003 |
| | (0.0001) | (0.0003) |
| Human Capital$_{t-1}$ | 0.0016*** | -0.0006 |
| | (0.0003) | (0.0007) |
| Metro | 0.0002 | 0.0002 |
| | (0.0003) | (0.0003) |
| $IE10_{t-1}$ | 0.0017*** | -0.0001 |
| | (0.0003) | (0.0003) |
| Observations | 312458 | 312458 |

Notes: $BCI_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. All specifications include year-, cohort-, industry- and firm age fixed effects Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. [a]Average marginal effects. [b] Time averages of all time varying control variables included in both equations.

Table 9: Trademark registration$_t$ - Recursive bivariate probit estimates

| | Pooled | CRE$^a$ |
|---|---|---|
| | Trademark registration$_t$ | |
| BCT$_{t-1}$ | -0.062 | -0.083 |
| | (0.219) | (0.201) |
| Log(total assets)$_{t-1}$ | 0.262*** | 0.320*** |
| | (0.017) | (0.074) |
| IE10$_{t-1}$ | 0.224*** | 0.037 |
| | (0.055) | (0.132) |
| Constant | -7.293*** | -6.761*** |
| | (0.436) | (0.504) |
| | BCT$_{t-1}$ | |
| NewOBCT1$_{t-2}$ | 2.318*** | 2.315*** |
| | (0.088) | (0.088) |
| NewOBCT2$_{t-2}$ | 1.887*** | 1.886*** |
| | (0.089) | (0.090) |
| Log(total assets)$_{t-1}$ | 0.054*** | -0.008 |
| | (0.011) | (0.024) |
| IE10$_{t-1}$ | 0.135*** | -0.170*** |
| | (0.033) | (0.044) |
| Constant | -3.552*** | -3.146*** |
| | (0.230) | (0.336) |
| $\rho$ | 0.257*** | 0.260** |
| | (0.122) | (0.112) |
| Observations | 312458 | 312458 |

Notes: BCT$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (trademark) firm. New OBCT1$_{i,t-2}$ (New OBCT2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with trademark experience in year $t-2$ ($t-3$) and were employed in a different firm without trademark experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.$^a$ Time averages of all time varying control variables included in both equations.

Table 10: Trademark registration$_t$ - Recursive bivariate probit AME[a]

| | Pooled | CRE[b] |
|---|---|---|
| $BCT_{t-1}$ | -0.0002 | -0.0002 |
| | (0.0006) | (0.0006) |
| Log(total assets)$_{t-1}$ | 0.0007*** | 0.0009*** |
| | (0.0001) | (0.0002) |
| $IE10_{t-1}$ | 0.0006*** | 0.0001 |
| | (0.0002) | (0.0004) |
| | (0.0001) | (0.0003) |
| Observations | 312458 | 312458 |

Notes: $BCT_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (trademark) firm. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. [a] Average marginal effects [b] Time averages of all time varying control variables included in both equations.

## Appendix 1

Table 11: Patent application$_t$ - Probit estimates (12 categories)

| | Patent application$_t$ |
|---|---|
| *Category 1:* | |
| (ii)$_{t-1}$ | -0.022 |
| | (0.046) |
| (iii)$_{t-1}$ | -0.096$^{*}$ |
| | (0.050) |
| (iv)$_{t-1}$ | 0.052 |
| | (0.039) |
| (v)$_{t-1}$ | 0.182$^{***}$ |
| | (0.055) |
| (vi)$_{t-1}$ | -0.169$^{**}$ |
| | (0.077) |
| *Category 2:* | |
| (vii)$_{t-1}$ | 0.350$^{*}$ |
| | (0.194) |
| (viii)$_{t-1}$ | 0.016 |
| | (0.058) |
| (ix)$_{t-1}$ | 0.427$^{***}$ |
| | (0.058) |
| (x)$_{t-1}$ | 0.146 |
| | (0.129) |
| (xi)$_{t-1}$ | 0.628$^{***}$ |
| | (0.100) |
| (xii)$_{t-1}$ | 0.579$^{***}$ |
| | (0.133) |
| Log(total assets)$_{t-1}$ | 0.187$^{***}$ |
| | (0.026) |
| IE10$_{t-1}$ | 0.441$^{***}$ |
| | (0.055) |
| Constant | -6.067$^{***}$ |
| | (0.602) |
| Observations | 312458 |

Notes: For definitions of categories (i)-(xii) see Table 1. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects $^a$ Time averages of all time varying control variables included in both equations. Clustered standard errors in parentheses, $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

