THE LONDON SCHOOL OF ECONOMICS AND POLITICAL SCIENCE

Essays on Outward Foreign Direct Investment and Technological Innovation

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July 2021

A thesis submitted to the Department of Geography and Environment of the London School of Economics and Political Science for the degree of Doctor of Philosophy

Declaration

I certify that the thesis I have presented for examination for the PhD degree of the London School of Economics and Political Science is solely my own work.

I warrant that this authorisation does not, to the best of my belief, infringe the rights of any third party.

I declare that this thesis consists of 58,307 words.

Statement of conjoint work

The fourth chapter "The Material Basis of Modern Technologies - A Case Study on Rare Metals" is co-authored with Simona Iammarino and Andrea Ascani. My contribution is 50% of the total work.

George Yunxiong Li

July 13, 2021

Abstract

This thesis studies outward foreign direct investment (OFDI) of Chinese multinational enterprises (CMNEs) and technological innovation. The first three chapters explore how home country contexts influence OFDI decisions, strategies and post investment performance. Chapter 1 develops a "three internationalization advantages" framework in which CMNEs invest abroad not only on the basis of firm-specific advantages (FSA) but also on state-created and network-based advantages which can make up for the shortage of FSA. The necessary condition for the OFDI of Chinese firms is "relative FSA" over domestic competitors, to get access to state-created and network-based advantages. Chapter 2 combines the local-global connectivity literature with host location choice studies to explain the location strategies of CMNEs. Firms originating from different subnational home regions (31 Chinese provinces), show heterogenous spatial patterns in global expansion patterns, which can be partly attributed to prior connectivity between home regions and foreign countries. Export, patent co-invention activities as well as the "friendship city" relationship facilitate OFDI, and such an influence differs across investment motives. Chapter 3 focuses on post-OFDI innovation performance of CMNEs and the influence of inward FDI (IFDI). Using quasi-experimental models, empirical results indicate that OFDI has a significant impact on their subsequent innovation performance, which is affected by Chinese firms' prior within- and between-firm interactions with IFDI and also moderated by the country of origin of the IFDI. Chapter 4 focuses on technological dynamics and rare metals (RMs). Through text mining 5,214,307 USPTO granted patents over the period 1976-2015, we found that RMs work as an important material basis for modern technologies. At the level of technology subgroups, increases in the supply of a certain RM significantly boost the innovation output of technology areas which rely heavily on this RM.

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Acknowledgements

I would like to express my deepest gratitude to Simona Iammarino and Riccardo Crescenzi for outstanding supervision in the last four years. Without their guidance, I would not be able to complete my PhD studies. My supervisors have devoted a lot of time and effort to me and guided me in every step of my PhD studies, from finding research topics to building theoretical frameworks to learning empirical methods and even academic English writing. Their patience and enlightenment continuously give me the courage to think, to try and to face challenges. In addition to research, the encouragement from my supervisors helped me to adapt to life in the UK and go through the long and difficult time of the pandemic.

Thanks to Olmo Silva, Felipe Carozzi and Gabriel Ahlfeldt for their insightful suggestions in the Economic Geography work-in-progress seminar at LSE. I also would like to thank Davide Castellani, Lucia Piscitello and Jana Oslejova for organizing the PhD master class at Henley Business School, which has provided good opportunities for me to learn and communicate with many excellent scholars.

Last but not least, I thank my beloved families and friends for their support. I also thank the Chinese Scholarship Council for sponsoring all my tuition fee and living cost in the UK.

Introduction

This thesis focuses on outward foreign direct investment (OFDI) of Chinese multinational enterprises (CMNEs), and technological innovation. With unique internationalization advantages, Chinese firms have been rapidly expanding globally particularly over the last two decades. The rise of Chinese OFDI has attracted growing attention from different disciplines, including economic geography, international business and management, and international economics (e.g. Buckley et al. 2007; Li & Liu et al., 2017; Ascani & Iammarino, 2020; Ren & Yang, 2020; Crescenzi & Limodio, 2021). On the one hand, CMNEs are representative of some common characteristics of multinationals from emerging markets (EMNEs). On the other hand, due to the unique economic and institutional conditions of their home country, CMNEs show distinctive patterns in terms of their OFDI decisions, strategies, and post-investment performance (e.g. Quer et al., 2012; Lattemann et al., 2017; Ramamurti & Hillemann, 2018). Studying Chinese OFDI deepens our understanding of China's more proactive participation in globalization processes and the subsequent industrial, technological and institutional impacts on both China and the rest of the world. At the same time, it also helps expanding existing theories by interpreting how late mover firms from emerging markets globalize, evolve and catch up with incumbent MNEs.

This thesis is composed of 4 chapters: the first is a conceptual elaboration on Chinese OFDI, the following two chapters present empirical applications on the same broad theme, whilst the fourth chapter explores a different but complementary topic, focusing on the relationship between technological progress and availability of technology-critical natural resources.

Chapter 1 develops a "three internationalization advantages" framework to study Chinese OFDI. CMNEs invest abroad not only on the basis of firm-specific advantages (FSA) but also on state-created and network-based advantages which can make up for the shortage of FSA. Using this framework, this chapter attempts to critically review the extensive literature in this research field to contribute to our understanding of the strategies and choices made by EMNEs, and particularly CMNEs. The heterogeneity of CMNEs, their diversified OFDI behaviours and evolution trajectories are explained by different combination modes of the three internationalization advantages. This chapter provides a new interpretation of the unique internationalization process of CMNEs: unlike MNEs from developed countries (DMNEs) which have strong and established FSAs over global competitors, Chinese firms need "relative FSAs" over domestic competitors to get access to state-created and network-based advantages to internationalize.

Chapter 2 combines the local-global connectivity literature with host location choice studies to explain the location strategies of CMNEs. I argue that prior connectivity of a subnational home region with foreign countries influences the spatial behaviours of MNEs originating from it. This connectivity is measured with respect to three dimensions: international trade connectivity through exports and imports; innovation connectivity through patent co-invention activities; and social connectivity through international "friendship city" (city twinning) relationships. Chinese provinces have heterogenous patterns of global connectivity and, at the same time, MNEs originating from each province show significantly different destination preferences. Econometric models show that patent co-invention activities as well as the "friendship city" relationship facilitate OFDI, while the effect of international trade is ambiguous. This study contributes to further understanding the important role played by the subnational home location in explaining firms' internationalization behaviours: the advantages of a region or city not only depend on its own resources but also on how it is connected with other places and its position in the global network.

Chapter 3 focuses on innovation performance of CMNEs and the influence of inward FDI (IFDI). Since the 1990s, large-scale FDI inflows into China have been followed by accelerating outward FDI (OFDI) of Chinese MNEs. This two-way investment brings unique opportunities for Chinese firms to learn new technologies. However, the interaction between these two learning channels has been underexplored. This study uses quasi-experimental models to test the causal effect of OFDI on the innovation performance of Chinese firms, with particular emphasis on the influence of IFDI. Propensity Score Matching (PSM) and Difference-in-Difference (DID) approaches are combined to address endogeneity issues. Empirical results indicate that OFDI has a significant impact on their subsequent innovation performance, and this impact is long lasting and gradually increasing. This OFDI-led innovation gain is found to be significantly influenced by Chinese firms' prior within-firm and between-firm interactions with IFDI. Chinese firms with foreign equity participation or co-locating with intensive IFDI obtain higher innovation benefits in their subsequent OFDI. Moreover, this influence shows significant "country-of-origin effect" — IFDI originated from a certain country has a particularly strong influence if Chinese firms invest in that same country. Our findings indicate that inward and outward FDI interplay with each other and jointly shape the innovation path of CMNEs.

In addition to the studies on Chinese OFDI, Chapter 4 presents an original and exploratory research on technological dynamics and rare metals (RMs). Because of their unique technological properties, a wide range of RMs is crucially important in achieving the functionality of high-tech products and modern technologies. By text mining 5,214,307 USPTO patent summary texts during the period 1976-2015, this chapter systematically studies the technological dependence on 13 critical rare metals, with the aim of exploring the link between critical natural resources and frontier technological innovation. We found that RMs have grown in their importance as material basis for modern technologies. Moreover, the dependence degree varies significantly across technological areas, metal types and analysis levels, and it is particularly high for some emerging technologies such as semiconductors, nanotechnology, macromolecular and green energy technologies. Further, we use a panel of 2,187 technology-metal pairs over four decades to assess the impact of metal supply on innovation dynamics. The endogeneity is addressed through identifying the exogenous shocks on rare metal production from the metal companionability with the base metals. At the IPC technological subgroup level, increases in the supply of a certain RM significantly boosts the innovation output of technologies based on it. Using the case of rare metals, this study contributes to the classic debate on the driving forces of technological change by providing a broader understanding of how innovation dynamics are shaped by the availability of natural resources with technological criticality.

