Paper to be presented at
the DRUID16 20th Anniversary Conference
Copenhagen, June 13-15, 2016

MANAGING INNOVATION NETWORKS: A MULTIPLEX ANALYSIS OF THE GLOBAL WIND POWER INDUSTRY

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Abstract

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Abstract: In this article, we treat innovation as a multidimensional construct spanning people, technologies, and geographies. We study how these dimensions interact and impact firms' inventor networks and the ultimate innovation performance. We identify five distinct planes in which inventor networks reside. Specifically, we distinguish between the types of ties that are possible between any two inventor nodes with respect to (i) co-located inventors; (ii) technology cohort; (iii) co-located technology cohort; (iv) distant co-inventors; and (v) co-located co-inventors. We build a simple, yet parsimonious model of the costs and benefits of being centrally located on multiplex network versus having an equal distribution of ties between the different network layers. Using patent data on the global wind power industry, we find evidence suggesting that being centrally positioned on a multiplex network with an equal distribution of ties deteriorates rather than enhances innovation performance.

Keywords: Innovation, multiplex networks, heterogeneous knowledge, search costs, global wind power industry.

INTRODUCTION

Assuming that inventors are embedded in multiple innovation networks, what are the performance implications of being centrally located on multiplex network versus having an equal distribution of ties between the different network layers? Various strands of research have emphasized different inventor network dimensions. For example, research on social networks argues that strong social connections facilitate the creation of new knowledge within and across organizations (Tsai, 2001). Inventors with the ability to access rich and widespread knowledge from related and different technological fields are more likely to generate new products or services (Kodama, 1992). Research has also focused on the importance of being embedded in clusters to sustain innovativeness by virtue of knowledge-related local networks effects (Arrow, 1962; Almeida and Kogut, 1999).

Interestingly, while research within the different innovation dimensions has made seminal contributions on the relationship between networks and innovation, these are seldom studied simultaneously. For example, while research on social networks argues that strong social connections facilitate the creation of new knowledge within and across organizations, other potential networks such as technological and geographical centrality are not necessarily account for. Equally, while research has focused on clusters' ability to sustain innovativeness by virtue of knowledge-related local networks effects, the simultaneous impact of other related networks such as social connections are often left unaddressed.

This one-dimensionality of network studies is puzzling. Specifically, if each of the different inventor dimensions carries important innovation explanans, a simultaneously investigation of network dynamics and outcomes should offer superior prescriptions to the antecedents and outcomes of innovation behavior. Realistically, firms and economic actors are embedded in multiple networks and therefore partake in relationships of a different nature than sole one-dimensional networks (e.g. Schilling and Phelps, 2007). Hence, the omission of central inventor dimensions fosters a potential incomplete picture of the complex relationship between networks and innovation performance (Shipolov, 2012).

In this article, we propose a simple yet parsimonious model of the inventor performance effect of being embedded in multiple networks simultaneously. Using inventor-level data from the total population of patent data from the global wind power industry—an industry which came into existence in the early 1980s after the leading industrial nations of the world suffered the oil crises of the 1970s (Garud and Karnoe, 2003)—we investigate the effect of multiplex inventor networks spanning technologies, geographies and co-inventors. Specifically, we distinguish between the types of ties that are possible between any two inventor nodes with respect to co-located inventors, technology cohort, co-located technology cohort, distant co-inventors, and co-located co-inventors. We hypothesize that overall network centrality on all layers is positively associated with an inventor's performance. Being centrally located on the multiplex network allows inventors to exploit their many ties, and thus have access to broader knowledge-base (Almeida and Kogut, 1999; Ibarra, 1993; Tsai, 2000). However, as the heterogeneity of knowledge inputs can also be seen a key source of innovation (Nelson and Winter, 1982; Rodan and Galunic, 2004; Rosenkopf and Nerkar, 2001), we argue that inventors a more equal distribution of their ties between the different layers display higher performance. Inventors with rich and vast opportunities for mutual learning and cooperation between the different innovation dimension stimulate the creation of new knowledge and contribute to their ability to innovate (e.g., Kogut and Zander, 1992; Tsai and Ghoshal, 1998). Finally, we expect a trade-off effect between network centrality and participation. Specifically, while centrality and participation may yield innovation performance in isolation, we argue that having many ties both within a specific domain and across a number of domains entail substantial searching costs (Hansen, 1999). As the search for new knowledge is typically myopic and involves limited distance (Levinthal and March, 1993), we propose an incompatibility effects between the myriad of opportunities associated with both high centrality and participation coefficients. Our patent data support our expectations.

With this article, we make a number of important contributions. First, we present an innovative conceptualization of how multiple network layers may be used to study innovation performance, as we treat innovation as a multidimensional construct spanning people, technologies, and geographies. We study how these dimensions interact and impact firms' inventor networks and the ultimate innovation performance. As argued by Shipolov et al. (2014: 449) "Organizations, as complex adaptive systems, are embedded in heterogeneous networks consisting of many different nodes (people, projects, machines, building). Understanding how these networks interrelate offers the opportunity to uncover new pathways for research." Hence, we are able to simultaneously study the dimensions of technology, geography, co-inventors of firms' innovative behavior. As mentioned, our results suggest that accounting for these three dimensions reveal a murkier picture of firms' innovation performance than earlier found. In particular, we suggest that costs of searching for relevant knowledge on complex networks may undermine the benefits of potentially acquiring heterogeneous knowledge inputs. Thus, by examining the effects of various types of ties on the focal firm's innovation performance, our study helps to identify the differential value-added by investing in those ties. Further, the emerging industry setting brings in the temporal aspect to the study by showing which ties lead to superior innovation performance in the early years of an industry. A strategy to focus on those ties can potentially lead to early mover advantage.

