

Exploring New Opportunities through Collaboration Within and Beyond Sectoral Systems of Innovation in the 4th Industrial Revolution

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Abstract

This paper investigates how a leading Chinese multinational enterprise in a core sector of the 4th industrial revolution manages research collaborations within and beyond its Sectoral Systems of Innovation to create novel innovations and push the technological frontier of the industry. We find the firm expanded its technology boundaries through collaborations, particularly multidisciplinary collaborations in both core and non-core technological areas of the industry to establish and maintain its leadership in this dynamic sector. High disciplinary diversity in the company's collaborative research portfolio is positively associated with the novelty of its innovation outputs. Promising non-core technologies have been integrated into its production through collaborative research, thus promoting technological convergence at both the firm and the sectoral levels. As a result, the boundary of the industry is expanded.

JEL Classification: F50, O32

Key Words: Sectoral Systems of Innovation, The 4th Industrial Revolution, Multidisciplinary Collaborations, Industry Boundaries, Novelty of Innovation

1. Introduction

Firms innovate in a dynamic environment shaped by institutions, technologies and actors on a global scale in their sectoral systems of innovation (Malerba, 2002, 2005). However, the boundaries of sectoral systems of innovation (SSI) are blurred by the rapid changes in new technologies such as artificial intelligence, robotics, and the internet of things (Schwab, 2017) that have been described as technologies creating the 4th industrial revolution (IR). These technological changes may affect different aspects of SSI, such as the number and type of actors and the interactions among them; the knowledge and technology base; the learning processes, and even the institutions that influence the sectoral system (Malerba and Nelson, 2011, 2012). As the evolution of SSI can be driven by both exogenous and endogenous forces, firms also play an important role in shaping the evolution of the SSI from within (Lee and Malerba, 2017). It is important to understand how firms influence the evolution of the SSI, especially the pathways that leading firms take in pushing and blurring the boundary of the SSI in a time of rapid technological change.

Driven by fierce global competition and increasingly rapid and sophisticated technological changes, innovation has become an open and collaborative undertaking (OECD, 2002; Chesbrough, 2003; Chen, et al., 2019), in which a firm's knowledge integration practices are crucial for the success of the collaborations (Lakemond et al., 2016; Bengtsson et al., 2017). In this study, we focus on the strategies that one firm may take with respect to its research and development (R&D) collaborations and interactions with other players within and beyond its SSI when faced with disruptive technological change. In particular, the changes that the 4th IR poses for multinational enterprises (MNEs) manifest the necessity of creating highly novel innovations and developing innovation capabilities. We propose that collaborations,

multidisciplinary collaborations in particular, on R&D within and beyond their SSI may be a mechanism to incorporate knowledge from diversified fields and create groundbreaking innovations that push the technology frontiers of the firm. On the other hand, collaboration on promising non-core technology may enhance the novelty of innovation outcomes, and promote technological convergence at the firm and the sectoral levels. Consequently, firms may grow as leaders in their industries, maintain their leadership by exploring new opportunities, and subsequently, the boundaries of the SSI are expanded.

This paper aims to meet this need by investigating, as an exemplar, the development of a leading Chinese MNE in an industry at the heart of the 4th IR. This firm grew from an innovative follower to become a leader of its industry that now pushes the technological frontier and explores unknown future directions through collaborative research within and beyond its SSI. **Using quantitative methods**, our research study finds that the firm has expanded its technological boundaries through R&D collaborations, especially multidisciplinary R&D collaborations in both core and non-core technological areas of the industry. This has enabled the firm to establish and maintain its leadership in this dynamic sector. High disciplinary diversity in the company's collaborative research portfolio is positively associated with the originality of its innovation outputs. In addition, promising non-core technologies have been integrated into its core production systems, expanding the boundary of the industry.

This paper contributes to the literature in three main ways. First, it provides a ground-breaking analysis of the role of multidisciplinary innovation collaboration in the dynamic evolution of the technological boundary of a leading company and consequently the SSI of the industry. Specifically, we observe the changes in collaboration patterns that help the firm to develop innovation capabilities when facing rapid technological change. Second, it provides rare

evidence about the impact of disciplinary diversity on the novelty and creativity of research outputs. Our results testify that greater disciplinary diversity in a research community leads to exponential growth in research novelty. Moreover, research collaboration appears to be an effective way to integrate non-core technologies into a firm's core business and helps push the boundaries of the firm and the industry. Finally, this is the first study to investigate this important issue using a project-level dataset obtained from a single large MNE in the digital sector.¹ This unique dataset allows us to investigate how collaborative innovation contributes to the dynamics in an industry that is at the heart of the 4th IR. It enables us to control potential omitted variable biases and address the endogeneity and identification problems.

2. Theoretical Framework

2.1 The challenges of 4th IR

The rapid emergence of new disruptive technologies of the 4thIR – such as industrial robots, artificial intelligence (AI), big data analytics, 3D printing, et cetera – can radically change how production is organized, how profit is produced, and how public and private services are provided in several industries (Manyika et al., 2013; OECD, 2017; World Economic Forum, 2016). These technological changes have generated technological turbulence in the environment of firms (Teece, 2007), especially for MNEs that perform in Global Value Chains (GVCs) in sectors related to the 4th IR like the digital sector, which are highly sensitive to international changes (Malerba, 2002; Malerba and Nelson, 2011).

MNEs in emerging countries can derive a competitive advantage from the abundance of natural

¹ According to the International Monetary Fund (IMF), “the digital sector covers the core activities of digitalization, ICT goods and services, online platforms, and platform-enabled activities such as the sharing economy” (IMF, 2018, p. 1).

resources or inputs that are relatively cheaper. To become leaders in the international context, however, MNEs from emerging countries must innovate at a pace commensurate with that of MNEs from industrialized countries and develop innovation capabilities that will allow them to maintain their competitive advantage in times of technological change (Teece, 2007, 2010; Fu et al., 2011; Lema et al., 2020). Overseas direct investment by emerging market MNEs, innovation, and co-invention are found to be important factors that drive technological learning (Fu et al., 2018) and catch-up (Giuliani et al., 2016, Fu et. al., 2017; Lema et al., 2020; Bathelt and Li, 2020). These processes are global learning processes within MNEs global production networks. They effectively generate cross-border knowledge within subsidiaries and the headquarters of MNEs (Bathelt and Li, 2020).

