IN SEARCH OF SOLUTIONS:

The Influence of Knowledge Diversity and Leader Choice on Search Quality

PRELIMINARY WORKING PAPER.

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ABSTRACT

The importance of collaborative efforts in creating competitive advantage through novelty and successful innovation has been well documented in a range of empirical settings by the increasing attention from strategic management scholars. The search for and combination of diverse knowledge from a range of different sources is found to be central to this innovation and novelty creation. Meanwhile, limited absorptive capacity suggests limits as to how much diversity and ensuing complexity may be encapsulated and managed in the effort to search for solutions to innovation challenges. Despite the importance of this inherent challenge, we know little about how to balancing and managing knowledge diversity in external search. This paper explores this field as well as the ability of different project leaders to combine diverse knowledge into a coherent, high-quality search effort. Findings show that projects in immature technologies benefit more from high knowledge diversity than those in mature technologies, albeit both face decreasing returns. Application oriented research organizations are found to benefit the integration of diverse knowledge in mature technologies, while the higher diversity and complexity in immature technologies are best managed by basic research focused universities.

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INTRODUCTION

This search for and combination of different knowledge, whether from internal or external sources, universities, suppliers or others, has been shown to be central to finding solutions to challenges related to innovation(Katila and Ahuja, 2002, Rosenkopf and Nerkar, 2001). Searching externally for input to such solutions in local knowledge domains where sources may to some degree already be familiar with the problem is shown to be efficient in mature technologies, while the challenges faced in immature technologies require spanning of both organizational and knowledge boundaries(Rosenkopf and Nerkar, 2001, Rosenkopf and Almeida, 2003). This implies that as technological challenges are more complex and unlikely to have been faced before by others in the emerging and immature technologies, the value of novel and different ways of viewing the problem and proposing solutions are high. Meanwhile, in mature technologies the same or similar challenges are more likely to previously have been faced by others, and thus the solution is more likely to be found in proximate knowledge areas.

The importance of searching for and accessing external knowledge to compliment the existing internal is at the core of the stream of literature on open innovation, which has emerged following Chesbrough's coining of the term (Chesbrough, 2003). The central argument to the importance of external search and openness is that the assets and competences necessary for the development and commercialization of innovations are dispersed across different firms and organizations, rather than being centralized in one (Chesbrough, Vanhaverbeke and West, 2006). Research has increasingly sought to understand how the search for knowledge from different external partners helps firms become and remain innovative. Findings show that the performance of firms is influenced by strategies for searching the external environment for knowledge, which can be utilized in innovation efforts. Increasing the breadth and depth of such search, the amount and intensity of external sources searched, is important, albeit with upper boundaries due to limited absorptive capacity(Laursen and Salter, 2006, Cohen and Levinthal, 1990). Furthermore, the choice of which sources to direct the search for knowledge towards will impact the likelihood of introducing different types of innovations. Science-based search has been show to increase the likelihood of introducing new-to-market products, while search directed towards competitors is likely to help in the imitation of existing products(Köhler, Sofka and Grimpe, 2012).

An underexplored but important aspect of the external search for solutions is the diversity of the knowledge domains searched. Diversity is important as heterogeneity is shown to be an important condition for novelty creation and innovation(Nieto and Santamaría, 2007). However, extant research has focused on a count of the number of sources searched(Laursen and Salter, 2006) and the fact that the knowledge searched is different from the firm's existing knowledge(Rosenkopf and Nerkar, 2001), which provides little insight into how diverse the knowledge involved in the search is. As such, searching five sources from the same non-local industry may entail only limited diversity of knowledge, while searching five sources from five different industries would entail a greater degree of diversity. Increasing the understanding of the influence of diversity is relevant given that firms' combination of knowledge that is different from their own through external search into a solution to a specific innovation challenge, is central to the very value of engaging in external search(Rosenkopf and Nerkar, 2001). This research gap concerning the diversity of the knowledge domains searched in efforts to develop solutions is relevant to cover given the findings that spanning knowledge boundaries is valuable to innovation(Katila and Ahuja, 2002, Rosenkopf and Almeida, 2003, Rosenkopf and Nerkar, 2001), while over-searching and too much complexity can be counter-productive(Cohen and Levinthal, 1990, Laursen and Salter, 2006). In extension of the understanding of the influence of knowledge diversity, the choice of which leader should combine the diverse knowledge in a search effort with a high likelihood of solving the challenge faced is relevant to both academics and practitioners in the field of innovation management. The aim of this paper is to address this dual issue through answering the research question of how knowledge diversity and search leadership influences the quality of search efforts?

As projects are the point of execution of firm-level strategies(Haas, 2010) and the same firm is likely to adapt overall strategies to the specific context of a particular search effort, this paper answers the above research question through an analysis of search efforts in individual projects. These search efforts are targeted at solving specific innovation challenges in technological areas of different maturity, which extant research finds to be relevant to the value of different search strategies(Laursen and Salter, 2006, Rosenkopf and Nerkar, 2001, Rosenkopf and Almeida, 2003). This empirical setting allows a comparison of both different levels of diversity and different leader choices since multiple search efforts are made in competition to solving each challenge. Following extant research the analysis makes use of expert evaluations to determine the quality of a proposal (Franke, Poetz and Schreier, 2013, Poetz and Schreier, 2012, Salge *et al.*, 2013), which is this context represents the likelihood that the search will solve the particular problem depending on knowledge diversity and leadership. The knowledge of each participant involved in a search effort is reflected by NACE-codes, as coming from different industries would indicate possessing different knowledge. The types of leader can be private research organizations, universities or private commercial firms. The structure of the paper is as follows. Section two reviews extant literature introduces the concept knowledge diversity and builds hypotheses. Section three presents the empirical setting, data, variables and analytical approach used to test the hypotheses. Section four then presents the results, before section five rounds of with discussion and limitations.