We proceed with a review of literature employing a network perspective on innovation performance before we introduce the logic of the multiplex network analysis. We then develop a set of hypotheses on the relationship between different aspects of the multiplex network and innovation performance. Next, we present the data, methods and results. Finally, we discuss the implications of our study.

THEORETICAL BACKGROUND

Innovation, networks and dimensions of knowledge

Innovation has often been described as the result of a process where existing technologies are recombined in a novel way (Schumpeter, 1939). For example, research investigating technological heterogeneity as a source of innovation has focused on aspects such as the relevance and potential obsolesce of internal technological search (Sorensen and Stuart, 2000), the role of technological and organizational boundary spanning in technological evolution (Rosenkopf and Nerkar, 2001), and the relationship between scientific research, technological advance and economic growth (Fleming and Sorensen, 2004). Equally, a parallel research stream has also emphasized how search along the geographical dimension may impact innovation, focusing on areas such as the geographical composition of co-inventors (Gittelman, 2007), global innovation systems (Mudambi, 2008), knowledge spillover effects within regional boundaries (Jaffe et al., 1993), and co-location and agglomeration effects (Porter, 2000)

Important to this view is the assumption that the any innovation efforts depend on the ability of the inventor to access, select and combine existing pieces of knowledge. In this respect, an important strand of research has argued that inventor networks position determines their degree of access to new and redundant information and, thus, their ability to generate further creative output (Burt, 2004; Obstfeld, 2005). Inventors operating in industries with superior network structures may be better able to exploit their capabilities and resources and thus enhance their innovation performance (Zaheer and Bell, 2005). Inventor units that are well-positioned in their respective network are enabled to gain access to critical knowledge and competencies that spur learning, opportunity discovery and innovation (e.g., Tsai and Ghoshal, 1998).

In this study, we focus on three important network dimensions of innovation: technologies, geography and co-inventors. First, much research has explored the ability of firms and their inventors to foster new technologies through the means of organizational characteristics (Cohen and Levinthal, 1990), structures (Henderson and Clark, 1990), and culture (Chandi and Tellis, 1998). The literature has also extended the analysis to actors beyond organizational boundaries such as firms' alliances (Schilling and Phelps, 2007) and network positions (Ahuja, 2000; Gulati, Nohria, and Zaheer, 2000; Tsai, 2001; Zaheer and Bell, 2005).

Second, a related stream of research on geography of innovation evaluates has explored questions related to characteristics of the location where innovation is generated. Studies on innovative clusters form a major portion in this stream. Cluster studies evaluate the antecedents to innovative cluster formation (Bresnahan, Gambardella, and Saxenian, 2001; Klepper, 2007) and clusters' ability to sustain innovativeness by virtue of knowledge-related local effects (Jaffe, Trajtenberg, and Henderson, 1993; Bathelt, Malmberg, and Maskell, 2004; Bathelt, 2005).

Finally, much research has explored inventor profiles (Allen and Cohen, 1969; Tushman and Katz, 1980; Henderson and Cockburn, 1994; Darby and Zucker, 2001; Rothaermel and Hess, 2007; Hess and Rothaermel, 2011), their mobility (Song, Almeida, and Wu, 2003; Zucker and

Darby, 2006; Singh and Agrawal, 2011), and their network stature (Balconi, Breschi, and Lissoni, 2004; Singh, 2005; Fleming and Frenken, 2007). Indeed, research investigating the knowledge-based view of the firm suggests that social networks facilitate the creation of new knowledge within organizations (e.g., Kogut & Zander, 1992; Tsai, 2000).

While the extant research notes the presence and importance of these various dimensions of innovation, they are seldom studied simultaneously (though, see e.g. Breschi & Catalini, 2010; Shipolov et al., 2014). In particular, studies cited above use network theory to understand the technology of innovation often model networks of inventors consisting of only one type of ties. Examples of these types of ties are co-invention ties, citation ties indicating knowledge flows, alliance ties, or managerial/directorial ties. On the other hand, the literature on geography of innovation is primarily concerned with the networks of locations or inventors, depicting co-invention, citation, or co-location ties. Above the majority of network study consists of only one type of nodes which makes the analyses, and therefore the conceptualization of innovation, one-dimensional or uni-modal.

Multiplex innovation networks

To simultaneously study the different network dimensions of innovation, we adopt a multiplex innovation network perspective, which can be defined as "the fact that the same actors may be simultaneously embedded in multiple collaboration networks and thus involved in relationships of a different nature" (Maggioni et al., 2013: 186). Although the notion of multiplexity in network research is not new (e.g., Granovetter, 1973; Verbrugge; 1979), it is only recently that management studies have started to embrace this area of inquiry (e.g., Shipolov et al., 2014). Maggioni et al. (2013: 189) argue that the new interest in multiplex networks comes from the fact that “many scientists are nowadays facing different and often contrasting logics and norms of behavior; on the one hand, the logic of science, with its emphasis on norms and openness and communalism; on the other hand, the logic of technology, with its stress on norms of private appropriation and exclusion.”