During periods of increased technological change, latecomers have the opportunity to catch-up and upgrade rapidly in their GVC through the development of disruptive innovations (Malerba and Nelson, 2011; Pietrobelli and Rabelloti, 2011; Lema et al, 2018; Miao et al., 2018; Lema et al., 2019). To implement rapid upgrading firms need to rely on their dynamic capability to exploit and transform external and internal knowledge into innovation (Tushman and Anderson, 1986; Teece, 2010). In the case of Chinese MNEs disruptive innovations have been created by their ability to modify their R&D and innovation processes through the internationalization of R&D; the modularization and use of parallel product development processes, and rapid and pragmatic evaluation of R&D projects (Wan et al., 2015).

2.2 Innovation of MNEs in GVCs and SSI

MNEs are important players in SSI and GVCs and are often the drivers of innovation that push the boundary of an industry. Firms participating in GVCs are also part of a local innovation system (IS) and SSI. Firms improve their learning capacities by being exposed to GVC

knowledge and standards and as a result increase their capabilities and promote their upgrading within the GVCs. However, the capabilities and learning capacities of firms are dependent on the strength and development of the local innovation system (Lema et al., 2019), generating a co-evolution of GVCs and ISs (Lee et al., 2020; Pietrobelli and Rabelloti, 2011; Lema et al., 2018). In addition, although MNEs are part of GVCs and operate in an SSI, they can take advantage of their position to gain access through collaborations to the best innovation practices and knowledge of each country in which they operate or have subsidiaries, and in the countries where they have relations with local firms through their GVCs. This is particularly relevant for MNEs from emerging economies in which the local IS is perhaps less developed than in industrialized countries. For example, China has supported the upgrading of local MNEs because its IS promotes the absorption and learning from foreign direct investment (FDI) during the first stages of development of new sectors (Lee et al., 2020; Primi and Toselli, 2020) and later, MNEs have increased their knowledge absorption and innovation through foreign collaborations.

When faced with disruptive technological changes in an SSI, there will be changes in the technological regime, the knowledge base, and the innovative activities. These changes could force firms to adapt to new forms of innovation and capabilities in order to survive (Malerba, 2002; Zirulia, 2009; Malerba and Nelson, 2011). This may lead to changes in industrial leadership at the local SSI and in the GVCs of the sector. In the case of the digital sector, technological changes have occurred rapidly in recent decades and have been an opportunity for MNEs from emerging economies to catch up and take a leading position in the GVCs, especially in China (Lee et al., 2020; Primi and Toselli, 2020; Grimes and Yang, 2017; Malerba and Nelson, 2011). Leaders of GVCs can exert their relative power in R&D collaborations, obtaining the most benefits in terms of patenting and innovations from collaborating with

partners located in different SSI across the world (Rikap, 2019). However, this strategy could also be followed by latecomers to catch-up or upgrade in their GVCs (Malerba and Nelson, 2011; Wan et al., 2015; Lema et al., 2018; Miao et al., 2018; Lema et al., 2019). Therefore, MNEs may respond to the disruptive technological change of a multinational enterprise in a global SSI with complex interrelations between SSI, GVC and IS. MNEs may exploit global innovation networks to gain a technological advantage through collaboration.

2.3 The benefits of collaboration

The need to increase innovation capabilities of firms in the context of rapid technological change in the 4th IR, leads firms to increase collaboration on R&D and innovation (Primi and Toselli, 2020). These collaborations traditionally take place within the SSI, which include the knowledge base and technology; organizations and their interactions; institutions, and the dynamic processes among them (Malerba, 2002, 2005). Given the rapid technological change, especially in a sector such as digital technology, which provides a general technological infrastructure to many other industries, such collaboration may also happen beyond the traditional SSI. The interactions between organizations on R&D activities within and beyond the SSI may generate groundbreaking innovations that push the boundary of an industry.

In a firm with an “open innovation strategy”, knowledge and ideas to develop innovation processes can come from both internal and external sources (Chesbrough, 2003). Open innovation may include formal or informal collaborations between the firm and various partners and the collection of information from external sources. Lakemond et al. (2016) argue that in open innovation involving different types of partners, both project management and knowledge matching are related to performance gains. In particular, they find that project management matters more for open innovation involving numerous and varied types of

collaboration partners and that knowledge matching is important regardless of the collaboration partners' differences from the focal firm. The openness of a firm is related to a firm's innovation, since linkages with external institutions increase a firm's knowledge base and innovation capacities (Freeman and Soete, 1997; Goes and Park, 1997; Hoffman et al., 1998; Powell et al., 1996; Tsai, 2001). External sources of information also help to expand the knowledge base and reduce the costs of elaborating solutions for the development of a new product (Fu, 2012; Laursen and Salter, 2006). For example, Laursen and Salter (2006) study the effects of the breadth and depth of external sources of information about innovation on the data of UK firms. They find that both search strategies are positively related to innovation outcomes, but for radical innovations new to the world, the depth of information from external sources is more crucial.

When there is more uncertainty about markets and technological change firms choose to collaborate more on R&D and innovation (Lin et al., 2019; Fu et al., 2020). In particular, Chinese manufacturing firms that face higher levels of knowledge and skill constraints to innovation are found to develop greater openness to innovation activities (Fu et al., 2014): Chinese manufacturing firms boost their internal R&D capabilities by introducing more diverse external knowledge. In the face of technological change, firms can maintain or improve their position in their sectors by acquiring knowledge to reduce the knowledge gap between their knowledge base and the new technology (Danneels, 2004). This external knowledge can be acquired through strategic alliances, joint ventures, and licensing or R&D collaborations.

2.4 Diversity, multidisciplinary collaborative research, and novel innovation

Collaborations on R&D increase firms' innovation capabilities and MNEs can exploit their advantage of multiple locations to collaborate in different countries, gaining access to the

benefits of different SSI. International R&D collaboration has multiple benefits for MNEs. Vrontis and Christofi (2019) review the literature on R&D internationalization and its impact on innovation outcomes. They find that R&D internationalization has a positive effect on a firm's novel and radical innovations. They find that for MNEs from emerging economies R&D internationalization can also improve the MNEs' innovation capabilities and promote catching-up. However, international collaboration on R&D implies the management of diversity in those projects. The management of the diversity of types of partners; their organizational aspects and the diversity of their environment, and the diversity in their knowledge bases and technological focus (Parkhe, 1991). Diversity in collaborations can have important benefits for firms such as the development of radical innovations and the creation of global competitive advantages, however managing this diversity can also be costly, particularly the management of the mismatches between professionals from different disciplines working together (Parkhe, 1991; Simon and Lane, 2004; Bassett-Jones, 2005; Nooteboom, 2007).