This thesis contributes to the literature in various aspects. As shown in first three chapters, the originality of my study on Chinese OFDI comes from the following aspects. First, from the economic geography perspective, this thesis highlights the important role of "geographical location" in explaining CMNEs' behaviours. I set off by reflecting in depth on the advantages derived from the home country in the case of Chinese firms (Chapter 1), highlighting the crucial role of the home market for CMNEs. This thesis then goes down to the subnational level and analyses how the home region conditions shape CMNEs' internationalization strategies (Chapter 2) as well as the post-investment performance (Chapter 3). At the same time, I regard locations intertwined in interdependent spatial networks — location advantages are structured by connectivity, as shown by trade, innovation and social networks in Chapter 2, and by the "country-of-origin" effect of FDI in Chapter 3. Second, this thesis highlights the relevance of a dynamic and evolutionary perspective in interpreting CMNEs. Chapter 1 analyses different evolutionary trajectories of the CMNEs in changing domestic and international environments; Chapter 2 focuses on how different dimensions of global connectivity interact and evolve out of previous ones; Chapter 3 focuses on China's transition between two internationalization stages—from receiving IFDI to conducting OFDI, which embodies the evolution process of Chinese firms from passive internationalization as suppliers or contractors, to actively building their own value chains as global lead firms. Third, considering the diversified characteristics of Chinese firms and the huge scale of the China's economy, this thesis recognizes the importance of heterogeneity in interpreting CMNEs. In Chapter 1, CMNE heterogeneity is conceptualized as the diverse combinations of internationalization advantages. Chapter 2 considers the regions of origin within China to consider the heterogeneity of home country advantages; the third chapter focusses on CMNEs' heterogenous exposure to IFDI, distinguishing the different channels impacting the post-investment performance.

Furthermore, Chapter 3 and 4 analyse patent data and attempt to contribute to studies on technological change and innovation dynamics. The former focuses on firm-level innovation, explaining how two-way FDI shapes the innovation trajectory of Chinese firms. International economics and international business literature have discussed the spillover effect of inward FDI (e.g. Wei & Liu, 2006; Wei & Liu & Wang, 2012; Lu et al., 2017), as well as the strategic seeking OFDI of EMNEs (e.g. Luo, 2007; Li et al., 2012, 2017), however it is less clear how do these two-way investments interact with each other and jointly influence firm's innovation capabilities. Chapter 4 explores how innovation dynamics of the human society is influenced by the global supply of natural resources, providing a complementary and crucially important aspect of technological progress. The fundamental driving forces of innovation have been explained by the "technology push" from scientific development, "demand pull" from the end market as well as policy intervention (Mowery & Rosenberg, 1979; Martin, 2012), while the influence of natural resource supply has been largely ignored. As a special group of resources, rare metals are widely used in specialized fast-growing technology areas which can be identified by patent text mining, enabling us to fill in this research gap. This explorative work helps to understand the importance of the value chain within which innovation happens. In the current stage, Chapter 4 on rare metals is independent from the first three chapters on OFDI: however, it is my intention to pursue further the strong potential of linking these two research topics in future studies. For example, it is extremely relevant (and underexplored) to study how MNEs, especially CMNEs, organize their global RM supply chain, or how large high-tech MNEs, the major owners of RM-based technologies, react to the RM supply dynamics.

To test the research hypotheses, this thesis combines quantitative and qualitative methods and also adopts text mining and network analysis techniques. In Chapter 1, I attempt to build the theoretical framework to integrate literature and classify CMNEs using firm cases. Chapter 2-4 adopt econometrics models, including propensity score matching, difference-in-difference and instrument variable estimation to address endogeneity with the aim of understanding the causality between variables, such as OFDI's impacts on innovation performance, as well as the influence of resource supplies on innovation dynamics. I remain fully aware of the limitations of the thesis, which are also due to data availability. I discuss them in detail, both in each individual chapter and in the Conclusion.

Chapter 1. Research Framework and Literature Review on Chinese OFDI: Internationalization Advantages, Heterogeneity and Evolution

1.1 Introduction

Since the Opening Policy in 1978, China has begun an enduring development and globalization process. After 30 years' sustainable growth, it is already the second largest economy in the world by GDP (the largest by purchasing power), the largest exporter, the second largest importer and FDI recipient (World Bank, 2020). Chinese firms started to invest abroad on a large scale since 2000. OFDI flows increased exponentially and peaked in 2016 with USD 136.91 billion, turning China into the world's second-largest source of FDI, accounting for 13% of global out flows (OECD, 2020). Against this backdrop, the OFDI from Chinese multinational enterprises has attracted wide attention from the academia.

CMNEs are found to challenge the existing IB theories. A question at the core of this discussion is "what advantages make CMNEs invest abroad?". Traditional IB theories based on DMNEs explain OFDI on the basis of firm specific advantages (FSA) or ownership advantages (Dunning, 1988), which are derived from the monopoly advantages (Bain, 1956; Hymer, 1960) of owning valuable, exclusive and non-substitutable resources (Barney, 1991). Those advantages help to conquer the "liability of foreignness" and help MNEs to outperform competitors in foreign markets. However, MNEs from emerging economies (EMNEs), and CMNEs in particular, seem to contradict this argument – as late comers they lack conventional ownership advantages such as advanced technologies, management experience, global brands, but still invest abroad. Besides, compared with DMNEs or other EMNEs, CMNEs have different internationalization behaviours. They prefer to enter risky and distant markets countries (Buckley et al. 2007; Quer et al., 2012; Ramamurti, 2012), internationalize at high speed rather than gradually from near countries to distant ones, as depicted by the Uppsala model (Deng, 2009; Peng, 2012; Cui, Meyer, & Hu, 2014). Moreover, CMNEs are found to entry through high-commitment modes, especially mergers and acquisitions (M&A)

(Deng, 2007, 2009; Peng, 2012)

The distinct characteristics of CMNEs have been explained in wide number of studies. Some scholars argue that CMNEs have unconventional FSAs, which have been largely overlooked by existing theories (Ramamurti & Singh, 2009; Verbeke & Kano, 2015). Another explanation is that CMNEs, although lacking FSA, have strong country-specific advantages (CSA) at home, such as institutional supports, cheap labour, capital sources or access to natural resources (Rugman & Li, 2007; Cuervo-Cazurra, 2008; Dunning, 2008; Rugman, 2009). Other theories, such as the "linkage-leverage-learning" (LLL) model by Mathews (2002) and the springboard perspective by Luo & Tung (2007), argue that CMNEs invest abroad for exploring new advantages through external networks, rather than exploiting existing ones. Moreover, some recent literature adopts a dynamic view and argue that the characteristics of CMNEs are due to the early internationalization stage. As time goes by, CMNEs are rapidly accumulating their own FSAs and evolving to be mature MNEs (e.g. Narula, 2012; Casanova & Miroux, 2016; Ramamurti & Hillemann, 2018). As the result of different international advantages, institutional supports, external linkages as well the early internationalization stages, CMNEs have unconventional strategies, speeds and entry modes in their OFDI. These studies have provided various explanations to Chinese OFDI on the grounds of different theoretical foundations and at different levels of analysis.

Some recent theoretical and empirical studies build integrated frameworks to better understand Chinese OFDI. For example, Wang et al. (2012) and Lattemann et al. (2017) integrate different theories, including the resource-based view (RBV), institutional-based view, industrial organization theory and network-based approach in multilevel "firm-industry-country" frameworks to explain the investment motivation and location choice of CMNEs. In line with existing studies, my paper uses a dynamic three internationalization advantages framework ("3 IAs") within which Chinese MNEs invest abroad not only on the basis of FSAs but also on state-created and network-based advantages that work as facilitators for MNEs which lack sufficient assets to go abroad. The sources and effects of the 3 IAs are analysed in detail in the following section. Under this framework, the heterogeneity and evolution of Chinese OFDI are explained according to different combination modes of the 3 advantages which both support and constraints CMNEs in every aspect of their OFDI activities, including investment decisions, location choice, entry mode and post-investment performance.

This paper seeks to make the following contributions to the literature. First, through a critical literature review, I use the “3 IA” framework to link and reorganize the extensive studies on Chinese OFDI which are fragmented or even seemingly conflicting to each other. By doing so, I try to show a thorough picture of the current knowledge about Chinese OFDI and CMNEs. Second, this paper focuses not only on the three international advantages themselves but also on the underpinning interactions among them in different internationalization stages. I further analyse how the dynamic combinations of “3 IAs” determine the heterogenous OFDI strategies and evolution trajectories of CMNEs. By doing so, I intend contribute to further understanding the complexity of Chinese OFDI and CMNE by cross-fertilizing different streams of theories.

1.2 Research framework - three international advantages of Chinese MNEs

The starting point of this study is the composition of international advantages of CMNEs. Following exiting studies (Wang et al., 2012; Lattemann et al., 2017), I adopt a three-dimension framework arguing that, in addition to FSA, the home country endows CMNEs with two important facilitators, state-created advantages and network-based advantages. Elements of Chinese MNEs’ ownership advantages are shown in Table 1-1.