Specifically, we focus on innovation networks in which we allow the same inventor to be simultaneously embedded in multiple collaboration networks (Battiston et al., 2014). Therefore, rather than just investigating the effect of being embedded in either a technological or geographical network, we target inventors that may be connected to other inventors in the same location; may be connected with other inventors developing the same technology; and may above all be connected to other co-inventors. As such, we view innovation as an outcome of multiple dimensions and propose that only a simultaneous study of them can provide a more complete model of the reality of innovation.

*** Figure 1 about here***

Our multiplex logic is illustrated in Figure 1. In the left panel, the three dimensions are modeled as a network of inventors, technology and geography. This specific example illustrates an innovation generated by three inventors I1, I2, and I3. Inventors I1 and I2 are located at L2 and work in technological domain C1. Being a co-inventor of I1 and I2, inventor I3 also falls in the same technological domain but is located at L1. Further, location L2 has two more inventors I4 and I6 working in a different technological domain (C2) than I1 and I2. Inventor I5 also works in C2 but is located at L3 and has not co-invented with I4 and I6 yet. Such a network is multimodal consisting of different kinds of nodes and treats innovation as a multidimensional construct.

*** Table 1 about here***

In the right panel, the multimodal network is conceptualized as a multiplex network, in which the ties represent the interaction of three innovation dimensions. Based on the types of ties that are possible between any two inventor nodes, we identify five distinct types of ties: (i) co-located inventors, (ii) technology cohort, (iii) co-located technology cohort, (iv) distant co-inventors, (v) co-located co-inventors. As seen in Table 1, ties T1 and T2 are truly unidimensional capturing the effect of only one dimension. Ties of type T3 and T4 capture the interaction of two dimensions whereas T5 captures the effect of all three dimensions of innovation.

HYPOTHESES DEVELOPMENT

In the following, we develop specific hypothesis on the inventor performance effect of being embedded in multiple networks simultaneously. To accomplish this, we explore two important multiplex network characteristics: degree centrality and participation (Battiston et al., 2014). Specifically, we investigate the performance effects of an inventor being centrally located in certain layers, having more ties focused in other layers, or having a balanced distribution of all five types of ties across all layers. When ties concentrate in a few layers, the inventors are considered to be more focused on those layers. Within each these few layers, the inventors may both be centrally and peripherally positioned. Yet, when the ties are equally distributed in all the layers, the inventors are considered to display a high participation in the multiplex network. Again, within all the layers, the inventor may be central and peripheral.

*** Figure 2 about here***

The different multiple network positions are captured in Figure 2. Along the vertical axes, we depict degree centrality from peripheral to core. Along the horizontal axes, we depict the participation coefficient from an unequal distribution of ties between the different layers to an equal distribution. We discuss the innovation performance implications of the different constellations in the following sections.

Degree centrality on the multiplex network and the impact on performance

As earlier mentioned, the quality of any innovation efforts rests on the ability of the inventor to access, select and combine existing pieces of knowledge. In this respect, the centrality of an inventor's network position is has frequently been highlighted as an important vehicle of privileged knowledge-sharing opportunities and thereby access to new knowledge (Wasserman & Faust, 1994; Sparrowe, Liden & Kraimer, 2001). As centrally positioned inventors represent major channels of knowledge in networks, their many ties mean that they are in "the thick of things" and are focal points of communication (Freeman, 1978).

Empirical research on individual level networks supports the relationship between centrality, knowledge access and thus innovation efforts. For example, Anderson (2008) showed that a central network position is positively related to the amount and diversity of the knowledge that is acquired by an employee. Tsai (2001) argues that organizational units that are centrally positioned in their intraorganizational networks engage in more knowledge sharing and therefore are more innovative than units that are low in network centrality. Equally, Sparrowe and colleagues (2001) found that individuals who are centrally positioned in an organization's advice network exhibit higher levels of both in-role and extrarole performance. Research has also investigated the relationship between a central network position and the ability to absorb knowledge acquired elsewhere. For example, Reagans and McEvily (2003) demonstrate that having broad networks improves the individuals' ability to convey complex ideas to diverse audiences. A central network position can supplement someone's ability to respond to new challenges and changing environments when that person knows who to seek out for information or expertise relevant to a new project.

As a multiplex network, per definition, allows for access to more non-redundant knowledge and capabilities compared to a unidimensional, it should follow that having a central position on a multiplex network increases the likelihood of accessing knowledge, and thus spur innovative performance. Therefore, as we emphasize that the availability of non-redundant knowledge is important to the innovation performance, we expect that inventors who are placed centrally in a multiplex network spanning technology, geography and co-inventors are more likely to search for and access new knowledge inputs that may contribute to new innovation. According to Tsai (2001: 997), "*a unit's network position is an important aspect of "social structure" that can enhance the unit's ability to create new value and to achieve economic* goals". Accordingly, being centrally located on a multiplex network would allow inventors and firms to exploit more heterogeneous ties simultaneously (i.e., technological, geographical and social), and thus have access to broader knowledge-base which can spur innovation. This argumentation leads us to the following hypothesis:

Hypothesis 1: Multiplex network *centrality is positively associated with an inventor's* performance

Distribution of ties on the multiplex network and the impact on innovation performance

Next, while degree network centrality concerns the "amount" of knowledge accessible from the multiplex network, the heterogeneity and diversity of knowledge inputs is also a key source of innovation (e.g., Leiponen and Helfat, 2011; Nelson and Winter, 1982; Rodan and Galunic, 2004; Rosenkopf and Nerkar, 2001). For example, it is well established that firms' combinative capability drives innovation and competitive advantage (Kogut and Zander, 1992). Inventors with rich and vast opportunities for learning and cooperation from different fields stimulate the creation of new knowledge and contribute to their ability to innovate (e.g., Kogut and Zander, 1992; Tsai and Ghoshal, 1998). Henderson and Cockburn (1994) suggest that the ability to integrate knowledge across disciplinary class boundaries—i.e., possessing architectural competencies—spur innovation and firm performance.