Diversity of skills, experience, and knowledge has been found necessary for the development of radical innovation (Desrochers, 2001; Gilsing et al. 2008). Cummings and Kiesler (2005) find that multidisciplinary research projects are more successful in generating new ideas and knowledge. Nooteboom et al. (2007) find that cognitive distance can contribute to novel innovations by combining and connecting diverse knowledge. Although Battard (2012) argues that multidisciplinary research has costs that may erode the benefits, Godoe (2000) finds that serendipity is an important factor in the creation of radical innovation. Serendipity plays an important role in the spill-overs of knowledge from different disciplines that can lead to productive convergence of diverse scientific fields and technologies (Hacklin et al., 2009; Jeong and Lee, 2015). Technological convergence can blur the boundaries of scientific fields and industries when generating innovative technologies and market applications of those

innovations (Hacklin et al., 2009). Therefore, R&D collaboration in technical fields that are cognitively far from the core technological field of the firm can lead to more disruptive innovations that can transform industries and sectors.

Therefore, the rapid exploitation of technology and expansion of fields of knowledge in the period of the 4th IR has two major consequences for firms. First, an increase in collaboration on R&D and innovation increases firms' ability to generate disruptive technologies, not only in the main field of firms in the digital sector but also for firms in other fields of knowledge. These collaborations allow firms to share the risk and to pool resources for innovation. This collaboration is more necessary in times of rapid technological change that increase the risk and uncertainty of innovation projects **than in times of only moderate technological progress.** Second, the increase of collaboration in different fields of knowledge allows the frontiers of the digital field to expand. These collaborations complement each other and have a transformative power to create and develop the new technologies that are leading the 4th IR. The cross-disciplinary nature of collaborations in the digital sector has transformed the sector and is needed to create disruptive and transformative technologies of the 4th IR, for example, the Internet of Things, Blockchain, and Smartphones.

These collaborations take place across geographical boundaries because scientific and industrial leaders of different disciplines are distributed across the world. These collaborations mostly involve industrialized countries. Therefore, firms will choose international collaborations to generate high-quality innovation. This strategy will blur the company's technological boundaries, expand the boundaries of its SSI, and generate innovation capabilities to maintain its leading role in the sector. Our prior assumption is that leading firms in an industry faced with rapid technological change, and with uncertainty in the direction of

the change, may diversify their research collaborations geographically and technologically to enhance the novelty and creativity of their innovation outputs, and produce groundbreaking innovations that may lead the development of an industry in a new direction. These innovation capabilities enable firms to produce technological convergence and respond quickly to future technical revolutions. We expect that such diversification into international collaborations and non-core technologies will result in the firm and their SSI having an increasingly blurred technological boundary.

3. Methodology and Data

3.1 Methodology

We employ quantitative methods to examine whether MNEs create novel innovations through multidisciplinary R&D collaboration within and beyond their SSI. First, we use regression analysis to examine the impact of multidisciplinary R&D collaboration on innovation performance. Then we employ additional descriptive data analysis to capture the changes in R&D collaboration patterns for core versus non-core technologies to demonstrate the evolution of the innovation ecosystem of MNEs and to reflect the changes in their SSI. The explorative nature of our paper allows the use of inductive reasoning to analyze the data in this unique case study of a Chinese MNE in the ICT sector.

Regression analysis

We use the following model to estimate the relationship between collaboration diversification and innovation performance.

$$Y_{i,t} = \alpha + \beta \text{CDI}_{i,t} + \beta \text{CDI}_{i,t}^2 + \gamma \text{Z}_{i,t} + \text{Mode}_i + \text{Depart}_i + \text{Year}_i + \varepsilon_{i,t} \quad (1)$$

where Y denotes innovation performance. We develop two proxies for innovation performance

that can be used alternatively. The first proxy is PATENT, measured by the number of invention patents that are granted during the process of conducting a collaboration project. This proxy mainly captures the quantity of innovation outputs. The second proxy is VITALPATENT, measured by the number of invention patents granted in the patent offices of the U.S., Japan, Europe and the Patent Cooperation Treaty. This indicator was developed by Lanjouw et al. (1998) to represent the extent of patent families. It has been widely used as a proxy for the quality of innovation outputs or patent importance.

CDI denotes the collaboration diversification index, which is used to measure the degree of multidisciplinary R&D collaboration. We use the following model adopted by Cadot et al. (2011) for developing an export diversity index in order to construct CDI.

$$CDI = \sum_{k=1}^n \left(\frac{N_k}{N} \right) * \left(\frac{\mu_k}{\mu} \right) * \ln \left(\frac{\mu_k}{\mu} \right) \quad (2)$$

where N refers to the number of projects in a given year. N_k refers to the number of projects for certain technological field in a given year. μ refers to the total budget of projects in a given year. μ_k refers to the total budget of projects for certain technological field in a given year. CDI^2 is also included in Equation (1) to identify whether the relationship between CDI and innovation performance is quadratic.

Following the existing literature (Cassiman et al., 2010; Schwartz et al., 2012), we control for a series of project characteristics that may affect the project innovation performance. The control variable matrix Z includes FOREIGN, a dummy variable that equals 1 if the collaborator is from foreign countries and 0 otherwise. We exclude Hong Kong, Macao and Taiwan from our baseline models because they are individual administrative regions of China and possess regional autonomy; UNIVERSITY, a dummy variable that equals 1 if the collaborator comes from the universities and/or research institutions and 0 if the collaborator

comes from the enterprise; BUDGETSIZE, measured by the natural logarithm of the project budget; SELECT_STRATEGY, measured by a dummy that equals 1 if XTech selects the collaborator of this project by open-call and 0 otherwise; PRO_IMPORTANCE, measured by a dummy that equals 1 if XTech gives priority to this project and 0 otherwise; COLL_PURPOSE, measured by a dummy that equals 1 if the purpose of the project is patent application and 0 otherwise; IPROWNER, measured by a dummy variable that equals 1 if the IPR is solely owned by XTech and 0 otherwise; and COLL_EXPERIENCE, measured by a dummy variable that equals 1 if XTech has ever cooperated with this partner before and 0 otherwise.

In addition, $Mode_i$ captures the collaboration mode fixed effect, $Depart_i$ captures the business division fixed effect, and $Year_t$ the year fixed effect.² We also control for time-invariant heterogeneities among these factors by employing the fixed-effect model. Finally, we use negative binomial regression to estimate the model for three reasons. First, PATENT and VITALPATENT are count variables with nonzero positive integers. Second, a nontrivial portion of sample projects has these two variables equal to 0. Third, these two variables are both over-dispersed. We use “i” to denote the joint-innovation project and “t” to denote the year. Table 1 provides definitions of all the variables used in this study.