THEORY AND HYPOTHESES DEVELOPMENT

Knowledge Diversity

Previous research has shown that firms that engage in distant rather than local search will be more innovative as distant search involves new combinations of knowledge and exploration of new knowledge domains (Katila and Ahuja, 2002, Rosenkopf and Nerkar, 2001, Rosenkopf and Almeida, 2003). While these findings focus on the distance between the focal firm and the source of innovation, they also show that combining different knowledge domains positively influences innovation, particularly in immature technologies. Despite showing the influence of the number of(Laursen and Salter, 2006) and different types of sources in external search efforts (Köhler *et al.*, 2012), extant research not distinguished between hetero- or homogeneity in the composition of sources and how this greater or lesser diversity is linked to search efforts in mature or immature technologies and the related problem solving potential. As such, extant research has not differentiated between whether five different firms contribute the same, two, three, four or even five different types of knowledge to a search effort. In extant research one supplier is assumed to contribute the same knowledge as any other supplier, with no nuance of the potential heterogeneous differences in knowledge domains between these two independent actors. This paper argues that searching two external sources may result in significantly different knowledge despite the fact that they are both the same type of source, e.g. private companies. The paper thus promotes the idea that distinguishing between whether the knowledge that is provided by such two sources is homogeneous or heterogeneous is important to understanding both the nature and diversity of the knowledge which a firm searches, and subsequently how this diversity may influence the external search's likelihood of solving the problem at hand.

To capture this potential diversity of knowledge, the author introduces the term 'knowledge diversity, which captures the homogeneity or heterogeneity of knowledge searched in the effort to solve an innovation challenge. As such, knowledge diversity captures the degree to which a search effort involves different knowledge domains. High knowledge diversity entails a search effort, which involves several different knowledge domains, while low knowledge diversity entails a more homogenous composition of knowledge. Search efforts may have high breadth in terms of the number of participants, but have low knowledge diversity in terms of different knowledge domains. This would be the case when several firms from the same industry are involved in the search for a solution. The knowledge offered by these firms would be expected to be more homogeneous than if all had been from different industries. As diversity of source types as been found to increase innovation and novelty (Nieto and Santamaría, 2007) the author expects that higher knowledge diversity in search efforts will generally result in higher quality and thus higher likelihood of problem solution. The caveat of such increasing knowledge diversity in innovation search efforts is the issue of limited absorptive capacity (Cohen and Levinthal, 1990). As previously found in relation to external search, firms face decreasing returns from the increased use of external knowledge (Laursen and Salter, 2006). The upper boundaries of what can be understood and brought to use entails that firms cannot simply search unlimited amounts of sources and knowledge, as this will result in too much complexity and information, which cannot all be comprehended and brought to use (Cohen and Levinthal, 1990). The same limitations are expected by the author to apply for the knowledge diversity in search efforts. This entails that the amount of diversity that may be combined meaningfully and into a plausible, operational solution to an innovation challenge is limited and therefore the benefits of increased knowledge diversity should face decreasing returns. Based on the above, the first hypothesis of this paper states that:

H1: *Increased knowledge diversity has a positive influence on search quality, but faces decreasing returns*

Knowledge Diversity and Technological Maturity

Despite the benefits of searching widely and accessing distant knowledge from a variety of sources (Jeppesen and Lakhani, 2010), there are limitations. As show by Laursen and Salter, increasing breadth in terms of the number of external sources used by firms will eventually result in decreasing returns to their innovation performance (Laursen and Salter, 2006). The implications of this is that firms need to consider the upper boundaries of their absorptive capacity (Cohen and Levinthal, 1990), which is a significant restriction on the breadth of openness which will improve, rather than reduce, the firm's innovation output and performance. As argued by Laursen and Salter, innovation in mature technologies is likely to benefit most from high levels of breadth. This is due to an established dominant design (Suárez and Utterback, 1995, Utterback and Abernathy, 1975) and subsequent wide dispersion of knowledge related to the technology. As different sources can offer expertise on particular details related to incremental improvements on a mature technology, there are benefits from accessing a high number of these sources (Laursen and Salter, 2006). Conversely, in the less mature phase of technological life cycles the uncertainties regarding the technology is higher, previous knowledge of both the focal firm and their collaborations is likely to be obsolete and innovation are likely to be more radical (Afuah and Utterback, 1997, Anderson and Tushman, 1990, Utterback and Abernathy, 1975). Understanding and implementing uncertain and new, unknown knowledge will strain firms' absorptive capacities (Cohen and Levinthal, 1990), and exposure to too many radical ideas or too much new knowledge related to the immature technology is hence likely to negatively influence innovations in the immature phase (Koput, 1997). Innovation in immature technologies is hence argued to benefit from lower search breadth than the mature technologies, since accessing fewer sources in depth will better facilitate the intake and utilization of complex and potentially distant knowledge needed for radical innovation at this fluent stage of technological maturity (Laursen and Salter, 2006).