Table 1-1. The composition of international advantages of CMNEs

International advantages	Theorical foundations	Factors
Firm-specific advantages	Resource-based view; Monopoly advantages	Capital accumulation and technology upgrading Previous international experience
State-created advantages	Institutional-base view; State capitalism	Financial, diplomatic support, Domestic protectionism
Network-based advantages	Network-based view; Linkage-Leverage-Learning	Domestic networks through industrial agglomeration, business groups Foreign networks through inward FDI connections

1.2.1 Firm-specific advantages

FSAs are the features and resources a firm has on its own, such as technological capabilities, innovative designs, management practises or prior experience. Existing studies prove that CMNEs have accumulated conventional FSAs facilitating their internationalization. First, firm's financial performance is one important determinant of OFDI (Radlo, 2012). A suitable liquidity situation increases firms' tolerance for uncertainty during internationalization (Meyer & Xia, 2012). Chinese firms accumulate capital in the domestic market and also through continuous exports. The trade surplus of China reached up to 510 billion dollars in 2016 (Chinese Customs, 2017), and this capital accumulation has been further enhanced by the appreciation of the RMB (Sauvant & Davies, 2010), making it more financially feasible to invest abroad. This situation was further amplified by the 2008 financial crisis, when firms in developed countries met financial stringency (Yang & Stoltenberg, 2014), which made Chinese firms aggressively seek strategic assets through M&A. Empirical studies prove that Chinese firms with better domestic financial assets have greater propensity to internationalize (Driffield et al., 2021), and this is true especially for privately owned enterprises (POEs) who have less access to financial support from the national banking system than state-owned enterprises (SOEs) (Driffield et al., 2021).

Second, technological capabilities are crucially important for internationalization, not only providing monopoly advantages in the global competition but also increasing the learning capability after strategic assets-seeking investments. Technologies of Chinese firms have been improved significantly in the last few decades due to increasing R&D investment and inward FDI spillovers (Liu & Wang, 2003; Zhang et al., 2003). For example, the firm-level total factor productivity (TFP) is found to have increased at an annual rate of 7.96% between 1998-2007 (Brandt, 2012). Wei et al. (2014) argue that this technology capability improvement significantly affects both the OFDI decision and investment volume of Chinese firms.

Moreover, a firm's prior experience helps its OFDI (Liu, 2008). Substantial export experience enhances CMNEs' technology capability through "learning by exporting"; on the other hand, it brings information about market demand, policies, and institutional environment (Pradhan, 2004), thus exporting firms are more likely to invest abroad and on a large scale (Gao, 2010; Wei et al., 2014). The experience of operating in China equips them with the adaptability to environments with institutional voids (Buckley et al., 2007). Besides, some scholars also believe CMNEs have others unconventional advantages, such as the price leadership — the ability to make products and services at low costs — and a better understanding of their customer needs (Madhok & Keyhani, 2012; Lattemann et al., 2017).

1.2.2 Network-based advantages

The network-based ownership advantages come from the linkages to other firms in the business network. Like other developing and emerging countries, social networks are often complementary to legal institutions in China (Park & Luo, 2001). Studies recognize Chinese firms have been successfully using social networks and social capital to achieve organizational goals and improve performance. Networks lower the transactional costs and bring better access to crucial resources, such as finance, technologies and human resources (e.g. Standifird & Marshall, 2000; Park & Luo 2001). These social capital and networks also help them to participate in OFDI. The literature has highlighted different kinds of networks within which Chinese firms are embedded: business groups, local industrial clusters, and linkages to foreign firms in China.

The network with other Chinese firms is an important facilitator of Chinese OFDI. First, similar to firms from other emerging countries, Chinese firms operate in business groups (Khanna & Rivkin, 2001), within which member firms work together to create internal markets and share risk, to deal with the difficulties in raising money in the Chinese stated-owned financial system and other imperfect environments such as the lack of sound intellectual property regulations (He et al., 2013). Business group members collectively share the high costs of OFDI and enable some members to invest abroad. In return, other members may get access to advanced foreign assets indirectly through frequent information sharing and resource exchange with the investors (Chen & Yang, 2017). Secondly, local industrial clusters help to improve the efficiency and competitiveness of Chinese firms (Lin, 2011; Hu, 2015). Some large clusters, such as industrial parks and export processing zones, are fostered by the Chinese government, while smaller ones are built on kinship or local social ties. Through spatial proximity, Chinese firms obtain agglomeration externalities and build up demand-supply networks, knowledge learning networks and technological relatedness networks (Tveteras, 2006; Howell, 2016; Poncet, 2013). Many cluster firms work in the same or related value chains and have strong capacity to operate interdependently and interactively in a flexible production model (Zeng & Williamson, 2003). Currently, these business ties help them in OFDI — many Chinese firms, especially small and medium-sized firms, go abroad in groups and build collaboration networks abroad (Yao, 2009). Moreover, this collective OFDI mode has been coordinated by the government through investment contracts with foreign governments. Some major SOEs or lead POEs also actively provide platforms and share overseas information and resources with other local firms.

Another network-based advantage relies on the relationships with foreign MNEs. China has received large inflows of foreign investments before CMNEs started to invest abroad. Some foreign investors are successful global MNEs who have networks within China and have deep interactions with local firms. Linkages with inward FDI help to improve FSAs, such as resource endowments, access to information, managerial and organizational skills of Chinese firms before they internationalize. Moreover, Chinese firms have built up strong long-term cooperation and trust links with incumbent DMNEs through OEM and supply-demand linkages (Mathews, 2006). CMNEs have been found to duplicate these relationships to foreign locations and internationalize by following the DMNEs in partnership. For example, the global expansion of Fuyao, the largest Chinese automobile glass producer, follows Volkswagen whose Chinese subsidiary has long term collaboration with it (Hertenstein, 2017). Moreover, some CMNEs even (partially) acquired foreign firms which used to be their OEM leaders or partners in China, such as Lenovo with IBM, BOE with Philips (Deng, 2009). Prior partnership with target firms enables CMNEs to clearly evaluate the value of acquisition targets (Deng, 2009; Klossek et al., 2012).

1.2.3 State-created advantages

Under the state capitalism model, the government plays a dominant role in the Chinese economic development. A serial of plans and policies have been implemented aiming at economic growth, employment increase and technology catch-up (Wu et al., 2019). The OFDI of CMNEs is also regarded as “an intrinsic part of state capitalism of China” (Clegg & Voss, 2018. p.4). Most studies adopted an institutional fostering perspective, arguing that Chinese OFDI is facilitated by the government involvement, resulting in state-created advantages.

Some CMNEs, especially those in strategic sectors receive subsidies, tax reduction or low-interest loans from the national-owned banking systems (Cooke, 2012; De Beule et al., 2018). They also face lower liability of foreignness in host countries with friendly diplomatic relationship with China (Duanmu, 2014). Moreover, the Chinese government has launched a series of foreign aids or collaboration projects with foreign countries, providing platforms for CMNEs. For example, the Belt and Road Initiative between China and other Eurasia and Africa countries has expanded Chinese OFDI and exports （Ramamurti & Hillemann, 2018). In those projects, CMNEs, especially the stated-owned ones, have priority to win the contacts of infrastructure building and natural resource exploitation (Zhang & Smith, 2017).

One important but largely overlooked aspect of the state-created advantages is the government’s protectionism toward indigenous Chinese firms in Chinese market. DMNEs, on the other hand, have less access to China’s country-specific advantages due to various market barriers before and after entry (Bhaumik et al., 2016). First, foreign investors are not allowed to invest or hold the major share in sensitive sectors related to the national security, natural resource, and strategic industries (National Development and Reform Commission, 2017), such as Facebook and Google being banned in China. Second, some investors also face restrictions in entry mode choice. Automobile firms can only establish joint venture companies with SOEs and share their technologies (Wang, 2003; Nam, 2011), that is the so-called “exchange market for technology” mode. After entry, foreign firms face strict regulations, curbing their expansion, such as the strict antitrust laws preventing foreign firms from acquiring Chinese domestic firms in certain sectors (Horton, 2016). Moreover, the incomplete intellectual property right protections cause the risk of technology leakage, making foreign firms reluctant to transfer advanced technologies from parent firms. The barriers above help Chinese indigenous firms to control domestic markets through scale economies: CMNEs thus have strong incentives to acquire assets abroad. On the other hand, foreign firms may prefer to sell or franchise strategic assets to CMNEs due to difficulties of direct exploitation in the Chinese market.

It is important to note that firms do not benefit equally from state-created advantages, which depends on the distance to the government. Companies closest to the government are SOEs directly owned by the central government (central SOEs), whose governors are also senior officers of the Chinese Communist Party. The second-tier firms are the SOEs affiliated to the provincial governments and the large private-owned national champions which are often in the strategic and emerging sectors (Lattemann et al., 2017), such as Huawei and Geely. They establish various connections with the central and local governments and have long been supported by a series of preferential policies domestically. The farthest are small-medium private companies which have no political ties and fail to be chosen as star firms. This institutional distance determines whether and to what extent a firm is supported by the state. Compared with POEs, SOEs have privileged access to strategic political and financial resources for OFDI (Sutherland & Ning, 2011). Within SOEs, affiliation to a higher-level government means more preferential support, which significantly influences the OFDI willingness and strategies (Wang et al., 2012; Li, 2018).