Therefore, inventors with a knowledge base that spans a variety of knowledge streams can potentially explore across disciplines and recognize resource recombination opportunities to generate innovations (Schumpeter, 1934; Penrose, 1959; Nelson and Winter, 1982). Research has even shown that industries such as biomedicine, nanotechnology, new media (Feldman and Lendel, 2010) and digital photography (Tripsas, 2009) were created as a result of usefully recombined knowledge from several industries to generate revolutionary products or services (Kodama, 1992). Thus, a broad knowledge base is critical for successful innovation (Bierly and Chakrabarti, 1996).

In terms of the multiplex network, we therefore propose that inventors with a high participation in all layers—rather than in just a few—are more likely to access heterogeneous knowledge inputs which can drive innovation. As Rodan and Galunic (2004: 541) put it, "while network structure matters, access to heterogeneous knowledge is of equal importance for overall managerial performance and of greater importance for innovation performance." To some extent, inventors with a diverse knowledge base can be characterized as generalist inventors with the particular ability to recombine knowledge in contexts where the procedures for solving problems are not clearly established. Understanding the general principles from different technological landscapes at the same time allows generalist researchers to make more informed choices about the combination of distant pieces of knowledge (Gruber et al., 2013). Taken together, we argue that inventors with a high participation in all layers are presented with more recombination opportunities to generate innovations. Thus, we hypothesize:

> Hypothesis 2: Higher simultaneous participation in the geographical, technological and co-invention layers *is positively associated with an inventor's performance.*

The costs of searching on complex networks

Thus far, we have provided arguments supporting a positive direct relationship between degree centrality and participation, respectively, and innovation performance. However, to understand the implications of inventors with both high degree centrality and participation on the multiplex networks, we highlight that searching through non-redundant ties comes at a price and bears certain risks. Specifically, as a centrally located inventor with a with participation in all layers on the multiplex network is faced with a comparatively higher number of ties and nodes through which innovation can be spurred, the requirements toward searching for and identifying the most appropriate sources of innovation are substantially higher. Inventors will find themselves using more time managing the many ties of the different layers. Thus, there are significant costs attached to the process of searching for knowledge along multiple dimensions of innovation networks. Hansen (1999: 84) captures the potential limitations of network search as follows:

> *"In a multiunit organization, a product development team situated in an operating unit* may want to obtain useful knowledge residing in other operating units, but the team may not know that such knowledge exists in the organization and where it resides. Team members are confronted with the task of looking for and identifying useful knowledge in an organization in which knowledge is dispersed among subunits. Assuming that project team members are boundedly rational, they cannot easily amass and process a large

number of opportunities for interunit knowledge sharing, however, and exhaustive intraorganizational searches will be very time-*consuming, if not impossible.”*

Given the portrayal of a multiplex network as one which as a system allowing for multiple types of relations among its basic units (Battiston et al., 2014), one can draw parallels to the costs of coordinating complex systems. Coordination costs can be understood as the costs of devising the necessary communication and decisions among organizational members to complete work jointly or individually across or within organizational boundaries (e.g., Gulati and Singh, 1998). The assertion is that complex systems require more coordination, which challenges actors' coordination capacity. Unless appropriately managed, complexity and the resulting coordination costs undermine precision in decision-making and eventually challenge performance (Levinthal, 1997; March and Simon, 1958).

Therefore, as the search for new knowledge is typically myopic and involves limited distance (Levinthal and March, 1993), we expect an incompatibility effects between the myriad of opportunities associated with both high centrality and participation coefficients. While centrality and participation alone spurs the possibilities for novelty creation, their combined effect at higher levels may impede the possibilities for absorption of this novelty. Therefore, to increase innovation performance, inventors will therefore have to make a choice between building connection in the same layer (increasing centrality) or distributing the fixed set of ties across all layers (increase participation). We hypothesize:

Hypothesis 3: There is a trade-off effect between network centrality and participation and *their effect on an inventor's performance.*

DATA AND METHODS

Research context: global wind power industry

To investigate the effects of multiplex networks, we draw on innovations in the global wind turbine industry. To elaborate, a wind turbine is a mechanical device that converts kinetic wind energy to electromagnetic energy (Garud and Karnøe, 2003). Wind power is one of the fastest growing sources of energy in the world. By the end of 2010, the global cumulative installed wind power capacity was 194,390 MW, an increase of about 22.5% over the figure for 2009 (GWEC, 2010). This is equivalent to about 2% of the global energy consumption (WWEA, 2009). Today, the industry is highly concentrated with the five largest manufacturers together having a market share of over 50%. These are Vestas (12.5%), GE Wind Energy (12.4%), Suzlon (9.8%), Sinovel (9.2%) and Enercon (8.5%) (MAKE Consulting, 2010).