Somewhat in opposition to the above findings on the benefit of limited use of external sources in immature technologies is the finding that distant search is particularly beneficial for innovation in immature technologies (Katila and Ahuja, 2002, Rosenkopf and Nerkar, 2001, Rosenkopf and Almeida, 2003). This is due to the availability of knowledge not previously accessed by the firm as immature technologies require more novel solutions and novelty is found to increase through the use of more heterogeneous sources (Nieto and Santamaría, 2007). As such, one finding is that immature technologies benefit from fewer sources(Laursen and Salter, 2006), while another is that these technologies benefit from greater heterogeneity in the type of sources(Nieto and Santamaría, 2007), which to some extent implies more sources. Indeed, this seemingly contradictory set of findings could potentially be caused by the under-exploration of knowledge diversity. From this, the expectation of the author is that a high diversity of knowledge, not high a high number of sources, is beneficial to immature technologies, while a higher number of sources but lower diversity of knowledge is beneficial in mature technologies.

Following the above reasoning, the author expects that increasing knowledge diversity will be beneficial to innovation in immature technologies as the search effort accesses diverse and heterogeneous knowledge, which can contribute to the novelty necessary to developing solutions to previously unknown problems. As the key is diversity of knowledge, the author does not expect a positive influence from simply increasing search breadth, the number of sources involved in the search effort. Conversely, increasing search breadth would be expected to improve search quality in mature technologies(Laursen and Salter, 2006)However, in terms of knowledge diversity, the positive influence of increasing this is expected to be less than in the immature technologies. As technologies reach a more mature stage of development they require specialist, detailed, in-depth knowledge about the technology in question to develop incremental innovations(Laursen and Salter, 2006)knowledge may be dispersed among multiple actors, it is likely to be found within few specific knowledge domains. This reduces the benefit of accessing multiple different knowledge domains as it may disturb the necessary focus on the particular expert knowledge needed. Following this, the second hypothesis of this paper concerns the difference in the influence from knowledge diversity on search quality between mature and immature technologies.

H2: *The positive influence of increasing knowledge diversity on innovation potential is higher for immature than mature technologies*

The Influence of Leadership

Extant literature's focus on the firm level of external search has lead to an under-exploration of the importance of leadership. By seeing the process of search as a firm seeking for a solution among a range of actors before choosing one and realizing this, there has been an oversimplification of the way in which this may often take place. The efforts related to searching for and developing solutions would be expected to often involve more than simply two actors in a joint-venture or alliance type arrangement, and may instead involve multiple actors collaborating with each other in complex structures (Chesbrough, 2003). The complexity of involving multiple knowledge domains and sources requires coordination and leadership to both search for and choose the relevant and valuable knowledge to solve the particular innovation challenge. The under-exploration of the influence of choosing one or the other type of actor to lead, coordinate and prioritize in the search for relevant and valuable knowledge is relevant to overcome in the research on innovation search. Indeed, recent research has found the choice of leaders to impact the quality of innovation projects with respect to the experience of such leaders (Salge *et al.*, 2013)In the context of the potentially increasing complexity from higher knowledge diversity in search efforts, the author similarly expects the choice of leader to play a significant role to the resulting quality of the search. In particular, the author focuses on whether the search effort is lead by a research organization or a university.

As each of the above actors has different expertise and competences, it would be expected that the choice of either as leader of the search effort would be reflected in the resulting quality depending on the stage of the technology in question. Previous findings have shown higher benefits in immature than mature technologies of including university sources in the search efforts related to innovation (Köhler *et al.*, 2012)Indeed these findings confirm the argument that the high novelty level of the knowledge available from e.g. universities (Cohen, Nelson and Walsh, 2002) is indeed well suited for innovations in immature technologies. On the other hand, as the science based knowledge sources are somewhat distant from commercial targets, rather focusing on basic research with high novelty and free sharing of the knowledge generated through publications (Link and Scott, 2005), these are argued and found to less beneficial to incrementally focused innovation in mature stages. Following the notion that universities are able to provide and comprehend complex knowledge, the author expects that they will also possess the ability to comprehend and combine both complex and diverse knowledge. The focus on knowledge generation rather than direct commercial impact is likely to lead to more objective estimations of which knowledge to include and prioritize for the purpose of generating novelty, which is key in the immature technologies. As such, the third hypothesis of this paper, and the first related to the role of leaders, is as follows.

H3: *University leaders increase the benefits of knowledge diversity in immature technologies*

The second type of leader explore in this paper is the research organizations. These organizations are often more applied in their approach when compared to university actors and seek to generate more immediate commercial value for clients or in projects. Examples in the dataset used for the paper includes the German Frauenhofer Institute, which is Europe's largest application-oriented research organization or the Danish Technological Institute[1]. In comparison to university leaders, the research organizations would be expected to focus more on the direct application of the search efforts in terms of a commercial outcome. As technologies develop from the immature stage, the road to commercial outcomes becomes shorter and the focus tends to shift towards more applicable and directly commercializable targets (Anderson and Tushman, 1990, Afuah and Utterback, 1997). As the goal is to combine knowledge to make incremental improvements to existing technology or products with direct translation into commercial benefits and products, the value of universities would be expected to decrease. On the other hand the value of leadership from research organizations would be expected to increase in value. Their application oriented focus should help focus on the knowledge that is most relevant to the development of an immediately commercializable outcome, which leads to the fourth hypotheses of the paper, and second in connection to leadership.