Table 12: Patent application$_t$ - Recursive bivariate probit estimates - Board educational background

| | Pooled | CRE[a] |
|---|---|---|
| | Patent application$_t$ | |
| BCI$_{t-1}$ | 1.280*** | 1.305*** |
| | (0.176) | (0.169) |
| Log(total assets)$_{t-1}$ | 0.196*** | 0.083 |
| | (0.024) | (0.067) |
| BHC$_{t-1}$ | 0.261*** | 0.288 |
| | (0.070) | (0.264) |
| BEB diversity$_{t-1}$ | -0.053 | -0.040 |
| | (0.135) | (0.267) |
| IE10$_{t-1}$ | 0.429*** | -0.018 |
| | (0.054) | (0.069) |
| Constant | -6.836*** | -7.071*** |
| | (0.652) | (1.258) |
| | BCI$_{t-1}$ | |
| NewOBCI1$_{t-2}$ | 2.372*** | 2.368*** |
| | (0.117) | (0.117) |
| NewOBCI2$_{t-2}$ | 1.831*** | 1.842*** |
| | (0.109) | (0.109) |
| Log(total assets)$_{t-1}$ | 0.065*** | 0.003 |
| | (0.012) | (0.027) |
| BHC$_{t-1}$ | 0.750*** | 0.844*** |
| | (0.037) | (0.135) |
| BEB diversity$_{t-1}$ | 0.552*** | 0.333*** |
| | (0.067) | (0.121) |
| IE10$_{t-1}$ | 0.323*** | -0.191*** |
| | (0.035) | (0.046) |
| Constant | -4.242*** | -4.540*** |
| | (0.300) | (0.538) |
| $\rho$ | -0.271*** | -0.298*** |
| | (0.089) | (0.085) |
| Observations | 312458 | 312458 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 13: Patent application$_t$ - Recursive bivariate probit estimates - No previous patents

| | Pooled | CRE[a] |
|---|---|---|
| | Patent application$_t$ | |
| BCI$_{t-1}$ | 0.954*** | 1.200*** |
| | (0.273) | (0.347) |
| Log(total assets)$_{t-1}$ | 0.100*** | 0.536*** |
| | (0.022) | (0.111) |
| IE10$_{t-1}$ | 0.384*** | 0.315** |
| | (0.066) | (0.150) |
| Constant | -4.521*** | -4.178*** |
| | (0.448) | (0.508) |
| | BCI$_{t-1}$ | |
| NewOBCI1$_{t-2}$ | 2.480*** | 2.470*** |
| | (0.115) | (0.115) |
| NewOBCI2$_{t-2}$ | 1.930*** | 1.935*** |
| | (0.112) | (0.111) |
| Log(total assets)$_{t-1}$ | 0.067*** | 0.008 |
| | (0.012) | (0.027) |
| IE10$_{t-1}$ | 0.270*** | -0.199*** |
| | (0.038) | (0.050) |
| Constant | -4.109*** | -4.417*** |
| | (0.293) | (0.531) |
| $\rho$ | -0.150 | -0.238 |
| | (0.124) | (0.155) |
| Observations | 310886 | 310886 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 14: Patent application$_t$-Recursive bivariate probit estimates - Venture capital

| | | No VC in$_{t-1}$ |
|---|---|---|
| | CRE[a] | CRE[a] |
| | Patent application$_t$ | |
| BCI$_{t-1}$ | 1.272*** | 1.257*** |
| | (0.171) | (0.175) |
| VC$_{t-1}$ | 0.496** | |
| | (0.205) | |
| Log(total assets)$_{t-1}$ | 0.084 | 0.078 |
| | (0.066) | (0.067) |
| IE10$_{t-1}$ | -0.001 | 0.021 |
| | (0.068) | (0.069) |
| Constant | -7.093*** | -7.134*** |
| | (1.246) | (1.248) |
| | BCI$_{t-1}$ | |
| NewOBCI1$_{t-2}$ | 2.464*** | 2.464*** |
| | (0.115) | (0.115) |
| NewOBCI2$_{t-2}$ | 1.927*** | 1.928*** |
| | (0.109) | (0.109) |
| VC$_{t-1}$ | 1.637*** | |
| | (0.204) | |
| Log(total assets)$_{t-1}$ | 0.006 | 0.006 |
| | (0.026) | (0.027) |
| IE10$_{t-1}$ | -0.179*** | -0.185*** |
| | (0.047) | (0.047) |
| Constant | -4.581*** | -4.586*** |
| | (0.531) | (0.531) |
| $\rho$ | -0.256** | -0.287*** |
| | (0.088) | (0.085) |
| Observations | 312400 | 312400 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 15: Patent application$_t$ - Recursive bivariate probit estimates - No citations