Although the modern wind turbine industry can be regarded as an emerging or "sunrise" industry (Andersen and Drejer, 2008), the first windmills used for practical purposes – such as grinding corn and drawing water – were built in Persia during the 7th century. The first electricity generating wind turbine was designed and built in Scotland in the late 19th century, closely followed by the first automatically operated electricity producing wind turbine installed in Cleveland, Ohio. In the early 20th century, an increasing number of electricity producing wind turbines were built in Denmark. The restrictions on fossil fuel imports during the two world wars further promoted the development of wind turbines as an important source of electricity (Musgrove, 2010).

However, it was the oil crises of the 1970s and the subsequent rise in demand for renewable energy sources such as solar and wind energy that provided the necessary impetus for the establishment and growth of the modern wind turbine industry. This was further boosted by a favorable U.S. policy environment for wind energy in the early 1980s. The policy environment was especially favorable in California and created a large demand for low-cost, robust, and reliable wind turbines. This period has been called "the California wind boom" (Musgrove, 2010).

By the 1990s, the most favorable policy environment for the industry shifted to Europe, so that much of the industry growth occurred there. More recently, new growth in the market for wind turbines has grown beyond the locations in Europe to include larger markets in the U.S. as well as India and China. In 2010, a larger share of wind power capacity was, for the first time ever, installed in developing and emerging economies than in the more traditional OECD countries (GWEC, 2010).

The industry has traditionally been dominated by Western (and particularly European) firms such as Vestas, NEG (Denmark), and Enercon (Germany). However, in the 1990s, it witnessed the entrance of a number of emerging economy manufacturers that offered turbines for considerably lower prices than the more established industry players (Musgrove, 2010). In particular, Chinese and Indian companies such as Goldwind (China), Sinovel (China) and Suzlon have displayed highly impressive growth rates, both domestically and internationally, and have begun to challenge the more established players in the industry.

The most recent wave of entrants has been the large multinational conglomerate firms whose main businesses lie outside the manufacture of wind turbines (Vietor and Seminerio, 2008). For example, firms like General Electric and Siemens entered the wind turbine industry in the early 2000 and Hyundai Heavy Industries followed in 2008. The combination of these trends has converted the wind turbine industry from being a collection of mainly national industries to become a truly global one (Musgrove, 2010).

Data

To create the multiplex network and test our hypotheses, we use patents from the United States Patents and Trademarks Office (USPTO) database and extracting data on the three dimensions of innovations namely the inventors, their geographic location and the technology classifications or classes from the patent records. The data is used to create multi-modal networks (or 3-mode networks, to be specific) of technology class–inventor–location. Each patent contains information on inventors' names, their geographic location as well as the technology class of the claimed innovation. Thus, the inventors form the link between the location and technology.

Specifically, from the patents, we extracted inventors, their locations, and the technological classifications (or technology classes) assigned to them. We then performed several rounds of automated and manual checks to identify unique locations, inventors, and technology classes. These checks handled spelling errors and incorrectly formatted diacritic symbols. In the case of unique inventor identification, the checks handled the "who's who" problem in which the same name may be spelled differently across inventor's patents and the "John Smith" problem in which the exact same name may correspond to two different inventors (Trajtenberg, Shiff, and Melamed, 2009). The procedure resulted in 2204 unique inventors, 566 locations, and 177 technology classes from 1961 until 2011.

Measuring the multiplex network

We used the data on inventors, locations, and technology classes to create 3-mode networks consisting of nodes representing the three types of data. The nodes thus spanned the three dimensions of innovation. An inventor node connects to location node on one side and a technology class node on the other side. Thus the inventor nodes fall in between technology and location nodes. This setup is logical since the technological knowledge resides with the inventor who is located at a place. In other words, inventor dimension truly connects the technological with the geographic dimension.

We create 3-mode networks as shown in Figure 1 for each year from 1974 to 2011. We then created 1-mode network of inventors with multiplex ties. Thus, a tie exists between two inventors if they share a location node or a technology node or both. With this procedure, we effectively reduce the dimensionality of data by projecting the three-dimensional system on the single dimension of inventors. With regular projection, this will result in considerable data loss. However, with multiplex projection, the information of location and technology dimension is retained through the type of tie between the inventors. Therefore, one useful way of measuring a multiplex network is to consider it as a multilayered network with each layer containing one type of ties (Battiston et al., 2014). In our data then, for each year, we have a five-layered network with each layer representing the five types of ties T1 through T5. We use a three-year moving window to create inventor networks as is common in the network literature (Nerkar and Paruchuri, 2005). Thus, a tie between two inventors is only valid for three years unless renewed. For example, a network in 1990 represents inventors ties formed in 1988, 1989, and 1990.

Operationalization of variables

Inventor performance: We use the number of patents generated by an inventor to measure the inventor's innovation performance (see e.g., Nerkar and Paruchuri, 2005; Vasudeva et al., 2013).[1]

[1] In the later rounds of analysis, we plan to extend this variable to citation-weighted patent count to capture the inventor's impactful innovation performance.

Centrality: We measure the centrality of inventor i in each layer α as the valued degree centrality t_i^{α}:

$$t_i^{\alpha} = \sum_{all\ ties\ in\ layer\ \alpha} tie\ weight\ of\ inventor\ i$$

Since T1 and T2 are unidimensional ties, their centrality score captures the effect of the respective dimensions on the innovation performance. Centralities of ties T3 through T5 capture the interactive effects of the multiple dimensions on the innovation performance. We also measure the overall centrality (o_i) of an inventor as the sum of centralities in all five layers.