H4: *Research organization leaders increase the benefits of knowledge diversity in mature technologies*

METHODOLOGY

Research Setting and Sample

The energy sector is chosen to test the influence of knowledge diversity and different leaders in search efforts pertaining to innovation challenges in mature and immature technologies respectively. This sector is characterized by a number of both mature and immature technologies, which produce an identical homogenous

[1] See www.frauenhofer.de or www.dti.dk for details

commoditized good. As these have different levels of market penetration and cost of production of this good, cross-technology comparisons according to maturity are possible. The data used contains information on external search efforts to solve particular innovation challenges put forth by the European Commission under the 7th Framework Program. These search efforts are described in the data in the form of applications for funding from the EC in which information is given on which sources are part of the search effort proposed in solution of the specific problem. Essential to the purpose of this paper, the data provides information on the NACE-code of each source and thus the knowledge domain each represents and of the type of organization each source is, enabling the testing of hypotheses on knowledge diversity and leader type respectively. Data is available for 608 search efforts in the shape of proposals submitted between 2007 and 2012. These cover 32 different calls, each of which represents a particular innovation challenge to be solved through external search. The data contains information on the 6,096 sources involved in the different search efforts, which allows exploration of the configuration of knowledge diversity and leadership on each effort, and how this is reflected in the quality of the search represented by the likelihood of solving the specific problem defined in the call.

Dependent Variable: Search Quality

The dependent variable in the analysis is the score given to each specific project by three to five anonymous, independent third party experts hired by the EU. Each project represents the search for a solution to the particular problem described in the call, which the project is directed at. As such, a high score reflects a high likelihood that the search effort will solve the particular innovation challenge proposed in the call toward which the search effort is directed. As external search efforts are essentially about solving an identified problem, the paper uses the score to indicate search quality. Initially the experts create individual evaluation reports, before meeting to finalize the evaluation and provide the score. The evaluation consensus is created at a physical meeting in Brussels with participation of all the experts, a European Commission staff member acting as chair to ensure that all voices are heard and all aspects covered, and finally another expert acting as rapporteur to summarize the agreements on, among other, the project score. This process ensures that bias and subjectivity of individual evaluators is minimized, thereby creating a high level of reliability and validity for this measure. All experts sign both a confidentiality agreement and a declaration of absence of conflict of interest, ensuring an unbiased peer review. Furthermore, the selection of the expert team is done to ensure a balance in backgrounds and the experts are required to evaluate the search efforts based on the same criteria each time, to ensure cross-comparison.

The use of a dependent variable consisting of experts' ex-ante evaluation of quality or potential of a proposed solution has been applied in previous related work. In their recent study of health care innovation projects, Salge et. al. apply a similar approach by using a dependent variable consisting of evaluations of innovation projects (Salge *et al.*, 2013). These evaluations were performed by chief executives and reflected usefulness and likely success and implementation of the proposals. In their work of analyzing the value of different problem solves' contributions to new products, Franke et. al. use the evaluations of independent market experts to rate the novelty and usefulness of proposals (Franke *et al.*, 2013). Similarly, Poetz and Schreier use executives' assessments of proposed solutions for the purpose of analyzing the value of user generated ideas compared to those provided by professionals (Poetz and Schreier, 2012). Indeed, the use of evaluations or ratings performed by supervisors, experts or other external evaluators ex-ante to determine the quality of a solution, team or project is found by Anderson et. al. to be predominant in extant individual, team and project levels research (Anderson, Potocnik and Zhou, 2014).

In the context of external innovation search and the effects of different configurations, the dependent variable has the advantage of capturing the quality of a specific search effort. Although not a standard performance measure it is well recognized in previous studies, and has several advantages: Firstly, it is isolated from exogenous factors as it is only related to the configurations of a given search effort at a given point in time. The measure is not influenced by factors such as a financial crisis, unobserved changes in markets and demands, policy changes, entry/exit of competitors etc. over time and unobserved influences on the firm. Such factors would be difficult to measure and control if using traditional firm level measures. Secondly, the variable is directly linked to specific search efforts directed at identical innovation challenges. This enables a comparative analysis of the influence of knowledge diversity and choice of leader. This would also be difficult to achieve with firm level measures, as numerous other factors apart from the specific search effort would be expected to influence the firm level performance. Thirdly, the data includes both approved and rejected proposals. Studies of firm or project performance based on allocation of funding would disregard the large and important sample of firms or projects, which do not receive funding. Inclusion of approved projects only would also have the consequence of not understanding whether the approved projects do in fact differ from those rejected, and if so, how. While recognizing the limitations of the ex-ante measure to capture the quality of the specific search efforts, the author argues that it does provides an opportunity to carry out a analysis, which provides knowledge about the influence of certain specific configurations. The preference would be to use an ex-post measure, however this is not available at an individual search effort-level. Regardless, the use of ex-ante measures is both well established in other studies and provides the opportunity for novel insights in the study not available from firm-level measures.