| | CRE[a] Patent application$_t$ without citation to other patents$_t$ |
|---|---|
| BCI$_{t-1}$ | 0.890$^{***}$ |
| | (0.245) |
| Log(total assets)$_{t-1}$ | 0.083 |
| | (0.079) |
| IE10$_{t-1}$ | -0.175 |
| | (0.114) |
| Constant | -7.259$^{***}$ |
| | (1.262) |
| | BCI$_{t-1}$ |
| NewOBCI1$_{t-2}$ | 2.469$^{***}$ |
| | (0.115) |
| NewOBCI2$_{t-2}$ | 1.930$^{***}$ |
| | (0.109) |
| Log(total assets)$_{t-1}$ | 0.007 |
| | (0.026) |
| IE10$_{t-1}$ | -0.182$^{***}$ |
| | (0.047) |
| Constant | -4.615$^{***}$ |
| | (0.532) |
| $\rho$ | -0.159 |
| | (0.132) |
| Observations | 312458 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Standard errors in parentheses, $^*$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 16: Patent application$_t$ - Recursive bivariate probit estimates - Trademark spillovers

| | Pooled | CRE$^a$ |
|---|---|---|
| | Patent application$_t$ | |
| BCT$_{t-1}$ | 1.174*** | 1.208*** |
| | (0.169) | (0.168) |
| Log(total assets)$_{t-1}$ | 0.204*** | 0.069 |
| | (0.024) | (0.064) |
| IE10$_{t-1}$ | 0.465*** | -0.024 |
| | (0.052) | (0.069) |
| Constant | -7.106*** | -7.291*** |
| | (0.640) | (1.195) |
| | BCT$_{t-1}$ | |
| NewOBCT1$_{t-2}$ | 2.301*** | 2.296*** |
| | (0.089) | (0.089) |
| NewOBCT2$_{t-2}$ | 1.878*** | 1.875*** |
| | (0.090) | (0.090) |
| Log(total assets)$_{t-1}$ | 0.054*** | -0.009 |
| | (0.010) | (0.024) |
| IE10$_{t-1}$ | 0.137*** | -0.175*** |
| | (0.033) | (0.044) |
| Constant | -3.541*** | -3.135*** |
| | (0.230) | (0.335) |
| $\rho$ | -0.363** | -0.397** |
| | (0.079) | (0.079) |
| Observations | 312458 | 312458 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. BCT$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCT1$_{i,t-2}$ (New OBCT2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with trademark experience in year $(t-2)$ $((t-3)$ ) and were employed in a different firm without trademark experience in year $t-3$ $(t-4)$. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects. Standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 17: Patent application$_t$ - IV Linear Probability Estimates

| | Pooled | | CRE[a] | |
|---|---|---|---|---|
| | BCI$_{t-1}$ | Patent application$_t$ | BCI$_{t-1}$ | Patent application$_t$ |
| BCI$_{t-1}$ | | 0.034** | | 0.034** |
| | | (0.013) | | (0.013) |
| NewOBCI1$_{t-2}$ | 0.677*** | | 0.674*** | |
| | (0.026) | | (0.026) | |
| NewOBCI2$_{t-2}$ | 0.532*** | | 0.529*** | |
| | (0.032) | | (0.032) | |
| Log(total assets)$_{t-1}$ | 0.003*** | 0.001*** | 0.000 | 0.000 |
| | (0.000) | (0.000) | (0.001) | (0.000) |
| IE10$_{t-1}$ | 0.020*** | 0.005*** | -0.008*** | -0.001 |
| | (0.002) | (0.001) | (0.002) | (0.001) |
| Constant | -0.059*** | -0.014*** | -0.070*** | -0.013*** |
| | (0.012) | (0.003) | (0.016) | (0.004) |
| Observations | 312458 | 312458 | 312458 | 312458 |
| Kleibergen-Paap rk LM statistic | | 173.203 | | 174.748 |
| $\chi^2$ p-value | | 0.0000 | | 0.0000 |
| Kleibergen-Paap rk Wald F statistic | | 364.953 | | 358.093 |
| Hansen J statistic | | 0.882 | | 0.890 |
| $\chi^2$ p-value | | 0.3477 | | 0.3456 |

Notes: BCI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. New OBCI1$_{i,t-2}$ (New OBCI2$_{i,t-2}$) indicates whether any of the outside directors were newly hired in a firm with patenting experience in year $t-2$ ($t-3$) and were employed in a different firm without patenting experience in year $t-3$ ($t-4$). All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

**Appendix 2**

Table 18: Samples

| A: *All new firms formed in year t* | |
|---|---|
| A1 | all independent firms |
| A2 | independent firms, no spin-outs |
| A3 | independent firms, no spin-outs, $< 10$ employees at start |
| A4 | independent firms, no spin-outs, $< 10$ employees at start, and more than one employee throughout the sample period |