Moreover, the state-created advantages change with the OFDI-related regulations. During the 1980s-1990s, the main objective of OFDI was to promote exports of state-owned manufactures and meet the natural resource demands in China (Lu, 2002; Sauvant, 2005): only SOE were allowed to invest abroad. Since the "Going abroad" policy in 2003, POEs have also been encouraged to invest abroad in order to seek technologies, brands in developed countries and enhance Chinese firms' competitiveness (Child & Rodrigues, 2005). In recent years, the policy makers started to give priority to investments along the Belt and Road, as a result, the OFDI share in these countries has increased significantly (MOFOOC, 2017).

1.2.4 The relationship between FSA, state-created and network-based advantages

FSAs have strong interdependency with the other two additional advantages. Before OFDI, FSAs are shaped by the institutional environment and business networks in which firms are embedded. More importantly, although the FSAs of CMNE are not enough to compete with the incumbent DMNEs in the global market, a basic level of FSAs is still crucial for CMNEs to get access to state-created and network-based advantages for OFDI.

First, under the state capitalism development model, the Chinese government uses a "picking the winner" strategy to promote indigenous technological capabilities (Stiglitz et al., 2013). Empirical studies on Chinese industrial policy found that firms with larger scales, higher sale growth and labour productivity are more likely to receive government subsidies (Howell, 2017). Leading firms are often chosen to be "national champions" and then blessed with various forms of support. This selection further widens FSA gaps with their domestic peers, for instance in terms of technological capabilities (Guo et al., 2016), which make them more likely to conduct OFDI. Similarly, in order to access the network-based advantages through building connections with foreign firms or domestic lead firms, Chinese firms need a certain level of FSAs to outperform other domestic peers in the selection to become suppliers or contractors (Zhang et al., 2019).

Second, as discussed, the huge and rapidly growing domestic market gives CMNEs financial capabilities and incentives to bear the high costs of investment abroad. Empirical results find CMNEs do have certain level of FSA to achieve this through outperforming non-MNE domestic firms and the foreign investors in China (Bhaumik et al., 2016). The basic FSA gives some CMNEs monopoly advantages and help to accumulate the initial capital in the consequent OFDI. On the contrary, DMNEs are subject to significant liability of foreignness and cannot equally leverage CSA in China (Hennart, 2012; Hertenstein, 2017).

In summary, the additional advantages from the state and business networks make the prerequisites for OFDI differ between CMNEs and DMNEs. DMNEs' internationalization requires "absolute" FSA to compete with other global competitors, while CMNEs' OFDI only needs "relative" FSA over their peer firms to obtain state supports, network connections and home market control.

1.3 Literature review and integration under the “3 IAs” framework

Next, I review the literature on Chinese OFDI and analyse how it is shaped by the three international advantages. Following existing studies (Deng, 2012), this review covers three major aspects of Chinese firms’ internationalization, 1. antecedents (investment prerequisites) which have been mainly discussed in the last session; 2. the international processes (location choice, investment motivation, entry mode and post-acquisition) and 3. outcomes (post-OFDI performance). The aim of this literature review is not to cover all studies on Chinese OFDI but to use the representative ones to provide an integrated picture using the “3 IAs” framework. In this way, I attempt to exhibit a clearer structure for the extensive and highly diversified literature in this research area. The representative literature and their findings are listed in Table 1-2.

Table 1-2. Integration of literature on CMNE under the "3 IAs" framework

Chinese OFDI	Firm-specific advantages	State-created advantages	Network-based advantages	Other home country factors
Investment Decision	The OFDI decision is facilitated by: Better financial situations (Driffield et al., 2021), Previous investment Experience (Lu et al., 2011), Productivity, technological capability (Wei et al., 2014), Export experience (Pradhan, 2004; Liu, 2008), Human resources (Wang et al., 2012)	Industry policy encouragement (Lu et al., 2011), SOE invest less (Cui & Jiang, 2012), SOEs are more likely to invest (Wang et al., 2012), The level of government affiliated (Wang et al., 2012)	Domestic networks: Industry association (Wei, 2014), CMNEs follow domestic peers in related and unrelated sectors (De Beule et al., 2018), Linkages with Inward FDI (Deng, 2009; Klossek et al., 2012)	Home region marketization, IPC protection (Wei, 2014), Domestic industry competition (Wang et al., 2012), Escaping from home country with unfavorable institutional environment (Shi et al., 2017)
Location choice & Investment Motivation	Domestic experience lowers sensitivity to institutional voids (Buckley et al. 2008, Morck et al. 2008), Follow-up investment by using the prior internationalization experience (Lu et al., 2014), Technology- advantages with strategic asset seeking (Lu et al., 2011)	SOEs are less sensitive to risks (Duanmu, 2012), SOEs prefer resource OFDI (Amighini et al., 2013), Government preference and BRI influence location choice (Lu et al., 2014; Shao, 2020)	Follow domestic peers in a herd mode (De Beule et al., 2018; Jiang et al, 2020), Follow foreign IFDI partners (Hertenstein, 2017), JV experience facilities assets seeking investment (Deng, 2009)	Seeking host locations with complementary advantages to home country (Deng, 2004; Luo & Tung, 2007, Kolstad & Wiig, 2012), Psychological, social and cultural cross-national distance influence location choice (Yin & Bao. 2006; Blomkvist & Drogendijk, 2013)
Entry mode	Asset limitation makes CMNE prefer M&A rather than greenfield investment (Liu & Buck, 2009), Firm with more international experience prefer risky entry mode (Tao et al., 2017; Alon et al., 2020), The inverted U shape between age and high-equity entry (Xie, 2017)	SOEs with high risk tolerance prefer acquisition (Williamson & Zeng, 2007; Warner et al., 2004), SOE use M&A to enhance national pride and images (Tao et al.,2013)	CMNEs with IFDI collaboration prefer M&A and high control degrees (Tao et al.,2013), Previous JV experience leads to path dependence (Deng, 2009; Xie, 2017)	Larger cross-national economic distance increases JV tendency (Tao et al., 2013), Cultural distance has no significant effect (Rienda et al., 2012)
Post-acquisition integration	"Light-touch" mode due to the lagging positions of Chinese acquirors (Schueler-Zhou & Schueller, 2013)	SOEs' larger organizational distance with overseas subsidiaries hinders integration (Liu & Woywode, 2013)	Previous ties with acquisition target lead to effective integration (Deng, 2009; Klossek, et al., 2012)	Management practice difference (Schueler-Zhou & Schueller, 2013), Chinese culture: long-term orientation, non-subjugation traditions (Liu & Woywode, 2013; Marchand, 2017)
Post-OFDI performance	Country-bound FSA lowers overseas performance (Rugman, 2017), Absorptive capabilities increase innovation gains (Fu et al., 2018; Elia et al., 2020)	SOEs have higher long-term profitability after investment (Tu, 2021), Political ties of headquarter hampers the knowledge transfer from subsidiary (Su & Kong, 2020)	Domestic business ties lead to higher innovation gains (Cheng & Yang,2017), Inward FDI spillovers substitute strategic assets seeking OFDI (Li et al, 2012).	OFDI innovation gains increase with cultural and formal distance to the home country (Elia et al., 2020), increase with absorptive capabilities in home regions but decrease with competition intensity (Li et al, 2016)

1.3.1 Location choice and investment motives

Most of the studies on Chinese MNEs during the period between 2000 and 2010 focus on the location choice behaviour and use it to infer the investment motives according to the classification of Dunning (1993)—market seeking, resource seeking, strategic asset seeking and efficiency-seeking. There is abundant evidence confirming that CMNEs also have strong market-seeking motivation (e.g. Cheung & Qian, 2008; Pradhan, 2009; Sanfilippo, 2010). It is also verified that Chinese OFDI prefers to locate in countries with abundant nature resources. In line with the springboard perspective, it is found that human capital, R&D endowment, famous brands, etc., significantly attract CMNEs, especially those investing in developed countries (Buckley et al., 2007; Kolstad & Wiig, 2010). However, scholars have not found support for the last motive – efficiency-seeking – because cost reduction is not a major concern for CMNEs (Cheng et al. 2007). These findings indicate that CMNEs prefer host countries with location advantages which are complementary to the home country advantages, where a large manufacturing sector requires market expansion, extensive natural resource supply, and technology improvement through OFDI. The spatial rationales would vary with time due to changes in the economic structure and production factor prices, as for example the increasing labour costs which accelerates OFDI into India, ASEAN countries and Africa to relocate some low-end manufacturing sectors (Miniesy et al., 2015; Yan & Enderwick, 2021). Other studies focus on how different dimensions of cross-national distance influence the liability of foreignness and matter for their location choice. It has been found that Chinese OFDI depends on ethics ties of Chinese diasporas, close historical, cultural and trade ties to control risks (Quer et al., 2012; Blomkvist & Drogendijk, 2013; Karreman, 2017)

The location rationales are also found to be directly influenced or indirectly moderated by the three dimensions of IAs. First for FSA, prior internationalization experience endows firms with knowledge and capabilities specific to particular locations. CMNEs are found have advantages in dealing with institutional voids from their domestic experience and are less sensitive to incomplete host institutional environments (Buckley et al. 2008, Morck et al. 2008). In addition, as in the case of DMNEs, CMNEs also follow up previous investments in the same destinations (Lu et al., 2014), which emphasises the importance of experimental experience.