Participation: As a first step, we measure the multiplexity of an inventor, i.e. his/her focus on maintaining the different types of ties, with participation coefficient (P_i), following Battiston et al. (2014). For an inventor i,

$$P_i = \frac{5}{5-1}\left[1 - \sum_{\alpha=1}^{5}\left(\frac{{t_i}^{\alpha}}{o_i}\right)^2\right]$$

The participation coefficient takes values [0, 1] with 0 indicating inventors with ties in only one layer whereas 1 indicating that inventor's ties are equally distributed in all five layers, making them truly multiplex.

Control variables: We control for the innovative age of an inventor by capturing the years since his/her first filing of a wind patent. As noted in the literature, wind power industry experiences high proportion of patenting in the core classes of electricity and aerodynamics (Awate, Larsen, and Mudambi, 2015). Thus, following Vasudeva, Zaheer, and Hernandez (2013), we control for the technological scope of inventor's activities to see what percentage of inventor's patents fall in the industry's core classes. We also control for year effects by adding year dummies.

Estimation procedure

We present univariate descriptive statistics, including correlations in Table 2. As can be seen, the dependent variable is an over dispersed count variable. This led us to opt for a negative binomial regression methodology for our inventor-year panel data. We use fixed effects to account for the time-invariant unobserved heterogeneity. We also performed Hausman test, which justified the use of fixed-effects over random effects.

Table 2 about here

RESULTS[2]

The results of the negative binomial fixed effects regression on inventor-year panel are shown in table 3. The 1st column adds only the control variables. The 2nd column adds the participation coefficient, overall degree centrality and their interaction. The 3rd column replaces overall centrality with the centralities in each layer and finally the 4th column reruns the 3rd column model with standardized variables. As seen from columns 2 and 3, while the overall centrality has a positive effect, individual layer centralities show a more nuanced picture. Centralities in T2 and T3 have positive and significant effects whereas T5 has a negative and significant effect. Among these, only T2 is a unidimensional layer representing technological ties. We thus find partial support for H1. The interactive effect of technology and geography, captured by T3 has a smaller effect than T2 as seen from column 4. Further, we see that the interactive effect reduces further and becomes negative in T5 where technology, geography, and co-invention ties interact. The smaller effect of T3 and the negative effect of T5 provide support to H3 and not H2. Finally,

[2] We are currently working on a more elaborate analysis of our data. While the analysis will give the same overall message, we explore in substantially more detail curvilinear effects; the optimal balance between centrality and participation; and which layers drive and deteriorate performance.

we see that the effect produced by the participation coefficient capturing inventors' multiplexities is negative throughout; further adding support to H3.

Table 3 about here

DISCUSSION AND CONCLUSION

The purpose of this study has been to investigate the inventor performance effects of treating innovation as a multidimensional construct simultaneously spanning people, technologies, and geographies. In particular, we investigate the innovation performance effects of networks characterized by (i) co-located inventors; (ii) technology cohort; (iii) co-located technology cohort; (iv) distant co-inventors; and (v) co-located co-inventors. In doing so, we portray innovation networks as multiplex, which allows us to study multiple types of relations among the basic units of the network. We use the context of the global wind power industry to explore the implications of the multiplex innovation network, whose pre-commercial emerging phase lasted well into the 1980s and had only established dominant wind turbine design and grid capability by about 1990 (Andersen and Drejer, 2008; Awate et al., 2013; 2015; Garud and Karnøe, 2003; Musgrove, 2010).

Supported by theories on the costs of searching for sources of knowledge and capabilities in complex systems (e.g., Cyert and March 1963, Gavetti 2005, Levinthal 1997), we find evidence suggesting that being centrally positioned on a multiplex network actually deteriorates innovation performance. Specifically, new technologies and changing environments force boundedly rational inventors who are centrally located on a multiplex network to engage in processes of search to identify the relevant sources of knowledge and capabilities to spur innovation. As multiplex network are characterized by a higher number of nodes and ties which may potentially lead to new innovation, the costs of searching on a multiplex network should equally be higher than on a one-dimensional network, and hence undermine innovation performance.

Obviously, we are not suggesting that being centrally located on a multiplex network is unanimously negative for innovation performance. There are strong theoretical reasons why access a broad range of heterogeneous of knowledge inputs should function as a key source of innovation (Leiponen and Helfat, 2011; Nelson and Winter, 1982; Rodan and Galunic, 2004; Rosenkopf and Nerkar, 2001). Being centrally located on a multiplex network should allow for access to more non-redundant knowledge and capabilities compared to only being located a unidimensional network. Thus, it follows that having a central position on a multiplex network increases the likelihood of access heterogeneous knowledge, and thus spur innovative performance. Yet, we are able—as a result of our research design—to disentangle the costs of such network positions, at least in initial periods. This is an important observation in terms of understanding the evolution of the relationship between different dimensions of networks and innovation performance (e.g., Tsai and Ghoshal, 1998; Tsai, 2001; Zaheer and Bell, 2005), as it suggests that the benefits of being centrally positioned on a multiplex network are only realized to the extent that inventors can hold the costs of searching at bay. Thus, inventors face a potential trade-off between being granted access to vast opportunities of learning and knowledge and the costs of searching for the relevant sources of innovation.