(Table 1 inserted here)

Descriptive analysis

To examine the effect of changes in technological fields and the differences in disciplines we create an index of technological change. We ask two experts in the digital sector to rate the

² XTech adopts four different collaboration modes, including innovation research, technical consultation, technical development, and technical research.

technical field of each collaboration project in our dataset according to how core to the technology of the sector was the area of research collaboration, considering two reference years, 2006 and 2016.

There were three categories: core field, closely relate to core field, and remotely or not core field, for both 2006 and 2016. From this classification, we construct two categorical variables, for 2006 and 2016, respectively, which take the value 3 for projects working on core technical field, 2 for projects working on technologies closely related to core field, and 1 for projects working on technologies remotely or not core field. We then construct a variable of change of importance of technical area for each project, which is normalized for the average technical importance of the projects for each year. To evaluate the diversification of collaborations, we present graphic analysis and descriptive statistics showing the changes in XTech's collaborations through the years.

3.2 Data

The data for this study come from a single large Chinese MNE. To preserve confidentiality we anonymized the company and call it XTech Corp. Ltd. (hereafter XTech). XTech is a global leading digital company located in China. The digital industry is rapidly changing and involves great technological demand and high product reliability. Hence, the company continually expands its capabilities to master more advanced technology and further improve its innovation efficiency by conducting joint-innovation projects with technological leaders around the world. XTech has established close partnerships with prestigious research institutions and manufacturing firms, both in emerging countries and developed countries and thereby accumulated a large database that records all the details of their innovation collaborations. A unique feature of this database is that XTech provides project-level data within a specific firm

rather than firm-level data, which enables us to control potential omitted variable biases and to reduce the endogeneity and identification problems (He and Tian, 2013; Acharya and Xu, 2017).

We obtained from XTech all the joint-innovation projects from 2006 to 2016, 6,893 in total, that involve collaboration with other institutions. After cleaning the data, we obtained 714 joint-innovation projects involving foreign collaborators during the period between 2009 and 2016,³ and 714 comparable domestic collaboration projects selected by using propensity score matching methods.

Table 2 shows the summary statistics for our sample. In our sample, the average number of granted invention patents (PATENT) is 0.5658, and the average number of granted vital patents (VITALPATENT) is 0.3018. The average collaboration diversification index (CDI) is 0.1584. Foreign collaborators (FOREIGN) consist of precisely half of our sample, which is consistent with the one-to-one matching. A total of 55.32% of the projects work with academic institutions (UNIVERSITY), such as universities or scientific organizations. The average project budget (BUDGETSIZE) is 2,212 thousand Chinese Yuan.

(Table 2 inserted here)

4. Empirical Results

4.1 Regression results

Table 3 presents the empirical results of the impact of multidisciplinary collaboration on

³ We cleaned the data using the following procedure: First, we excluded the repeating projects that have the same identification number. Second, we deleted those projects unrelated to innovation, for example, IP license purchasing and certification tests.

innovation performance. We report heteroskedasticity-robust standard error between parentheses to avoid general misspecification in the regression. The coefficient on CDI is significant and positive in both Columns (1) and (2), suggesting that high disciplinary diversity in the company's collaborative research portfolio is positively related to novel innovation. The finding is consistent with that of Cummings and Kiesler (2005), who also find that multidisciplinary research projects can generate more new ideas and knowledge.

(Table 3 inserted here)

Another interesting finding is that the coefficient on CDI^2 is significant and positive, in both Columns (1) and (2). Figure 1 is produced based on the result, which demonstrates that the relationship between collaboration diversification and innovation is upwardly convex showing an exponential increase in innovation performance alongside an increase in multidisciplinary R&D collaborations. In other words, the increase in collaboration diversification leads to a sharper increase in innovation performance. This finding implies that the firm may expand the boundaries of its SSI and generate innovation capabilities to maintain its leading role in the sector through an increase of collaborations in different fields of knowledge.

(Figure 1 inserted here)

It is also worthy of note that the coefficients on both FOREIGN and UNIVERSITY are significant and positive in Column (2), suggesting that international collaboration and collaboration with universities/research institutions could generate more vital patents. The result is in line with the extant studies. For example, Fu (2015) and Li et al. (2010) find that through international cooperation, firms in China can access the international knowledge pool and thus enhance the firms' research capabilities. In addition, Belderbos et al. (2004) find that firms can integrate different sources of knowledge that could be useful in exploring new

technologies and for developing comparative advantages that enhance R&D competitiveness.

4.2 Changes in the R&D Collaboration Patterns

The digital sector has experienced rapid technological change since the 1990s, increasing the knowledge and technological base and bringing new actors to the sector (Malerba, 2002; Malerba and Nelson, 2011; Grimes and Yang, 2017). This forced firms in the sector to change their innovation strategy (Wan et al., 2015). A descriptive analysis of XTech's R&D collaborations can give us information on the main changes that have occurred in its collaboration strategy. Table 4 lists the number of R&D collaboration projects per technological field and the changes in their relative importance (i.e., Core vs. Non-Core technology) for the sector between 2006 and 2016. It shows that, over the sample period, XTech's R&D collaborations cover 36 technology areas. Among them are 16 areas that were in Non-Core technology areas in 2006 but changed to Core technology areas in 2016. During this period, 2,170 out of 4,848 projects located in these areas experience this kind of evolution.

(Table 4 inserted here)

In Figure 2, we observe the rapid increase in the number of projects, and the importance of Non-Core technologies compared to Core technologies in the diversification of the search and creation of knowledge for XTech, showing that the company was striving to increase their breadth of knowledge. In Figure 3, we show that the diversification of technology areas happens fast between 2009 and 2013, increasing from five to 35 different fields, maintaining projects in about 30 different technological fields thereafter.

Visual examination of the disciplinary distribution of research projects over time (Figure 3) suggests several clear patterns. First, there is a rapid increase in collaborations on non-core

technologies that become highly relevant within the total portfolio of collaborations at the beginning of the sample period. Second, the number of different technologies in the set of collaborations increases in both, core and non-core areas, showing a diversification of the technologies studied by XTech. Third, while at the end of the sample period the proportion of core and non-core technologies is almost 50%, many non-core technologies in 2009 had become core technologies by 2016. This shows the integration of promising non-core technologies into core production technologies and the consequent enhancement of its innovation capabilities. The rapid increase of collaborations can be a sign of the industrialization of R&D processes within the firm that results in purposeful disruptive innovations (Wan et al., 2015).