Explanatory Variables: Knowledge Diversity and Leadership

Knowledge Diversity

To explore the influence of the concept knowledge diversity, the analysis includes the variable *knowledge_diversity*. This variable captures the NACE code of each participant and provides a count of the number of different codes on each project. Higher numbers of knowledge diversity thus reflects higher heterogeneity in the knowledge domains searched. This allows exploration of hypotheses that search conducted in immature technologies benefit strongly from increasing knowledge diversity, while projects in mature technologies will benefit less. Similarly to extant findings on the decreasing returns to the number of sources searched(Laursen and Salter, 2006), the author expects that the effects of increasing knowledge diversity will only remain positive until a certain point. After this, it is expected that further increases in knowledge diversity will have negative influences on search quality as absorptive capacity limits are reached and the complexity of combining too many and too diverse knowledge domains becomes increasingly difficult. To capture this potential effect, the author includes the squared term *knowledge_diversity2*.

Type of Leader

The importance of leadership of the search effort is expected to increase as the diversity of knowledge, and hence complexity, increases. As hypothesized, different types of actors are better suited to assume the role of leader under different circumstances, as the purpose of search efforts related to different levels of technological maturity changes. The data allows identification of the leader of each search effort, which is combined with the type of organization assuming this role to identify whether leadership is in the hands of either research organizations or universities. By interacting this with the measure of knowledge diversity, the analysis captures the effect of either a research organization or university leader as knowledge diversity increases. The variables *knowdiv*unilead* and *knowdiv*reslead* capture the interaction of knowledge diversity and a university or research organization a leader respectively.

Control Variables

Project Level Controls

A number of controls are included at the level of each project, which represents a search effort. To control for any influence from the total costs of the project on the evaluation of the quality of the search effort, the variable *project_cost* is included to capture the full cost of the project in Euros. In order to control for any influence from the accumulated experience of the parties involved in the search effort of the particular project the variable *project_parts_exper* captures the total count of all the participants' involvement in other search efforts in the data. Extant research has found search breadth to have a positive effect on innovation although taking an inverted u-shape, meaning that increasing breadth will improve innovation, albeit only to a certain point, after which further increase will decrease innovation (Laursen and Salter, 2006). The positive effects of increasing search breadth is furthermore shown to be higher in mature than immature innovation (Laursen and Salter, 2006). This is argued to be due to the need for more in-depth interaction with fewer sources to absorb the complex and distant knowledge needed to develop new products or technologies in an immature phase. In the context of search efforts related to individual projects the author controls for the influence of breadth on search quality by using the size of the project, which counts the number of participants. The variable *project_size* thus represents the number of participants, while *project_size2* is the squared term, used to capture any returning effects to increased size (breadth) as found previously.

Extant research has shown the importance of science-based search directed primarily at universities and how these will benefit either incremental or radical innovation efforts in the mature or immature technology phases respectively (Köhler *et al.*, 2012, Laursen and Salter, 2006). Complementing the notion of the type of knowledge available from university sources (Cohen *et al.*, 2002) these findings find larger benefits to the immature technologies, as universities are somewhat distant from commercial targets, rather focusing on basic research and free sharing of the knowledge generated through publications (Link and Scott, 2005). Consequently, the analysis controls for science-based search as represented by the participation in search efforts from either universities or research organizations. The variable *university_part* is a dummy taking the value 1 if the search effort includes a university participant, while the dummy *research_part* takes the value 1 if this is the case for a research organization.

Participant Level Controls

Similarly to controlling for other influences on the quality of search at the project-level, the analysis controls for a number of factors at the level of each participant, representing each sources searched. The potential influence of firm size is controlled for through a dummy variable *size*, taking the value 1 firms larger than 250 employees. Participant turnover is included through the dummy *turn_over*, which takes the value 1 for firms with annual turn overs larger than €50mio. The variable *subsidiary* controls for whether the participant belongs to a parent company with a dummy taking the value 0 for subsidiaries. The variable *participant_experience* is included to control for any effects on the search quality resulting from the previous experience and is a count of the number of other search efforts in the data, which the particular participant has participated in. The control *otype* indicates the organization type of each participant to control for any influences thereof. Similarly, the variable *garea* captures the geographical origin of each participant to control for potential national or regional influences. The regions are separated into Northern Europe, the Mediterranean region, Western Europe, Eastern Europe, North America and Australia, Africa, South America, Asia, and finally Others.

Defining Maturity

The paper differentiates between mature and immature technologies based on data on the market penetration of the individual technologies in 2007 in terms of generation of electricity, heating or cooling from the different sources (European Commission, 2010, Sanner *et al.*, 2013). When a technology is either not used for electricity generation or so immature that no data is available for market shares, the categorization is based on the categorization conducted previously by relevant sources. Market figures are available for the mature energy technologies "*Wind*", "*Hydro*" and "*Bio*", and for the immature technologies "*Geothermal*" and the immature "*Solar*" technologies photovoltaic and concentrated solar power. The market shares of these technologies are reported in table 1 alongside the other technologies with categorization and number of projects in the data. As "*Energy Efficiency*" technologies were already in 2005 at a maturity level to enable a 20% decrease of energy consumption (European Commission, 2005), this is categorized as a mature technology.