Accordingly, we argue that we make number of important contributions with our study. Besides unraveling the consequences of searching on complex networks, we introduce multiplex networks analysis to management and innovation research. Indeed, one of the most important challenges in understanding the relevant networks of firm and innovation performance is the task of quantify the information encoded in complex network structures. We present an innovative conceptualization of how multiple networks layers may be used to study aspects such as innovation performance. Specifically, we portray innovation as a multidimensional construct spanning people, technologies, and geographies, and study how these dimensions interact and impact firms' inventor networks and the ultimate innovation performance. Although the notion of multiplex networks is relatively new and underdeveloped in management and innovation studies, we argue that this way of perceiving and measuring innovation networks should be closer to the reality of how inventors develop new technologies. Indeed, there has been an increasing amount of effort being devoted to creating a consistent mathematical framework to study, understand and reproduce the structure of multiplex networks (Battiston et al., 2014), though not yet in to the same extent in management circles.

As argued, our results suggest that accounting for these three dimensions reveal a murkier picture of firms' innovation performance than earlier found. In particular, we suggest that costs of searching for relevant knowledge on complex networks may undermine the benefits of potentially acquiring heterogeneous knowledge inputs. Thus, by examining the effects of social capital of various types of ties on the focal firm's innovation performance, our study helps to identify the differential value-added by investing in those ties.

Moreover, the emerging industry setting of global wind power brings in the temporal aspect to the study by showing which ties lead to superior innovation performance in the early years of an industry. In particular, our study context is a new, emerging industry. Industry life cycle theorists depict the evolution of new industries as a staged process (Klepper, 1997). While models differ in terms of the number of stages and they are separated by fluid boundaries, there is a common underlying theme, which notes that the level of uncertainty reduces from one stage to the next (Williamson, 1975; Abernathy and Utterback, 1978; Clark, 1985; Klepper, 1997). We identify an emerging industry as the one spanning the lifecycle stages that appear before the established or mature stage. Thus, there is considerable uncertainty in terms of strategy, operations, external environment, demand and growth (Abernathy, 1978; Covin and Slevin, 1990). These are industries that witness high rates of new firm entry and highly unstable market shares (Abernathy and Utterback, 1978) and where product innovations tend to dominate process innovations (Klepper, 1996). Both technological regime and demand characteristics experience frequent changes. Thus, what appears to be a converging dominant design and steady output growth may be disrupted by discontinuities (Anderson and Tushman, 1990; Klepper, 1997). Yet, in spite of the operational uncertainties, emerging industries do offer certain advantages, such as smaller competitors, lower entry barriers, and available acquisition targets. For de novo entry, they may offer shorter ramp to technology frontier (Awate, Larsen and Mudambi, 2012; 2015). Thus, our study contributes by highlighting how explicating how inventor networks spanning technology, geography and co-inventors, drives subsequent innovation performance in such emerging industry contexts.

In conclusion, we provide a first step in modelling multiplex network to better understand the relationship between technological, geographical and co-inventor networks and innovation performance. While we have focused on the inventor-level in this study, the methodology underlying the multiplex networks is definitely transferable to other levels of analyses such as firm and inter-firm networks. Undeniably, this will pave way for a better and more accurate portrayal of the management of innovation.

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Figure 1: Left: 3-mode network of location-inventor-technology, Right: Multiplex 1-mode network of inventors