On the other hand, it is also found the state-created advantages may alter the location choice rationales: CMNEs' less sensitivity to the unstable environments is attribute to the protection of government (Duanmu, 2012), and especially SOEs are more likely to engage in natural resource investments compared with private-owned ones (Amighini et al., 2013). Moreover, the Chinese government adjusts the spatial distribution of Chinese OFDI by regularly issuing a list of countries to encourage CMNEs to invest in, which is followed by a series of support tools, including platforms for country specific information, diplomatic supports, favourable exchange rates and taxation reduction (Luo et al., 2010). This institutional preference, together with the recent Belt and Road Initiative, have significantly influenced location choices (Lu, et al., 2014; Shao, 2020). Moreover, the OFDI location choice is also influenced by network-based advantages: CMNEs without international experience are found to choose foreign countries by following domestic peers in a herd effect (De Beule, 2018), and also follow the overseas locations of inward FDI partners to lower the liability of foreignness (Hertenstein et al., 2015).

1.3.2 Entry mode choice

Another stream of literature focuses on CMNEs' entry mode choice in foreign countries. A major determinant is the limited FSA — CMNCs are subject to constrains of internal assets and are not likely to transfer existing advantages of parent firms and enter host country through greenfield investments. On the contrary, the lagging position pushes them to aggressively expand globally through acquisitions and mergers in order to rapidly obtain control over strategic assets and exploit them back in the home market (Liu & Buck, 2009). Moreover, different FSA levels determine the commitment degree in entry mode choice. High commitment modes like M&A involves high level of risk and are adopted generally by publicly listed enterprises with leading positions in China (Lau et al., 2007; Anderson et al., 2015), while firms with limited experience and competencies would perceive higher potential risk in OFDI and prefer low commitment and less risky modes, such as joint ventures or other collaborative partnership (Tao et al., 2013; Alon et al., 2020).

SOEs prefer to entry foreign markets through acquisition with strong government support — the financial sponsorship of the government improves their risk tolerance (Williamson & Zeng, 2007). Moreover, acquisitions in advanced countries enable state-owned CMNEs to achieve non-economic aims, such as enhancing the national pride and building national images, which is the same for other EMNEs (Hope et al., 2010; Tao et al., 2013). The influence of network-based advantages is mixed. On the one hand, previous collaboration experience with foreign firms in China helps CMNE accumulate technology, international experience and brand reputation, with which they are more able for M&A to have a high level of control (Tao et al., 2013). On the other hand, CMNEs who have inward JV experience have learnt how to effectively operate with such mode, and how to select and negotiate with foreign JV partners, therefore, they are likely to copy this entry mode in future investments (Xie, 2017). Even if they enter foreign countries through acquisition, the previous inward JV experience would lead them to prefer a partnership mode (Deng, 2009).

1.3.3 Post-acquisition integration strategy

Given the prominent role of acquisition in Chinese OFDI, another stream of literature focuses on CMNEs' integration strategies after the acquisition. It is recognized by the literature that they are more prone to have a "light touch" mode by leaving autonomy of operational decisions to the foreign subsidiaries in order to maintain the key management and technical personnel and the brand value of the target firm (Liu & Woywode, 2013; Schueler-Zhou & Schueller, 2013). Some studies attribute this strategy to the limited FSA of CMNEs — parent firms' technologies and managerial experience often lag behind the newly acquired subsidiaries in the developed countries. By "light-touching", CMNEs do not aim for immediate returns from acquisition, but in the long run they hope to gradually transfer the core technologies and know how back to China through within-organization projects, such as joint R&D centres and technical staff mobilization (Deng, 2009, Nam, 2011). Other scholars explain it by the distinct business system and cultural traditions of the home country. First, it is the optimal choice considering the difference in managerial practice and business systems between China and foreign countries (Schueler-Zhou & Schueller, 2013). Second, it is also found to reflect the long-run consideration nature (Liu & Woywode, 2013), and “non-subjugation” tradition of Chinese culture (Marchand, 2017).

The integration strategy is also influenced by the state-created and network-based advantages. As discussed, many SOEs conduct M&A under the governmental support. Liu & Woywode (2013) find that, compared with private-owned CMNEs, SOEs or firms with strong political ties have to adopt the “light touch” strategy because of the government involvement, as they face more complex organization structure, lack of transparency and difficulties in communication. All the above increases the organizational distance between headquarters and subsidiaries and hinders effective integration. On the other hand, previous ties of network-based IAs, in terms of prior partnership with target firms, enable CMNEs to more effectively manage the post-integration process (Deng, 2009; Klossek et al., 2012). The network connections of CMNEs not only change the integration strategy with acquired subsidiaries, but also influence their embeddedness strategies in the host country. Using the cases of Huawei and ZTE, Cooke (2011) finds that CMNEs overcome liability of foreignness and embed into local environment also through developing social and political networks with local entities.

1.3.4 Post-investment performance

Due to the relatively short time since Chinese firms started to significantly invest abroad, studies on their post-OFDI performance are mostly post-2010. The empirical results are mixed and the conclusions vary significantly with the definition and measurement of performance. Generally, parent firms are found to experience performance improvement — OFDI has an enhancement effect on total factor productivity (Li et al., 2017; Haiyue & Manzoor, 2020), scales of operation and domestic employment (Cozza, et al, 2013) as well as the overall performance, measured by Tobin’s Q (Tang, 2020). However, OFDI is found to be detrimental to their financial performance (Cozza, et al, 2013, Howell et al., 2020). In comparison, the performance of overseas subsidiaries is found to be unsatisfying — the sale growth of CMNEs is predominantly due to growth in the domestic market; in addition, the overseas performance are much poorer that their western counterparts (Rugman et al., 2016), and the transnational index is also much lower than DMNEs and other EMNEs (Gammeltoft et al., 2010). The impact on performance is also found to be moderated by the state-created advantages: for example, CMNEs with larger government ownership are more patient and long-term oriented, thus they are found to have higher long-term profitability after overseas acquisitions (Tu, 2021).

A large body of literature focuses on whether OFDI projects transfer strategic assets back to parent firms. Most empirical studies achieve positive conclusions that OFDI do help to improve the innovation performance of both the parent firms (Wu et al., 2016; Kafouros et al., 2018) and home regions (Li et al., 2016). Empirical results show that OFDI leads to an increase in R&D expenditure, patent number as well as citations (Howell et al., 2020). Through OFDI, especially aggressive M&A projects, CMNEs can overcome internal resource constraints and leapfrog towards the technological frontier (Yakob et al., 2018). This effect is contingent on OFDI strategies, firm features as well as the contexts of both home and host countries.

The FSA is an important facilitator of OFDI innovation effect because it is closely associated with the firm's absorptive capabilities. CMNEs with strong in-house R&D, strategic orientation, international experience as well as proper entry mode (through M&A) are more likely to benefit from OFDI (Fu et al., 2018; Elia et al., 2020). On the other hand, Su et al. (2021) find that home-country political ties of the parent firms may lead to larger organizational distance with the subsidiaries and therefore hinder the knowledge transfers. There are few studies focusing on the interaction between network-based IA and OFDI innovation. Cheng & Yang (2017) find that Chinese acquirors receive support from their business network before and after OFDI. The external ties with the partners bring them better innovation capability, information on acquisition targets and the ability to manage acquired subsidiaries in different locations. Therefore, they experience high post-acquisition innovation performance. When it comes to the inward FDI network, scholars find conflicting results. Li et al. (2012) argue that knowledge spillovers from inward FDI in China is substitutable to OFDI, thus preventing firm from investing abroad seeking for strategic assets. On the other hand, Li (2016), using China provincial data, argues that inward FDI helps Chinese MNEs prepare for learning in OFDI. Another emerging stream of literature adopts a geographic view and study how the OFDI innovation benefits are influenced by the home and host location contexts and the subsidiaries' geographic portfolios. First, the innovation performance of CMNEs is found to be improved by a variety of host country features such as a better host-country institutional condition, strong innovation endowment, highly specialized suppliers as well as larger cultural and formal institutional distance to the home country (Wu, 2016; Piperopoulos et al., 2018; Elia et al., 2020; Yi et al., 2020). For the home regions, Li et al. (2016) argue that Chinese provinces with stronger absorptive capabilities and less intense competition in the local market are expected to receive higher technological spillovers from OFDI originating locally.

In summary, the diversified studies on Chinese OFDI reviewed above can be integrated in the "3 IA" framework. On the one hand, the distinctiveness of CMNE can be largely attributed to the political connections and network relationships in the home country, which endow them with obvious Chinese identity, reflected by their internationalization behaviours and post-investment performance. On the other hand, this framework also helps to understand why existing studies on CMNE have drawn differentiated or even contradictory conclusions — because they are based on different theories, using diverse firm samples and study periods. Each of them may capture one certain aspect of CMNEs, whose behaviour is actually driven by a complex mixture of various international advantages under rapid transformation. Therefore, to fully understand the complexity of CMNEs, it is important to emphasis the heterogeneity by cross-fertilizing different streams of theories with an evolutionary perspective.