The technology area defined in the data as "*Future Technologies and Novel Materials*" is considered to be inherently immature and categorized as such in the analysis. According to the European Association for Coal and Lignite's 2012 report on clean coal technology this is still a very immature area with targets of the first operational plants being ready in 2020 (EURACOAL, 2012). Similarly the European Technology Platform for Hydrogen and Fuel Cells describes the 2015 goals of hydrogen and fuel cell technologies to be improvement and validation of technologies before any commercialization is feasible (HPF Europe, 2007). As such, the author defines both "*Clean Coal*" and "*Hydrogen and Fuel Cells*" as immature technologies as of 2007. The "*Ocean*" technology area is defined as immature as this still in 2011 is to gain any commercial scope and production (Jeffrey and Sedgwick, 2011). As a control of the classification the author uses the estimated levelized cost of energy (LCOE) provided by the US Department of Energy[2]. The reasoning is that immature technologies will have higher costs associated with production of energy than mature technologies. This approach provides confirmation of the above classifications of technologies.

Table 1 provides an overview of the technologies, the number of search efforts related to each area and the number of participants. The market share of the technology in terms of total renewable energy generation capacity in the European Union is provided where available. When not, the above arguments have been applied to substitute market share data in creating the categorization of the technologies also available in the table.

Table 1: Technologies, Projects, Participants and Categorization

Project Technology:	**Projects:**	**Participants:**	**Market Share:**	**Categorization:**
Wind	44	532	19,8	Mature
Geothermal	4	60	1,1	Immature
Ocean	29	303	0	Immature
Hydro	11	106	59	Mature
Fuel Cells and Hydrogen	63	529	-	Immature
Clean Coal	36	394	-	Immature
Future Tech and Novel Materials	61	447	-	Immature
Energy Efficiency	83	1,083	20*	Mature
Bio	172	1,737	19,4	Mature
Solar	105	905	0,9	Immature
Total	608	6,096		

*As potential of technology per 2007

Estimation Method

Because the analysis is focused on determining the influence of search efforts, which involve different levels of knowledge diversity and types of leader on solving innovation challenges, a fixed effects model is used to

[2] http://en.openei.org/apps/TCDB/

compare different search efforts related to particular innovation challenges. The variable *call_id* captures the particular call, which defines a certain innovation challenge to be solved by a search effort. The fixed effects approach focuses the estimation model on within-group variations, meaning that the results reflect the comparative effects of different search efforts within each call, i.e. related to the solving of the same problem with different search efforts. Using the fixed-effects model the analysis estimates the influence of the explanatory variables on the score given to the quality of each search effort. Robust standard errors are employed to account for potential heteroskedasticity caused by potentially omitted variables. To check for potential multicollinearity in the model the variance inflation factor is checked, which remains below 3.61 for any of the variables and with the mean VIF at 1.66 concerns of multicollinearity are rejected.

Prior to running the estimation model the projects not meeting certain minimum criteria are dropped from the sample. These criteria are: (i) Moving beyond the technological state of the art, (ii) Reaching results with international impact, (iii) The competence of the sources combined, and (iv) Relevance to the call. A search effort might fail to meet the minimum criteria set forth in one of these areas and reach a high score when all criteria are combined. As an example a search effort may have a lack of competences despite high scores on other the remaining criteria, thereby reaching a high combined score, despite falling short on a central criterion in evaluation of the overall quality of the search. To avoid a situation where below-minimum levels on one criterion but high scores on remaining criteria would bias the sample through ranking such a search effort as high quality, any efforts not meeting the minimum criteria in each category are dropped from the sample. Table 2 provides the distribution of the experts' scores by technological maturity. While the non-normality of the distribution requires that the interpretation of the coefficients remains attentive to this, the findings are not invalid due to this issue. Furthermore, the author runs a robustness check using a censored regression model using only the upper half of the score distribution, which produces results consistent with the use of OLS in terms of the significance and direction of the coefficients of the explanatory variables.

Table 2: Project Types and Score Distributions

		Rating Intervals				
		0-25	**25-50**	**50-75**	**75-100**	**Total**
Mature	Count:	998	0	790	1,670	3,458
	Percentage:	28.86	0.00	22.85	48.29	100.00
Immature	Count:	692	9	623	1,314	2,638
	Percentage:	26.23	0.34	23.62	49.81	100.00
Total	Count:	1,690	9	1,413	2,984	6,096
	Percentage:	27.72	0.15	22.18	48.95	100.00

The appendix provides descriptive statistics for the sample. The main potential cause of concern is the correlation between knowledge diversity and size of the project as a count of the number of participants. As described earlier the paper differs between these measures conceptually, and the VIF tests dismissed concerns of multicolliniarity of the measures.

RESULTS

The results of the regression analysis are provided in table 4 below, with model (i) showing the results of the full model, model (ii) and (iii) showing results for the model with the interaction of knowledge diversity and university or research organization leaders respectively. The output confirms extant literature's finding of an inverted u-shape relationship between breadth and innovation performance (Laursen and Salter, 2006) for mature technologies. However, for immature technologies the negative correlation between project size and rating indicates a stronger than previously estimated need for a low number external collaborators and in-depth interaction in the immature technologies. Furthermore, the results confirm extant findings on the value of science-based search (Köhler *et al.*, 2012), particularly for the immature technologies with positive and significant influence of both universities and research organizations. Interestingly, although not unexpected, university participants do not have a significant contribution to the quality of search in mature technologies. This is likely to be due to the previously described non-commercial and basic-science oriented nature of universities. As technologies mature, a directly applicable and commercial focus increases (Anderson and Tushman, 1990) and the value of this university focus is lost compared to during the immature stage of technological maturity. This is supported by the significant and positive impact of the more application-oriented research organizations, which more than universities focus on commercial outputs.