Table 19: Patent application$_t$ - Recursive bivariate probit AME$^a$ - Sample A1-A4

| | | Pooled | CRE$^b$ |
|---|---|---|---|
| Sample A1 | $\text{BCI}_{t-1}$ | 0.0048*** | 0.0047*** |
| | | (0.0009) | (0.0009) |
| | Log(total assets)$_{t-1}$ | 0.0008*** | 0.0003 |
| | | (0.0001) | (0.0002) |
| | $\text{IE10}_{t-1}$ | 0.0018*** | -0.0000 |
| | | (0.0002) | (0.0003) |
| | Observations | 490515 | 490515 |
| Sample A2 | $\text{BCI}_{t-1}$ | 0.0050*** | 0.0051*** |
| | | (0.0010) | (0.0010) |
| | Log(total assets)$_{t-1}$ | 0.0008*** | 0.0003 |
| | | (0.0001) | (0.0003) |
| | $\text{IE10}_{t-1}$ | 0.0018*** | -0.0001 |
| | | (0.0003) | (0.0003) |
| | Observations | 400757 | 400757 |
| Sample A3 | $\text{BCI}_{t-1}$ | 0.0049*** | 0.0050*** |
| | | (0.0011) | (0.0010) |
| | Log(total assets)$_{t-1}$ | 0.0008*** | 0.0004 |
| | | (0.0001) | (0.0003) |
| | $\text{IE10}_{t-1}$ | 0.0016*** | -0.0001 |
| | | (0.0002) | (0.0003) |
| | Observations | 365330 | 365330 |
| Sample A4 | $\text{BCI}_{t-1}$ | 0.0053*** | 0.0055*** |
| | | (0.0012) | (0.0012) |
| | Log(total assets)$_{t-1}$ | 0.0008*** | 0.0003 |
| | | (0.0001) | (0.0003) |
| | $\text{IE10}_{t-1}$ | 0.0017*** | -0.0001 |
| | | (0.0003) | (0.0003) |
| | Observations | 312458 | 312458 |

Notes: $\text{BCI}_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.$^a$ Average marginal effects. $^b$ Time averages of all time varying control variables included in both equations.

Table 20: Patent application$_t$ - Probit estimates - Inter/Intra-industry spillover

| | Pooled | CRE[a] |
|---|---|---|
| | Patent application$_t$ | |
| BCISI$_{t-1}$ | 0.4903** | 0.4409* |
| | (0.2221) | (0.2349) |
| BCISS$_{t-1}$ | 0.9592*** | 0.9311*** |
| | (0.0975) | (0.0979) |
| BCIDS$_{t-1}$ | -0.5404*** | -0.5524*** |
| | (0.1282) | (0.1308) |
| Log(total assets)$_{t-1}$ | 0.2181*** | 0.0911 |
| | (0.0244) | (0.0667) |
| IE10$_{t-1}$ | 0.4867*** | -0.0140 |
| | (0.0537) | (0.0717) |
| Constant | -7.4665*** | -7.8978*** |
| | (0.6451) | (1.2850) |
| Observations | 312458 | 312458 |

Notes: BCISI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm within the same 3-digit industry. BCISS$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm within the same sector (but different 3-digit industry). BCIDS$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm belonging to a different sector. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.[a] Time averages of all time varying control variables included in both equations.

Table 21: Patent application$_t$ - Probit AME$^a$ - Inter/Intra-industry spillover

| | Pooled | CRE$^b$ |
|---|---|---|
| BCISI$_{t-1}$ | 0.0016** | 0.0014* |
| | (0.0007) | (0.0007) |
| BCISS$_{t-1}$ | 0.0031*** | 0.0029*** |
| | (0.0004) | (0.0004) |
| BCIDS$_{t-1}$ | -0.0017*** | -0.0017*** |
| | (0.0004) | (0.0004) |
| Log(total assets)$_{t-1}$ | 0.0007*** | 0.0003 |
| | (0.0001) | (0.0002) |
| IE10$_{t-1}$ | 0.0016*** | -0.0000 |
| | (0.0002) | (0.0002) |
| Observations | 312458 | 312458 |

Notes: BCISI$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm within the same 3-digit industry. BCISS$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm within the same sector (but different 3-digit industry). BCIDS$_{i,t-1}$ indicates whether any of the directors on the board are connected to an innovative (patent) firm belonging to a different sector. All specifications include controls for board size$_{t-1}$, board size$^2_{t-2}$, human capital$_{t-1}$ and metro as well as year-, cohort-, industry- and firm age fixed effects Clustered standard errors in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. $^a$ Average marginal effects $^b$ Time averages of all time varying control variables included in both equations.