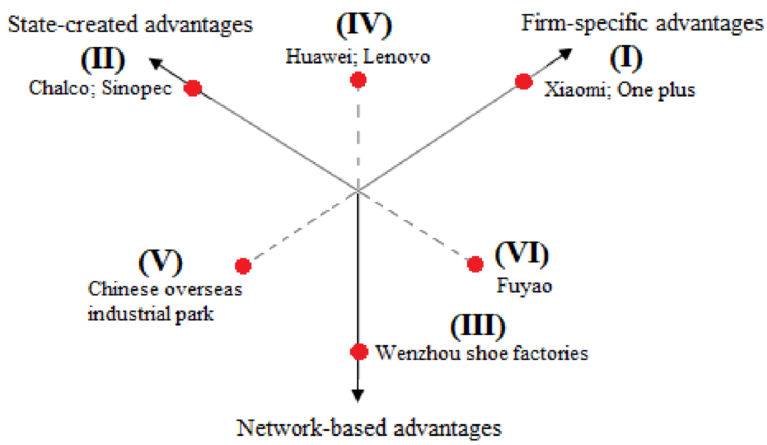
1.4 The heterogeneity of CMNEs and OFDI strategies

The significant complexity and heterogeneity of CMNEs have been emphasized in scholarly work (e.g. Huang & Wang, 2011; Duanmu, 2012). Current literature classifies firms by ownership (state-owned and private), sector, firm capability or investment motive (resource exploitation & exploration) and comparing their different OFDI behaviours. However, significant differences still exist within each class—any individual dimension fails to fully explain the complexity of CMNEs. Based on the “3 IAs” framework, in this paper I argue that the heterogeneity of CMNEs and their distinctiveness to other MNEs can be largely attributed to the different combinations of 3 IAs on which they rely in the global expansion. CMNEs are thus classified into six major types by different combination modes, as showed in Figure 1-1 below. Some firms are able to invest abroad on the basis of their FSAs, some need supports from the state-created or network-based advantages to make up for the shortage of FSA, while others may jointly use different IAs and accelerate OFDI. The characteristics of each MNE type and the corresponding heterogenous OFDI mechanism and strategies are further illustrated by firm cases, as show in Table 1-3. It is important to note that in this classification, if one CMNE is classified to have a certain IA, it only means that this IA plays a relative more important role in the OFDI without implying that the firm has no other IAs at all.

Table 1-3. Heterogeneity of CMNEs

	FSAs	State-created Advantages	Network-based Advantages	MNE type	Examples	Location choice mode	Sector
Type I	√			Large or medium-sized POE	Xiaomi, One plus	Independent	High technology
Type II		√		Large SOE	Sinopec, Chalco	Serve political needs	Natural resources & Infrastructure
Type III			√	Small or medium-sized POE	Wenzhou shoe factories	Collective, follow domestic partners	Specialized light industry
Type IV	√	√		Large SOE or POE	Huawei, ZTE, Lenovo	Independent with political constrains	High technology
Type V		√	√	Small POE (with SOE)	China-Indonesia industrial park	Collective with political constrains	Diversified manufacturer
Type VI	√		√	Large or medium -sized POE (contractors)	Fuyao	Collective, follow domestic or foreign partners	Specialized competitive contractors

Figure 1-1 Six combination modes of IAs and example CMNEs



Type I: CMNEs with strong FSAs are able to invest abroad independently. Those firms are often the successful POEs with relatively strong technologies and production capabilities. Many of them start OFDI in developing and emerging markets or the low and middle-end markets of developed countries. Some recent studies on Chinese POEs found that they are similar to the conventional MNEs from advanced economies which rely on their own technological capabilities, management, brands as well as experience for international expansion (Driffield, et al., 2021). For example, Xiaomi, a successful Chinese electronics firm, has strong in-house innovation ability and cost advantages over Apple and Samsung. It holds 23.5% of cell phone market in India (Abhijit, 2017). Other two examples are One plus and Tecno, two Chinese cell phone makers which have significant FSA in product designing and marketing. In contrast to nearly all CMNEs, these two firms first achieved business success in foreign markets (Europe and Africa respectively) rather than in the highly competitive domestic market where they lacked advantages of brands and institutional supports as private-owned start-ups.

Type II: The second type of CMNEs are those lacking adequate FSA and go abroad on the grounds of state-created advantages. The typical examples are the large SOEs, such as China Petroleum & Chemical Corporation (Sinopec) and China Aluminium Corporation (Chalco), two major SOEs affiliated to the central government. Those firms have strong institutional support due to the domestic market monopoly and also receive help from the government, in other words, they are parts of the Chinese government. On the other hand, they are not completely profit-oriented due to the need to satisfy the political aims of the Chinese government in domestic or foreign countries. Moreover, because of the monopoly position and lack of competition, the SOEs have less incentives for technology and management improvement (Zhang, 2003), and their efficiency is found to be significantly lower than Chinese POEs. Their OFDI activities are often related to natural resource and infrastructure projects under the agreement of both Chinese and host country governments such as Sinopec's acquisition of oilfields in Africa and Chalco's acquisition of mines in Latin America (Deng, 2009).

Type III: As discussed above, there are many industrial clusters of small firms working on the same or related value chains. A typical example is the town and village industrial clusters in the Zhejiang and Guangdong Province (Wang & Tong, 2019). Each individual firm lacks strong FSA by itself, at the same time most of them are regarded as traditional and operating in outdated sectors, with limited access to government subsidy. They survive by producing and exporting collectively in the local business network and use agglomeration externalities to increase their productivity (Sandberg, 2009; Fleisher et al., 2010). It is infeasible for them to invest abroad individually because of small scales and high degree of specialization. However, they can invest collectively by leveraging network-based advantages in the home region. For example, more than 40 small shoe factories from Ruian county of Wenzhou had invested together in Russia and built a production base in Ussuriysk (Wenzhou Daily, 2015). It is also found by recent empirical studies that some Chinese firms invest abroad in a herd mode, new entries follow the foreign locations of domestic peers in the up and downstream sectors (De Beule et al., 2018; Jiang et al., 2020).

Type IV: Some private companies or SOEs with advanced advantages and potentials are selected by the government to be "national champions" and are then blessed with institutional support in both domestic and foreign markets. They internationalize rapidly through combining FSAs with state-created advantages. The best example is Huawei, which domestically received considerable financial and policy support and also benefits from the Chinese foreign aid projects abroad (Tang, 2011, Cooke, 2012). A similar case is Lenovo, which started from the domestic market and was regarded as a national pride. In 2004 it acquired the PC product line of IBM with the diplomatic support from the Chinese government (Deng, 2009).

Type V: Like Type III, another group of firms embedded in business groups or industrial clusters invest abroad together with network-based advantages. Differently, their collective investments are organized or accelerated by the government or some lead SOEs. The typical examples are the Chinese overseas industry parks in ASEAN and Africa countries. Some foreign governments have contracts with the central or local Chinese government to jointly build industrial parks for attracting a group of CMNEs (Song et al., 2018). Moreover, for some investment projects, the lead companies are major SOEs who share important knowledge on investment abroad, such as information, experience and distribution channels, with small CMNEs, or integrate them into the value chain as contractors. In this way, some small and medium -sized CMNEs can internationalize through combining network-based and state-created IAs. Currently, the governors of local governments and SOEs have political incentives to organize the OFDI of local firms in response to Belt and Road Initiative of the central government. This collective OFDI mode with government orchestration is becoming a trend (Shao, 2019).

Type VI: Some POEs with strong production capabilities meet the strict technological standards of lead foreign MNEs whose subsidiaries operate in China. Advanced FSAs help them become the contractors of foreign MNEs and build long-term collaboration and mutual trust relationships. In this way, they participate to global production networks and obtain network-based advantages. In the subsequent OFDI, they often leverage this network by replicating the cooperation relationships abroad. For example, Fuyao, an important contractor of Volkswagen China, followed Volkswagen overseas production bases (Hertenstein, 2017).

1.5 The evolution of Chinese MNEs

Literature explains the internationalization stages and evolution of MNEs by the model developed by Rugman and Verbeke (1992), in which they distinguish firm specific advantages (FSA) to be non-location bound, and location-bound. The former has strong spatial mobility and can be exploited in both host and home locations, while the latter is specific to home country or other particular locations. According to this framework, CMNE are recognized as being in the infant stage when the firm advantages are largely bound to home country (Voss et al., 2009; Rugman et al., 2014; Rugman & Nguyen, 2014), and the internationalization degree is still very low. As found by Rugman & Nguyen (2016), "sales growth of Chinese manufacturing MNEs is mainly attributed to sales growth in domestic market" (p.292). On the other hand, scholars are optimistic about the future of CMNEs and believe that as time goes by, they are going to gain more non-location bound FSAs and gradually evolve into mature MNEs with a higher transnational index, lower dependence on the home market, globally well-known brands and wider geographic footprints (Casanova & Miroux, 2016; Ramamurti & Hillemann, 2018). CMNEs are going through the trajectories experienced by other EMNEs, such as Korean firms, which have now become mature MNEs (Kim et al., 2015).