Table 4: Estimation Results: Robust Fixed Effects OLS

	(i)		(ii)		(iii)	
Variables	**Mature**	**Immature**	**Mature**	**Immature**	**Mature**	**Immature**
knowledge_diversity	4.47***	9.24***	5.50***	7.11***	4.22***	9.89***
	(0.58)	(1.43)	(0.64)	(1.38)	(0.56)	(1.43)
knowledge_diversity2	-0.31***	-0.77***	-0.36***	-0.61***	-0.33***	-0.75***
	(0.05)	(0.13)	(0.05)	(0.13)	(0.04)	(0.13)
university_part	0.89	2.25**	0.61	2.40**	1.40*	2.53**
	(0.70)	(1.09)	(0.69)	(1.08)	(0.72)	(1.08)
research_part	1.87**	3.36***	2.31**	2.10*	2.41**	2.20**
	(0.95)	(1.12)	(0.95)	(1.09)	(0.94)	(1.08)
project_size	0.74***	-2.16***	0.77***	-2.08***	0.78***	-2.10***
	(0.24)	(0.38)	(0.24)	(0.37)	(0.24)	(0.37)
project_size2	-0.03***	0.05	-0.03***	0.05***	-0.03***	0.05***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
knowdiv*unilead			-1.69***	2.32***		
			(0.38)	(0.53)		
Knowdiv*reslead					1.77***	-1.71***
					(0.22)	(0.36)
Constant	33.17***	45.15***	30.96***	53.19***	35.40***	55.55***
	(3.51)	(4.90)	(3.29)	(5.02)	(3.10)	(4.84)
Participant Controls	Y	Y	Y	Y	Y	Y
Project Controls	Y	Y	Y	Y	Y	Y
Observations	3,458	2,638	3,458	2,638	3,458	2,638
R-squared	0.85	0.80	0.85	0.80	0.85	0.80

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Knowledge Diversity

The results confirm Hypothesis 1 as a significant and positive influence from knowledge diversity is found in both categories of technologies, which decreases beyond a certain point as shown by the negative coefficient from the squared term of knowledge diversity. This shows that while increasing the diversity of knowledge in search efforts, absorptive capacity limitations result in decreasing returns from too much diversity and ensuing complexity. When comparing the coefficients for the mature and immature technology categorizations support is found for Hypothesis 2. While both categories achieve an initial positive influence from increasing knowledge diversity before facing decreasing returns in an inverted u-shape relationship, the positive effect is stronger for immature technologies. This confirms the hypothesized stronger effect of knowledge diversity on immature technologies, which benefits from more diverse inputs into the search efforts aimed at solving previously unknown innovation challenges. Diversity is however also important to mature technologies, indicating that while fewer different knowledge domains need to be searched in order to find a solution, there is still a need to move beyond the proximate knowledge retained within the industry when innovating in mature technologies.

Type of Leader

Hypotheses 3 and 4 predicted the effects of the choice of universities and research organizations as leaders of search efforts related to immature and mature technologies respectively. Support is found for Hypothesis 3 that university leaders would increase the benefits of higher knowledge diversity in immature technologies as the need for combining diverse knowledge, managing high complexity and remaining distant from immediate commercial outcomes would have value. This is confirmed by the positive and significant effects of the interaction between the amount of knowledge diversity and a university leader in immature technologies, and strengthened by the significant and negative effect of the more commercially oriented research organizations in the role of leader. Similarly Hypothesis 4 is confirmed as the interaction between increased knowledge diversity and research organizations as leaders show positive and significant effects on the quality of the search in the mature technologies. At the mature stage a high application orientation and focus on commercialization is valuable, which corresponds to the positive effects of research organizations' leadership. As with Hypothesis 3, Hypothesis 4 is strengthened by the significant and opposite result of university leadership. The universities' lack of commercial focus thereby seems to have a negative impact on search quality in the mature technologies.

DISCUSSION AND IMPLICATIONS

Extant research on innovation search and open innovation has found the search for solutions to innovation challenges beyond firms' own knowledge domain to be valuable. In particular immature technologies are shown to benefit from search efforts, which span both organizational boundaries and knowledge domains (Rosenkopf and Nerkar, 2001, Rosenkopf and Almeida, 2003). Other findings have shown the benefit of including a higher number of sources (Laursen and Salter, 2006) as well as different types of sources (Köhler *et al.*, 2012). However, this has left the question of how inclusion of higher knowledge diversity (rather than simply more sources) might influence the quality of innovation search unexplored.

This paper has sought to address this question while also understanding, which types of actors are more suitable to lead the search efforts' integration of diverse knowledge. The study shows that the diversity of knowledge plays an important role in searching for solutions to innovation challenges. In mature technologies less diversity is required as solutions are more abundant and require less diverse knowledge to be combined in its development. In immature technologies however, solutions require more diverse knowledge to be combined in the search in order to develop solutions to problems, which are unlikely to have previously been faced by others. While both the mature and immature technologies benefit, they do so only to a certain point. After this, limitations in the capacity to absorb more knowledge causes decreasing returns to the further addition of knowledge and complexity.