(Figures 2 & 3 inserted here)

Overall, the descriptive analysis of the changes in the R&D collaborations shows that XTech has purposefully expanded its collaborations with partners. More importantly, XTech has successfully integrated the promising non-core technologies, developed through collaboration with partners outside the traditional SSI, into its innovative production systems. Many of these early-stage non-core technologies have gradually become core technologies in the industry and led to the expansion of the boundaries of the firm and the industry. Partly due to these efforts, XTech has also moved to the frontier of the digital industry, pushing the boundary of the sector and becoming an industry leader. As a result, XTech has increased its sectoral and geographical boundaries to maintain its leadership and generate innovation capabilities during the period studied.

This overview of XTech's strategy indicates a response to changes not only of technologies dominating the digital sector, but also promoted by new policies implemented in China that

promote indigenous innovations of Chinese firms (Grimes and Yang, 2017). The strategy adopted by XTech has allowed them to take advantage of their latecomer position in the digital sector and promoted its upgrading within the digital GVCs (Wan et al., 2015; Schaefer and Liefner, 2017). In addition, XTech's diversification research strategy shows the purposeful intention of the firm to create radical innovations through international R&D collaborations, and follows the tendency of lead firms in the digital sector (Schaefer and Liefner, 2017; Godoe, 2000).

5. Discussion

The evidence presented so far suggests that during times of great technological change, like the period of the 4th IR, MNEs can use their position in different countries to leverage collaborations and produce disruptive innovations, gaining advantage of knowledge from SSI in different countries, creating Global SSI (GSSI). For latecomers or MNEs from emerging economies, this scenario presents an opportunity to catch-up and upgrade within their GVC. In this context, diversifying R&D collaborations geographically, across various disciplines, and in technological areas far from the firm's core can produce more disruptive innovations, broadening not only the firm's boundaries, but also pushing the boundaries of the GSSI when firms become leaders in their GVCs and sectors.

This process is not unique for MNEs in emerging economies. Bengtsson et al. (2016) examine collaboration across organizational boundaries, knowledge boundaries, and geographical boundaries among 415 manufacturing firms in Italy, Sweden, and Finland. They find that knowledge flows across multiple boundaries in open innovation can be channeled by applying a combination of complementary knowledge integration practices. In addition, this process can

be found in world-renowned MNEs. For example, Amazon has been characterized for its broad collaboration with universities and even with competitors, thus creating new markets and broadening the sector frontiers of action (Ritala et al., 2014). A prime example is Amazon's development with Google of an automatic system to track COVID19 exposure,⁴ expanding its business to new markets and broadening their sectoral boundaries. A related example is the case of the multiple companies owned by Elon Musk. His companies are based in different sectors, ranging over automobile (Tesla), space exploration (SpaceX), construction (The Boring Company), artificial intelligence (OpenAI), and health (Neuralink). On its own, each company works on the technological frontier developing disruptive innovations and transforming their sectors.⁵ However, collaboration between firms, even if from different sectors, enhances their development and expands their frontiers.⁶

Another example is Google moving into the automotive industry.⁷ With the development of new technologies in telecom such as tracking devices, computers in vehicles, machine learning and artificial intelligence, the autonomous vehicle of the future will be more like a hyper-connected supercomputer in which Google has invested and may revolutionize the automobile industry, again creating fuzzy sectoral borders. In the automotive sector, the fusion of automation and electric vehicles, has also led to a convergence of industries such as automotive manufactures, chemical and electric manufactures, and the software industry (Von Delft, 2013),

⁴ <https://www.theverge.com/2020/9/1/21410281/apple-google-coronavirus-exposure-notification-contact-tracing-app-system>

⁵ <https://www.cbinsights.com/research/report/elon-musk-companies-disruption/>

⁶ <https://www.elonx.net/collaboration-between-elon-musks-companies-has-lead-to-synergies-but-also-problems/>

⁷ <https://www.forbes.com/sites/richardwindsoreurope/2019/01/29/failure-to-keep-google-out-of-vehicles-could-finish-the-automotive-industry-as-we-know-it/#310c9dd14cc9>

showing again the blurring not only of a firm's boundaries but especially the blurring of the GSSI technological boundaries.

Our results also fit with the literature on technological convergence. For example, Hacklin et al. (2009) have shown how the convergence of technologies in ICT towards optic and computer technologies has blurred the boundaries of the industry. The authors identify a process of industrial convergence that has four stages. First, knowledge convergence occurs by serendipity inside and outside the firm, eroding the knowledge base of the industries. In the second phase, the firm identifies the existence of knowledge convergence between fields and purposively invests in producing technological innovations that combine the knowledge and technologies of the different fields to expand the firm's technological regime. The third phase is the applicational convergence. The firm identifies new applications in the market or new markets for the technologies developed. Fourthly, an evolutionary process at the industrial level changes the technological regime. The convergence of different technologies leads to a convergence of industries, thus blurring the boundaries of the sectors. This perspective assumes that the firms have only an active role during the convergence process in the technological and applicational phases.

However, our data suggest that firms may gain a competitive advantage over their competitors. Firms that expand the knowledge convergence phase by collaborating broadly in non-core technologies, with different partners and in different SSI, may gain a competitive advantage over their competitors by generating innovative products with technological convergence allowing them to be early movers towards new technological regimes, therefore upgrading their GVC and becoming key players in their sectors (Figure 4). Therefore, based on the analysis and evidence from this research, we propose that (1) diversity in the technological fields of

R&D collaborations leads to more novel innovations; and (2) R&D collaboration on promising non-core technology enhances the novelty of innovation outcomes, and promotes technological convergence at the firm and the sectoral levels. When this knowledge is integrated into the production process of firms, it may gradually become core technology. Some of these novel innovations may expand the technological boundaries of the firm and the sector.

(Figure 4 inserted here)

6. Conclusions

This paper investigates the R&D collaboration strategy of a leading Chinese MNE in the digital sector during a period of rapid technological change associated with the 4th IR. We find that the firm expanded its knowledge frontier through collaborative projects within and beyond the traditional SSI. In particular, the firm has successfully integrated promising non-core technologies into its production systems through multidisciplinary innovation collaborations. With the rapid growth of the firm, especially as the firm gradually becomes the leader in the industry, these non-core technologies, tend to be peripheral to the core area. Some technologies initially more remotely related to the core technological areas become the core technologies of the industry.

These collaborations, co-inventions, integrations, and application processes promote technological convergence at both the firm and eventually the sectoral levels. Multidisciplinary collaboration enhances a firm's capacity to produce more creative and novel innovations by increasing the disciplinary diversity in its research portfolio. Hence, the technological frontier of the firm and, gradually, the industry boundary expands. In this process, the firm expands the technological frontier of its industry and becomes an industry leader. Moreover, evidence from

statistical analysis of a unique project-level database derived from one MNE reinforced our findings about the benefits of multidisciplinary research collaborations between industrial enterprises and their partners in the universities and within and beyond their sectors. The research finds significant evidence indicating that the more diversified the research collaboration portfolio, the more novel innovations this kind of collaboration can produce. These findings powerfully demonstrate how a firm can expand its technological and industrial boundaries through cross-disciplinary research collaboration.