In this section, I try to sketch the driving forces of CMNEs' evolution process, which can be understood under my framework as the changes of IA combination modes; again, firm cases are used to illustrate the diversified evolution trajectories. The major driving force of CMNEs is the accumulation of the FSA — as CMNEs learn frequently through strategic-asset seeking and continuously integrating host country specific advantages (Mathews, 2002): non-spatially bound FSA are thus increasingly important in internationalization advantages, decrease firms' reliance on the other two advantages, and have higher spatial mobility into more diversified markets with higher internationalization degree. This is the ideal evolution trajectory of CMNEs predicted by existing studies (Ramamurti & Hillemann, 2018).

Another largely overlooked force driving the evolution is that CMNEs may actively decouple with state-created and network-based advantages which may cause constraints. Firstly, firms under state support are also subject to responsibilities to serve political intents, for example, some have to invest in certain locations to meet diplomatic needs (Deng, 2004). Other firms internationalizing through network-based IAs have to follow the location of their domestic or foreign partners. There may be conflicts between the commercial interests of individual CMNEs and the political and collective interests of the state and business partners, which makes hard to make optimal OFDI decisions for the firms themselves.

More importantly, these two IAs can be extremely helpful in the early steps of active internationalisation, however, sometimes they are detrimental and leads to constraints in advanced stages of internationalization. CMNEs with governmental ties face resistance in the western developed countries where stricter rules are carried out against Chinese SOEs, especially in sensitive sectors (Cuervo-Cazurra et al., 2014): one example was the failure of Chalco's taking over Rio Tinto (Yao, 2009). In addition to SOEs, private companies with close connections to the government also receive stricter investigations in western countries (Van Dijk, 2009). In this way, the blessing from the state turns out to be a curse, which has become increasingly significant in the context of the escalating China-US competition. Secondly, network-based IAs may cause path dependency and lock-in effect for CMNEs. Scholars argue that firms may face a competency trap by over-relying on past successful experiences and not adjusting their organizational routines and business practise (Levinthal & March, 1993). Rugman et al. (2016) argue that the experience in domestic market makes Chinese MNEs difficult to adapt to host country conditions and less ready to develop knowledge-based FSAs.

In this way, too much reliance on the current supply and collaboration network may cause stronger embeddedness and path-dependency and make the contractor firms reluctant to change their partner and adjust production routines. Moreover, specialization in a value chain may have the risk of being locked into particular segments (OECD, 2014). The network-based advantages, in this way, may be detrimental to the long-term internationalization of CMNEs.

CMNEs would, on the one hand, increase the FSAs, on the other hand, they may actively decouple with previous political and business ties to avoid the backfire. Some firms who succeed in this process can evolve into a more advanced internationalization stage towards mature MNEs, while some others may face severe challenges and even degrade in internationalization. In this way, the IA combination is subject to changes and different CMNEs may experience various evolution trajectories, as illustrated in the three cases below.

Example 1. Fuyao used the network-based IAs in the initial internationalization stage, by following Volkswagen, its major partner in China (Hertenstein, 2017). In the second stage, it also built new networks with other companies such as Volvo and Landrover (Hertenstein, 2017). In this way, Fuyao further improved the production capability, built more external linkages out of their existing networks and significantly increased FSAs. Spatially, it expanded to more locations, such as the Great Lake region, the automobile cluster of the US, and significantly increased international sales. As a result, Fuyao achieved the evolution from Type VI towards Type I and is growing to be a mature MNE with more internationalization advantages unbounded to certain networks or locations.

Example 2. The second evolution trajectory is represented by Lenovo, who started business as a national pride in the domestic market and was endowed with strong support from the government. Following its business expansion in foreign markets, Lenovo started to actively reduce the influence from the home government. It not only established the operational headquarter in Raleigh, North Carolina, but also sponsored the US army (Lenovo, 2013). In 2019, facing the US sanctions against Chinese high-tech firms, the CFO Weiming Huang claimed to move the production lines out of China to avoid the increasing tax (Kharpal, 2019), a statement that was criticized by the media of the Chinese central government. In this way, Lenovo actively weakened its ties with China and the Chinese government in order to avoid the sanctions and maintain internationalization success, gradually evolving from Type IV towards independent MNEs of Type I.

Example 3. The third example, Huawei, received strong support from the government, at the same time establishing solid FSAs in frontier telecommunication technologies, product designs and global distribution networks. In the last 20 years, Huawei adopted a gradual OFDI strategy from home to developing countries then to developed countries (Cooke, 2012). Huawei was regarded as a mature MNE due to the increasing overseas sales and global coverage. However, since 2019, because of the relationships with the Chinese military and its dominance in the 5G technologies, the US government has severely sanctioned it through a number of export and technology restrictions (especially, being excluded from the Android system and Qualcomm semiconductors), as well as diplomatic lobbying of the US against Huawei. Up to 2021, those sanctions have led to a collapse of the Huawei's overseas sales (Whalen, 2021). Huawei, on the one hand, had to retreat to the domestic market where it has diversified the products and designed own systems. This move was sheltered by the Chinese government and nationalism emotions of the Chinese public. For the foreign markets, it lost 5G contracts with most of the developed countries but remained prominent in some developing countries with friendly relationships with China. In the Huawei's case, despite of FSA accumulation, internationalization was severely affected by the state connections under the background of China-US competitions. Its withdrawing from the western markets indicates a degradation and transfer from Type IV towards Type II.

In summary, CMNEs undergo a rapid evolutionary process driven by endogenous FSA accumulation, strategy adjustments and external environment changes. Currently the economic, technological and political competition between China and the US, has caused great uncertainty to their global expansion. These complex factors have differential impacts on heterogeneous CMNEs, leading them to diversified evolution trajectories, which can be reflected in the shifting among different combinations of IAs and types of MNEs. The argument about the gradual evolution of Chinese companies towards mature MNEs is overly optimistic, considering some companies, such as the case of Huawei that, despite of the FSA accumulation, still experience internationalization decline.

1.6 Discussion and conclusion

China is the most important emerging economy, with a GDP 15.28 trillion (current USD) (World bank, 2020) which is also predicted to surpass that of the US by 2030 (Bloomberg, 2021). Its economy and institutional environment fundamentally shape the unique internationalization paths of Chinese firms. Studying the internationalization of CMMEs deepens our understanding about how China actively organizes its global value chains and production networks across the world. It also provides an opportunity to better grasp the internationalization mechanism of EMNEs and helps to extend existing IB theories (Child & Rodrigues 2005).

In this paper, we provide an explanation of CMNEs' investment decision, heterogeneity and evolution process using a framework based on three internationalization advantages. Besides firm specific advantages which have been discussed widely in the IB literature (e.g. Bain,1956; Hymer, 1960; Ramamurti & Singh, 2009; Verbeke & Kano, 2015), CMNEs are also endowed with state-created advantages and network-based advantages. The former reflects the fact that China's economy is organized in the mode of state capitalism with strong influence from the planned economy legacy, which enables Chinese firms to control the huge domestic market and also gives them strong public financial and political support in foreign expansion. Chinese OFDI, therefore, embodies the will of the government and Chinese Communist Party. The other typology of advantages shows one important characteristic of Chinese firms — they are operating within different business networks. Domestically, they are affiliated to various business groups, industrial clusters, and sectoral associations, etc. This organization mode is embedded in the Guanxi-based society and collectivism mindsets of Chinese people, which is also common to other countries, such as Korea, Japan and Vietnam in the Sinosphere. Firms are prone to take collective and coordinated actions in performing OFDI. On the other hand, the network-based advantages are also derived from ties with incumbent MNEs, especially DMNEs. As late movers in the global arena, CMNEs use existing supplier and contractor connections to accelerate OFDI. These two additional advantages, on the one hand, make up for the shortage of FSA and enable Chinese firms, who are not eligible to internationalize, become MNEs. On the other hand, they are related to significant additional costs and potential constraints, which may hinder further internationalization in later stages of active internationalization through OFDI.

Different combination modes of the 3 types of advantages explain the significant heterogeneity of CMNEs, and the dynamics of such combination leads to diversified evolution trajectories. A literature review shows that existing studies on CMNEs are mainly carried out under this "3A framework" —CMNE's investment decision-making, diversified overseas investment strategies, including investment objectives, location choice, entry mode and post-integration modes, are all jointly shaped by the three advantages. The financial and innovation performance after OFDI is also subject to their long-term impacts.