Whereas extant research has assumed one source type such as private firms to provide one type of knowledge, this study has moved to embrace the diversity, which would be expected within each source. Viewing all suppliers as providing the same knowledge is shown in the results to be an oversimplification. Indeed, the knowledge provided should consider that particular industry from which the source originates. Using NACE-code classifications to determine industry origins, the analysis in this paper shows that knowledge from the same type of source is indeed diverse and that this diversity influences the quality of search and thus the likelihood of achieving a solution to the innovation challenge at hand. Furthermore, the importance of the choice of which type of organization leads the search effort was shown in the analysis, something which has so far been unexplored in extant research on collaborative search efforts. Both sets of findings provide contribution to theory and practitioners alike.

Theoretically the findings show that knowledge inputs to search efforts should not be viewed simplistically as represented simply through the type of sources accessed. Rather, analyses should seek to appreciate the underlying differences in the knowledge that is contributed by different actors, albeit these represent the same type of source. Furthermore, a theoretical contribution is made by an appreciation of the importance of who leads the search efforts. Viewing innovation search as one firm ordering knowledge from a second firm does not appreciate the process involved in finding and combining diverse knowledge as increasingly introduced in this paper, and it neglects the important aspect of who leads this effort. External search for solutions to innovation challenges is more likely than not to involve multiple actors. This means that a prioritization and selection of knowledge among the diverse and complex inputs offered is needed, and the increasing understanding of how different actors are able to manage this task is a relevant contribution to the literature on external search.

These findings also have practical implications for firms and managers involved in search efforts such as those analyzed in this paper. An appreciation of both the value and limitations of increasing the diversity of the knowledge domains searched will be helpful to make appropriate decisions contingent on the maturity of the technology which the effort pertains to. Furthermore, understanding how different types of actors are suited to lead and manage the demanding task of finding, selecting and combining diverse and complex knowledge is helpful in choosing who should lead particular search efforts as these relate to technologies at different stages.

Limitations and Future Research

A central limitation in the current version of this paper is the lack of more detailed control variables pertaining to the size and turn over of participants in the search efforts analyzed. Data that can provide more detail on these parameters is currently being accessed in the ORBIS database provided by Bureau van Dijk. More detailed controls will increase the robustness of the current findings, although there are presently no concerns that the improvement of the controls will devalidate the findings. An additional limitation in the data employed in this study is the use of an ex-ante expert evaluation measure as dependent variable to capture the quality of the search effort. Ideally, an outcome variable would be available, which provided an objective measure ex-post the completion of actual project related to the search effort. This is however not available and traditional measures of firm performance, patenting or similar, would do little to help estimate the quality of the search effort related to a specific problem due to multiple other influences from a variety of unobservable factors. As such, in the absence of an ex-post evaluation and with the inability of firm-level performance measures of capturing the quality of a specific search effort, the present study employs an ex-ante measure. However, it would be a valuable opportunity for future work to employ ex-post measures of the quality of individual search efforts.

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APPENDIX

Appendix 1: Descriptive Statistics: Means, Standard Deviations and Correlations

Variable	Mean	S.D.	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
qt_exp_score	60.20	32.17	0.000	100.000	1.00													
knowledge_breadth	5.30	2.02	1.000	13.000	-0.09	1.00												
university_part	0.87	0.32	0.000	1.000	0.16	0.06	1.00											
research_part	0.88	0.32	0.000	1.000	0.08	0.19	-0.02	1.00										
project_size	12.26	5.66	2.000	31.000	0.03	0.63	0.18	0.21	1.00									
project_parts_total_exper	81.37	79.45	2.000	564.000	0.09	0.23	0.15	0.22	0.38	1.00								
am_tot_cost	9.31e+06	1.60e+07	0.000	1.95e+08	-0.09	0.33	-0.06	0.04	0.24	0.07	1.00							
leader_org	3.05	1.62	1.000	5.000	0.02	0.17	-0.19	0.23	0.03	-0.00	0.11	1.00						
turn_over	0.41	0.49	0.000	1.000	-0.03	-0.01	-0.09	-0.02	-0.02	-0.14	-0.01	0.03	1.00					
subsidiary	0.64	0.48	0.000	1.000	0.02	-0.14	-0.03	-0.06	-0.05	-0.18	-0.09	0.00	0.36	1.00				
size	0.36	0.48	0.000	1.000	-0.05	0.02	-0.10	-0.01	-0.01	-0.12	0.01	0.03	0.84	0.31	1.00			
participant_experience	6.87	16.42	1.000	155.000	0.03	-0.01	0.03	0.07	-0.03	0.31	-0.01	0.02	-0.23	-0.10	-0.22	1.00		
org_type	2.91	1.42	1.000	5.000	-0.02	0.10	-0.17	0.19	0.03	0.05	0.05	0.20	0.16	0.03	0.16	0.14	1.00	
geo_area	2.71	1.76	1.000	9.000	-0.01	-0.06	0.01	-0.02	-0.04	-0.05	-0.04	-0.02	0.03	0.02	0.01	-0.10	-0.07	1.00

Appendix 2: Variance Inflation Factors

Variable	VIF
turn_over	3.61
size	3.46
project_size	1.99
knowledge_diversity	1.89
project_parts_exper	1.39
participant_experience	1.23
subsidiary	1.21
research_part	1.16
org_type	1.16
leader_type	1.15
project_cost	1.15
university_part	1.13
geo_area	1.02
Mean Variance Inflation Factor	1.66