The research findings have important managerial and policy implications. Government policies shall greatly encourage multidisciplinary innovation collaboration, in both industry and academia as well as between them. In other words, policies shall encourage ecosystem collaboration, within and beyond traditional sectoral systems of innovation. In particular, policies shall support the riskier ‘large-distance’ collaboration, for example the collaboration in non-core technological areas as we have seen in this study. These policies would increase the number of novel and groundbreaking innovations and hence enhance a country’s innovation performance. In order to achieve this, incentives shall be introduced to encourage firms to engage in multidisciplinary collaboration that can create large and long-term gains. Besides, reforms in funding structure and in education program are also needed to facilitate such collaboration and to train researchers with necessary skills and mindset.

For business leaders, multidisciplinary innovation collaboration will enable firms to create more groundbreaking innovations and hence enhance their competitiveness. Therefore, firms might well consider a corporate strategy of selecting multidisciplinary collaborations. A firm with an open innovation strategy could increase its capacity to absorb and create new technologies, which is particularly relevant in periods of rapid technological change and

widespread uncertainty. For latecomer firms, this may even give them the opportunity not only to catch-up with the innovators on the technology frontier but also to become leaders of the industry. For firms from emerging economies that need to move to the world frontier of technology and transform from followers and imitators into leading innovators, multidisciplinary collaboration will provide a pathway to achieve this. For firms at the industry technology frontier where there are no leaders to follow must find new opportunities like an explorer in a new country. A pioneering firm should promote multidisciplinary collaborations in fields beyond the traditional core technologies, or go even further to collaborate in technology areas beyond the existing SSI. This is a high-risk strategy but it may be very fruitful. The outcome will benefit the collaborating firm and also push the boundary for the industry.

Admittedly, this study bears limitations. The data for this study come from a single large Chinese MNE. Future research may usefully examine the same area using project-level data from firms in different industries to investigate whether the strategy works in firms in different industries and with different innovation strategies. Collaboration is not free from failures and downsides. More in-depth studies shall be carried out to understand the internal and external conditions that are necessary to facilitate successful multidisciplinary innovation collaborations and how best to manage the risks of collaborations, particularly in multidisciplinary collaborations.

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Table 1. Variable definition

Variable	Definition
PATENT	The number of invention patents granted during the process of conducting the project.
VITALPATENT	The number of invention patents granted in the patent offices of the USA, Japan, Europe and Patent Cooperation Treaty.
CDI	Collaboration diversification index, which provides an overall measure of collaboration diversification across various disciplines.
FOREIGN	A dummy variable that equals one if the collaborators are from foreign countries and zero otherwise.
UNIVERSITY	A dummy variable that equals one if the collaborator comes from an academic institution (i.e., university) and zero if the collaborator comes from an enterprise.
BUDGETSIZE	The budget amount of the project on a thousand RMB basis.
SELECT_STRATEGY	A dummy variable that equals one if XTech selects the collaborator of this project by open-call and zero otherwise.
PRO_IMPORTANCE	A dummy variable that equals one if XTech gives priority to this project and zero otherwise.
COLL_PURPOSE	A dummy variable that equals one if the purpose of the project is patent application and zero otherwise.
IPROWNER	A dummy variable that equals one if the IPR is solely owned by XTech and zero otherwise.
COLL_EXPERIENCE	A dummy variable that equals one if XTech has ever cooperated with this partner before and zero otherwise.

Table 2. Descriptive statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
PATENT	1428	0.5658	2.556	0	31
VITALPATENT	1428	0.3018	1.646	0	24
CDI	1428	0.1584	0.0490	0.1001	0.2246
FOREIGN	1428	0.5000	0.500	0	1
UNIVERSITY	1428	0.5532	0.497	0	1
BUDGETSIZE	1428	2212.12	1354.16	10	4660
SELECT_STRATEGY	1428	0.0084	0.091	0	1
PRO_IMPORTANCE	1428	0.0259	0.159	0	1
COLL_PURPOSE	1428	0.3529	0.478	0	1
IPROWNER	1428	0.6891	0.463	0	1
COLL_EXPERIENCE	1428	0.1275	0.334	0	1

Table 3. Innovation and multidisciplinary R&D collaboration

Dep. Var.	Negative Binomial Regression	
	PATENT (1)	VITALPATENT (2)
CDI	107.743*** (28.981)	128.126*** (31.831)
CDI^2	354.785*** (92.783)	427.844*** (101.635)
FOREIGN	0.093 (0.219)	0.637** (0.257)
UNIVERSITY	0.989*** (0.341)	1.112*** (0.387)
BUDGETSIZE	-0.055 (0.089)	-0.014 (0.107)
SELECT_STRATEGY	-1.226 (1.370)	-19.195*** (0.852)
PRO_IMPORTANCE	-1.190* (0.650)	-20.876*** (0.325)
COLL_PURPOSE	1.804*** (0.260)	1.859*** (0.320)
IPROWNER	0.533** (0.262)	0.726** (0.335)
COLL_EXPERIENCE	-0.875* (0.458)	-1.357** (0.605)
Collaboration Mode Fixed Effects	Y	Y
Business Division Fixed Effects	Y	Y
Year Fixed Effects	Y	Y
Pseudo R ²	0.118	0.125
Number of Observations	1428	1428

Note: Heteroskedasticity-robust standard errors are reported in parentheses. The coefficients are adjusted for marginal effect. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4. Core & Non-Core technology fields: 2006 vs. 2016

Technology Field	Non-Core Area 2006		Core Area 2006		Total
	Non-Core Area 2016	Core Area 2016	Non-Core Area 2016	Core Area 2016	
NC1		454			454
NC2		223			223
NC3		115			115
NC4		104			104
NC5		56			56
NC6	217				217
NC7		273			273
NC8		155			155
NC9		224			224
NC10		54			54
NC11		28			28
NC12	92				92
NC13		7			7
NC14		91			91
NC15		34			34
NC16		260			260
NC17		86			86
NC18	9				9
NC19	10				10
NC20		6			6
NC21	2				2
C1				55	55
C2				897	897
C3				302	302
C4			249		249
C5				30	30
C6				146	146
C7				225	225
C8				29	29
C9				3	3
C10				245	245
C11				24	24
C12				62	62
C13				45	45
C14				6	6
C15				30	30
Total	330	2170	249	2099	4848