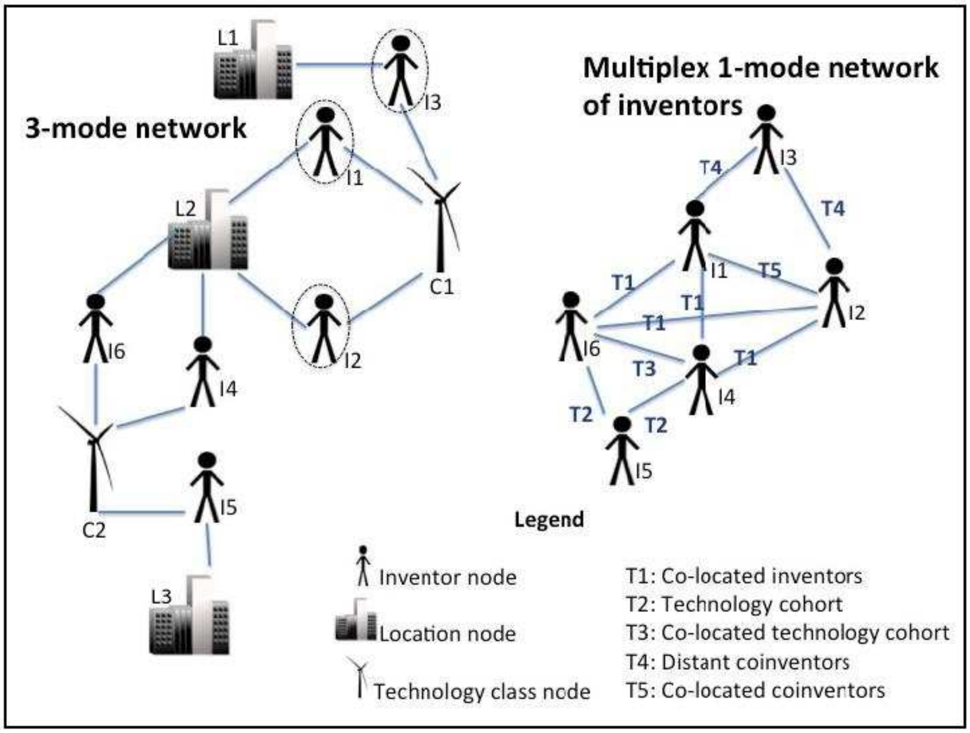

Figure 2: The relationship between degree centrality and participation

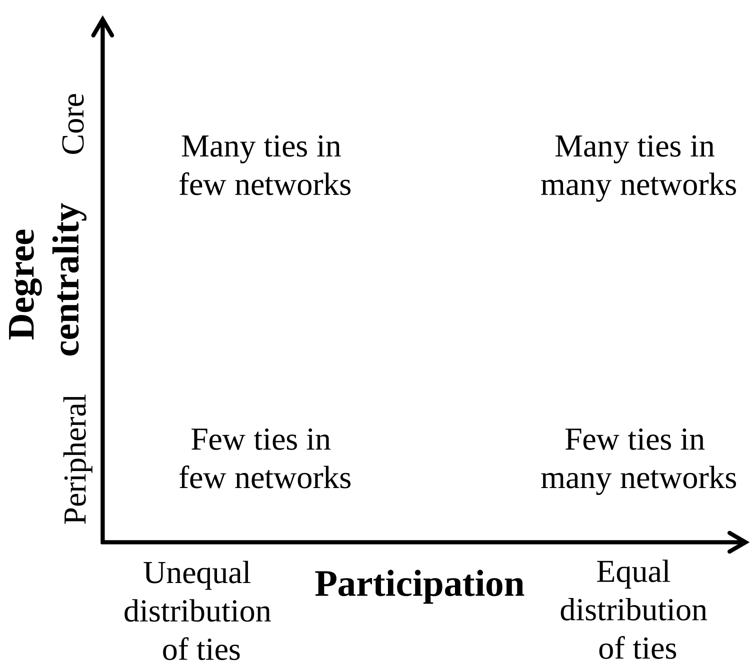

Table 1: Types of ties

Type of inventor tie	Do the two inventors share a technology class?	Do the two inventors share a location?	Do the two inventors appear on the same patent?
Colocated inventors (T1)	No	Yes	No
Technology cohort (T2)	Yes	No	No
Colocated technology cohort (T3)	Yes	Yes	No
Distant coinventors (T4)	Yes	No	Yes
Colocated coinventors (T5)	Yes	Yes	Yes

Table 2: Univariate statistics including correlations

VARIABLE	Mean*	Min	Max	1	2	3	4	5	6	7	8	9
1. Number of patents	0.155 (0.478)	0	11									
2. Participation coefficient	0.084 (0.183)	0	1	-0.01								
3. Overall centrality	23.123 (58.307)	0	655	0.11	0.24							
4. T1 centrality	0.745 (4.027)	0	77	0.11	0.38	0.51						
5. T2 centrality	21.185 (53.556)	0	644	0.10	0.20	0.99	0.42					
6. T3 centrality	0.493 (2.666)	0	61	0.13	0.31	0.62	0.69	0.55				
7. T4 centrality	0.368 (1.237)	0	27	0.09	0.42	0.58	0.41	0.55	0.38			
8. T5 centrality	0.332 (1.224)	0	28	0.11	0.39	0.53	0.48	0.48	0.59	0.31		
9. Age	10.050 (8.684)	1	39	-0.29	-0.34	-0.27	-0.12	-0.27	-0.12	-0.20	-0.19	
10. Share of core class patents	0.091 (0.285)	0	1	0.73	-0.02	0.06	0.07	0.06	0.09	0.06	0.06	-0.29

* Standard deviations in parentheses

Table 3: Fixed effects negative binomial regression results

Dependent variable Number of patents	(1) Controls	(2) Overall degree	(3) Individual degree	(4) Standardized
Participation coefficient		-2.2208***	-2.1306***	-0.2262***
Pi		(0.1474)	(0.1528)	(0.0162)
Overall centrality Oi		0.0034***		
		(0.0005)		
Pi X Oi		0.0046**		
		(0.0016)		
T1 centrality			0.0041	0.0091
			(0.0061)	(0.0133)
T2 centrality			0.0039***	0.1175***
			(0.0005)	(0.0167)
T3 centrality			0.0475***	0.0691***
			(0.0105)	(0.0153)
T4 centrality			-0.0106	-0.0073
			(0.0163)	(0.0112)
T5 centrality			-0.0382**	-0.0259**
			(0.0154)	(0.0104)
Age	-0.2307***	-0.2412***	-0.2419***	-1.5494***
	(0.0208)	(0.0216)	(0.0215)	(0.138)
Share of core class	3.2969***	3.2798***	3.2971***	0.512***
patents	(0.822)	(0.831)	(0.0834)	(0.0129)
Constant	23.0008***	0.1578	0.1365	-0.4782
	(205.6213)	(0.7618)	(0.7629)	(0.7904)
Observations	23,573	23,420	23,420	23,420
Number of inventors	2176	2172	2172	2172
Chi-squared	3089.71***	3382.73***	3379.14***	3379.14***
Log-Likelihood	-2318.78	-2197.81	-2189.66	-2189.66

Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$