Note: This table lists the number of projects per technological field and changes in their relative importance for the sector between

Figure 1. Innovation and R&D collaboration diversification

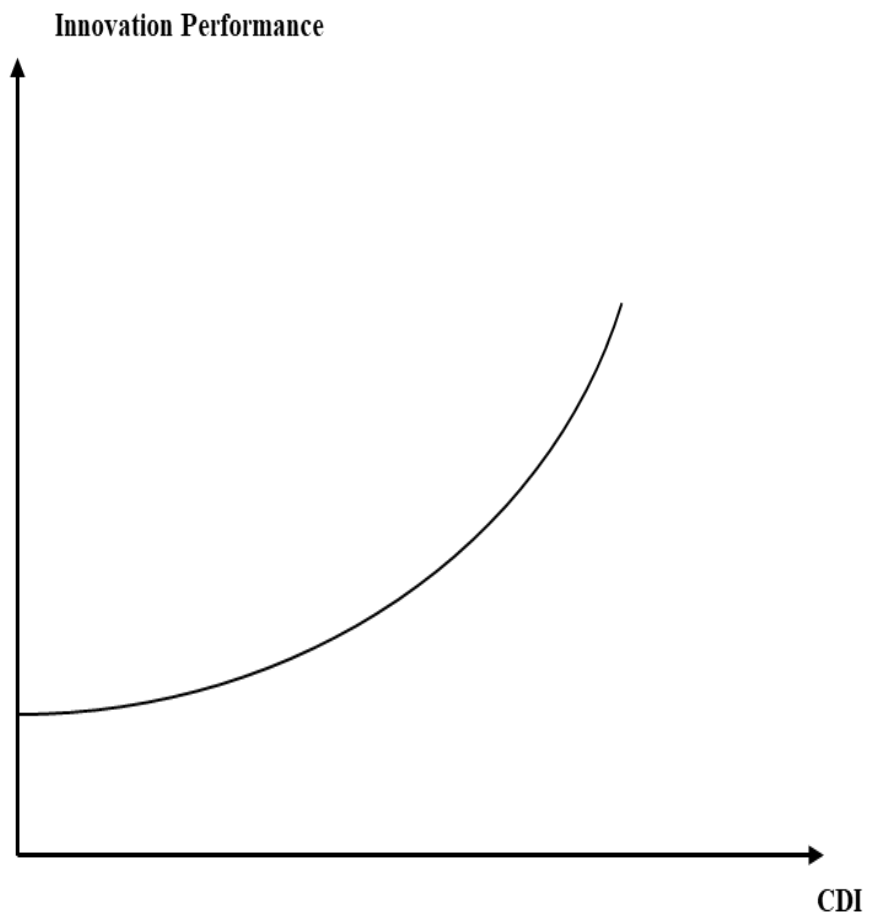


Figure 2. International R&D collaboration: non-core technology vs. core technology

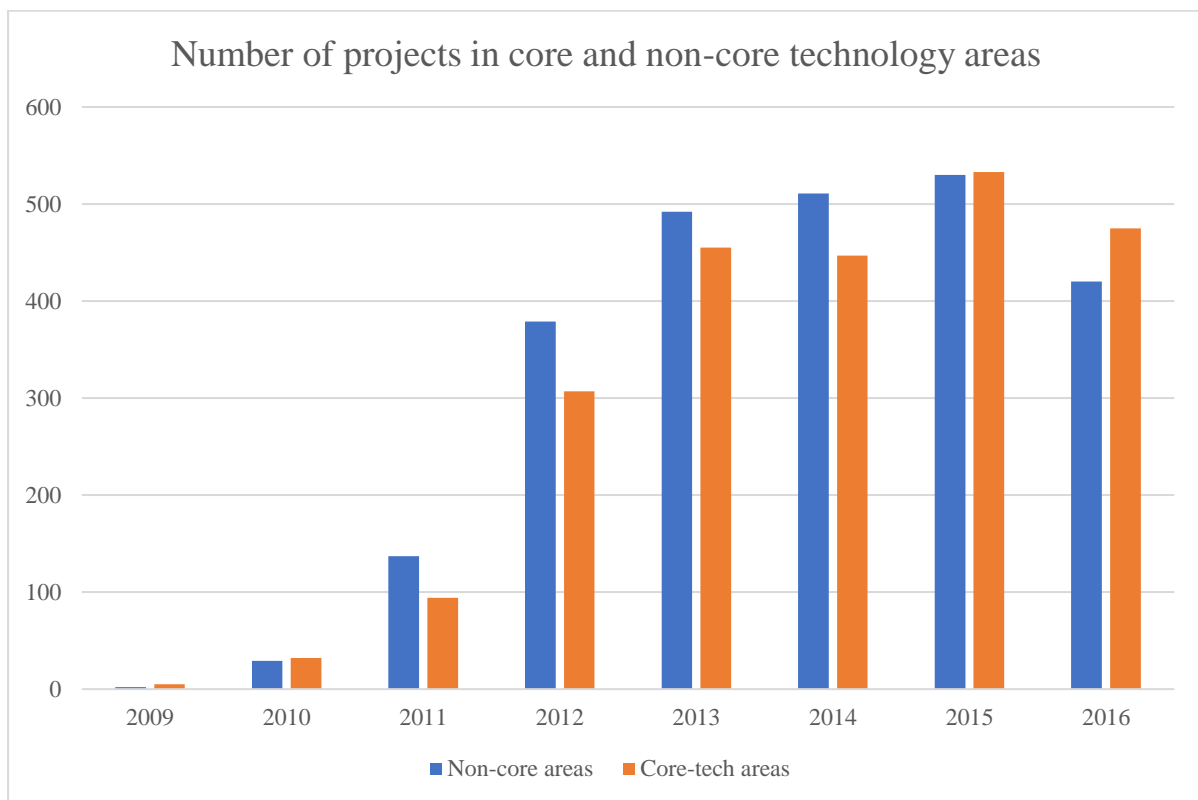


Figure 3. Distribution of core and non-core technology areas in collaborative projects

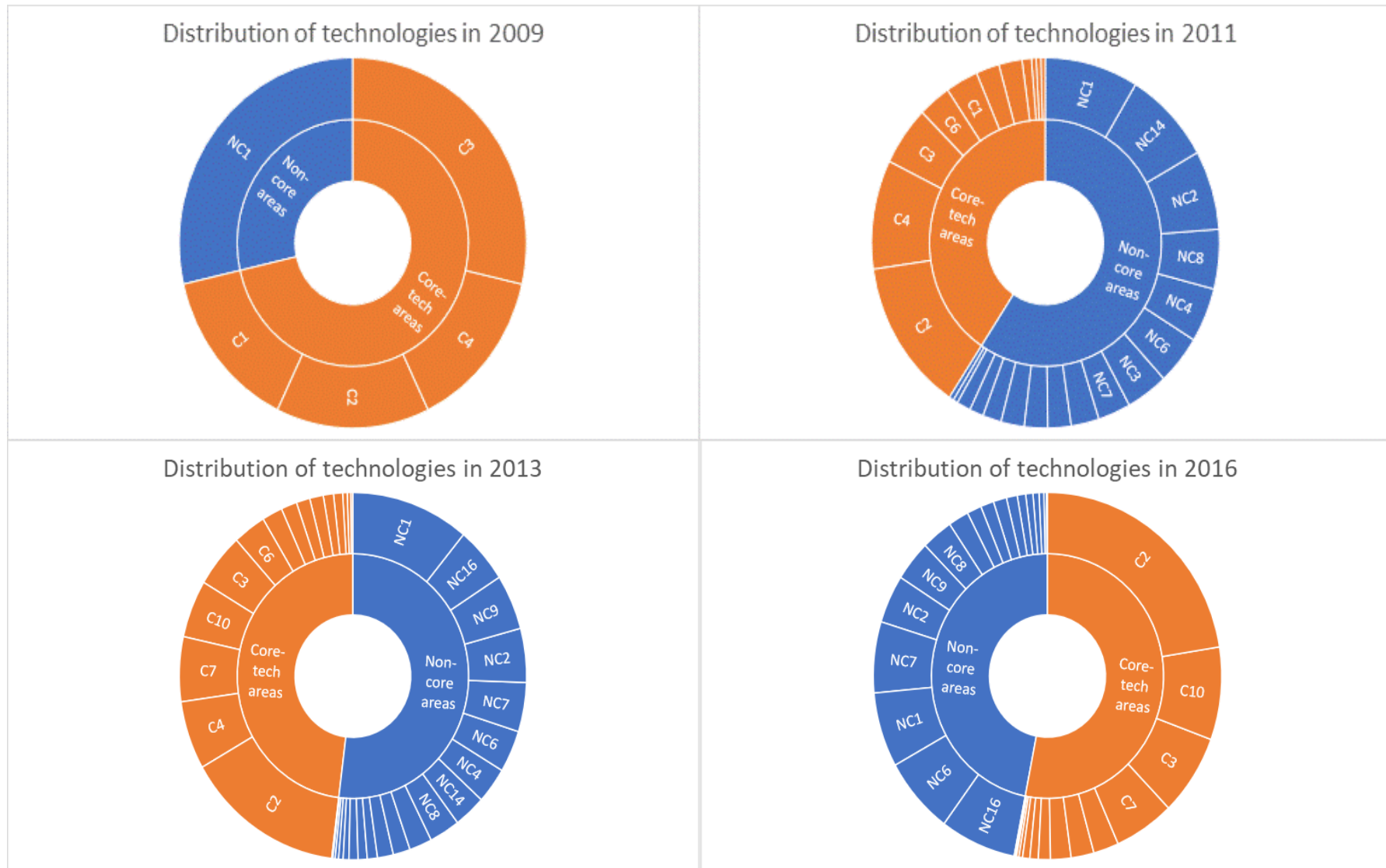
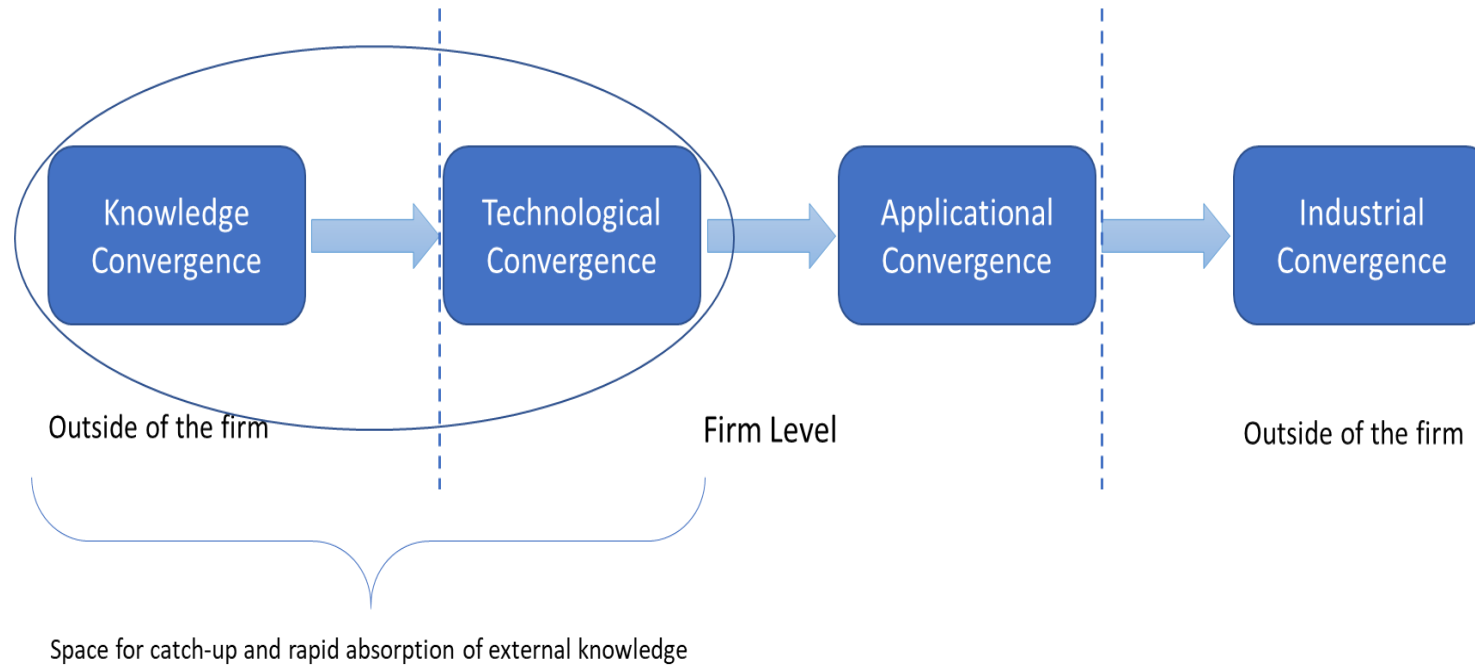


Figure 4. Collaboration within/beyond SSI and industrial convergence



Source: authors' illustration based on Hecklin et al. (2009)