Using this "3 IAs framework", this paper comes to four major propositions and try to integrate the literature on Chinese OFDI by:

1. Addressing the core question on the international advantages of CMNEs. This question has been controversial withing the debate between those who argue CMNEs as lacking adequate FSAs (e.g., Luo, 2007) and those who believe CMNEs have FSAs or unconventional FSAs (e.g., Ramamurti & Singh, 2009; Verbeke & Kano, 2015). Based on the "3 IA" framework, this paper argues that, to become MNEs, Chinese firms do need a certain level of FSAs which are not the "absolute advantages" over incumbent MNEs in the global competition, but the "relative advantages" in the Chinese market compared to other domestic firms and subsidiaries of foreign firms. This "relative advantage" helps to access the state-created and network-based advantages and also enables CMNEs to leverage the country-specific advantages in domestic market to invest abroad.
2. The home country has important and long-lasting influences on CMNEs. Many aspects of their activities, including marketing, producing as well as technology seeking, to a large extent, serve and rely on their home country, for example: 1. CMNEs are still highly dependent on the sale growth in domestic market (Rugman et al., 2016). 2. Even their overseas sales depend on domestic production capabilities (Rugman, 2009). 3. They invest abroad aiming for knowledge, know-how, and technology improvement of

home country and parent firms (Luo, 2007; Wu et al., 2016; Kafouros et al., 2018). These characteristics can be partly attributed to the early internationalization stage, since home country also plays an important role for the internationalization of other EMNEs. However, considering China's huge and rapidly growing market size, this situation is likely to last for a long time. Even after CMNEs become mature MNEs, the home country market share will still maintain a crucial importance, similar to many MNEs from the US (Gammeltoft et al., 2010). On the one hand, the domestic market gives them great advantages in overseas expansion, on the other hand, it may cause long-term reliance on their home country and government.

3. There is large complementarity between China's economy and the rest of world, particularly western countries, which is to be exploited by transnational investments of MNEs. However, the potential benefits of outward FDI of CMNEs are larger than those of inward FDI of DMNEs in China. This is because the Chinese government creates favourable conditions and encourages Chinese national champions to aggressively acquire resources abroad, at the same time preventing foreign firms from equally exploiting the Chinese market. Therefore, the rapidly growing Chinese OFDI is, to a large extent, due to this asymmetry in the bidirectional FDI flows. However, because of free market countries' resistance to China's protectionism, this model is facing challenges, although it can be useful to interpret the trends and evolution of MNEs from other emerging, developing and peripheral economies.
4. CMNEs are in rapid evolution. Existing literature regards FSA accumulation as the major driving force, predicting that differences between DMNEs and EMNEs will diminish as the latter evolve (Narula, 2012). This paper uses CMNE cases to illustrate that the evolution process of EMNEs could be more complicated. In addition to the FSA accumulation, to become mature MNEs, CMNEs may also need to actively decouple with previous state connections and business networks to prevent the potential political uncertainties and path-dependency risks. The evolution may not be a linear process where CMNEs upgrade to be mature MNEs with better FSAs and higher transnational degree but could also entails loss of competitiveness and retreating from international markets under the changing environment.

The 2nd and 3rd papers of this PhD thesis broadly follow the framework presented in this paper. The 2nd paper studies the location strategies of CMNEs and their space of origin heterogeneity. I find that the global connectivity of a subnational home region with foreign countries influences the spatial behaviours of CMNEs originating from it. The 3rd paper links network-based international advantages with innovation performance, and study how Chinese firms' prior linkages with inward FDI increase their innovation gains from the subsequent OFDI.

Chapter 2. The Location Choice of Chinese OFDI: The Influence of Home Region Global Connectivity

2.1 Introduction

Geographic space is one of the most important dimensions of a Multinational Enterprise's (MNE) organizational structure. It deeply affects every aspect of internationalization strategies and performance. Starting from the 'Ownership, Location, and Internalization' (OLI) paradigm of Dunning (1980), International Business (IB) scholars have been rediscovering the importance of space as MNEs are increasingly studied from a geographical perspective.

There are two critical locations of MNEs, the host or investment destination, and the home or the place of origin. On the one hand, many studies explain the location choice of MNEs among alternative host countries (e.g., Makino et al., 2002; Buckley et al., 2007; Ramasamy et al., 2012; Ascani et al., 2016; Crescenzi et al., 2016) or sub-national regions (e.g., Chung & Alcácer, 2002; Amiti & Javorcik, 2008; Castellani et al., 2021). MNEs are found to be attracted by various location-bounded resources and favourable institutional environments not available at home and, at the same time, deterred by various cross-national distances and the Liability of Foreignness (LOF) (e.g., Xu & Shenkar, 2002; Chao & Kumar, 2010; Schwens et al., 2011). On the other hand, surges of OFDI from emerging economies has led scholars to pay more attention to the origin of MNEs to understand their home country-specific advantages (CSA) (Rugman & Verbeke, 2001; Sim & Pandian, 2007; Luo et al., 2010; Prashantham & Birkinshaw, 2015; Buckley et al., 2018, Deng et al., 2018). Some recent studies go beyond the national level analysis and focus on subnational contexts within the home country. They found that heterogeneous 'regions of origin' set specific environments for local firms to internationalize and they are more important than the 'countries of origin' in explaining emerging market multinationals (EMNE) (Castellani et al., 2014; Liu et al., 2014; Sun et al., 2015; Li et al., 2018; Yang, 2018).

The two streams of literature mentioned above have provided a deep understanding of how characteristics of both home and host locations influence OFDI activities. However, there is a missing link, the relationship between them. The analysis on these two locations has been largely disconnected – it remains unknown whether connectivity or linkages between home locations and host locations influences FDI flows. Economic geographers maintain that regions have deep interdependency upon each other in interwoven networks through deep economic and social linkages (e.g. Sassen, 2002; Bathelt et al., 2004; Taylor & Derudder, 2004; Boschma & Frenken, 2009). Ignoring this cross-regional spatial interdependence undermines our understanding of location advantages and the spatial behaviours of MNEs.

To fill in this research gap, this study draws upon EG and IB literatures to explore whether and how prior global connectivity of subnational home locations (31 Chinese provinces) is correlated with the FDI location choices of Chinese MNEs. I treated subnational regions as network nodes that are connected to foreign locations. Empirically, I found that Chinese MNEs originating from different provinces differ significantly in their host location among 125 foreign countries. I then utilize a gravity model to explain this locational choice pattern by the conditions in Chinese provinces and foreign countries as well as connectivity between them before OFDI, including: (1) international trade (2) cross border co-invention activities, and (3) international 'friendship city' relationships. China provides an appropriate empirical context to test these relationships because Chinese firms have invested abroad much later than their western counterparts – hence various aspects of global connectivity such as historic and cultural ties, international trade, inward FDI or social and political relationships have often already existed long before Chinese OFDI started. Prior connectivity increases the proximity between Chinese firms and certain host locations and thereby helps alleviate LOF in connected regions and influence their location strategies. Moreover, as the largest emerging market globally, China has substantive within-country variation in terms of OFDI intensity, external connectivity, economic development stages and institutional environments (Ahlstrom et al., 2003; Alon, et al., 2013), which has also experienced significant changes over recent decades. These substantial geographic and temporal variations enable us to quantitatively test this relationship using a panel-based model.

In this paper, I try to make the following contributions to the IB and EG literature. First, this paper contribute to deepening the understanding of location advantage in the IB studies.

As one of the three corner stones of the OLI paradigm (Dunning, 1980), the ‘location advantage’ has received extensive attention, however, it is mainly understood as resources and conditions bounded to certain territories. Differently, for EG scholars, location should be also considered as ‘space’ with network and relational characteristics rather than ‘place’ with only location-specific characteristics (McCann, 2011). In this paper, by integrating the concept of regional global connectivity, I link the home and host locations and argue that locational advantages are not only limited to the location itself but also derived from the external relations with other locations and their positions in international networks.

Second, this paper broadens our understanding of the heterogeneity of EMNEs and the local environment in which they internationalize. The location strategies of EMNEs are found to be influenced by various firm characteristics including innovation capabilities (Mi, et al., 2020), ownership (Chen et al., 2016; Shi et al., 2021); investment motives (Zhou & Guillen, 2017), or internationalization experience (Yeoh, 2011; Quer et al., 2019). However, often the home country has been treated as a homogenous whole, assuming that firms with different origins have the same access to the home country advantages and the same sensitivity to cross-national distances. Building on recent research emphasizing within-country difference (Hutzschenreuter et al., 2020), this paper employs a fine-grained analysis and find that subnational origin heterogeneity is important for EMNEs, not only influencing the investment willingness (Liu et al., 2014; Sun et al., 2015; Yang, 2018), but also shaping their foreign location choice. This perspective is especially important considering the remarkable spatial heterogeneity within large emerging economies, such as the BRICS (Brazil, Russia, India, China, South Africa).

Third, this paper also contributes to the literature on regional global connectivity, by exploring its multidimensional nature and the evolution process. The existing literature has focused on the role of global connectivity in local industrial structural change and innovation of clusters and regions (Bell & Giuliani, 2007; Lorenzen & Mudambi, 2015; Crescenzi & Iammarino, 2017; Ascani et al., 2021). Most existing studies have been emphasizing MNE's transnational investment as a major facilitator of global connectivity or even define it as the connectivity itself. However, very few studies have paid attention to how the FDI connectivity is built and evolves and especially how it interacts with other dimensions of global connectivity except recent work of (Bathelt & Li, 2020; Castellani, et al., 2021). In line with these related studies, this paper further explores the relationship between FDI and prior trade, innovation and social connectivity arguing that connectivity building is a path dependent process where new connections depend on the old ones and different dimensions co-evolve with each other.

The paper is structured as follows. The next section introduces the literature background and develops the hypotheses. Section 3 presents the data and describes the general trend of Chinese OFDI as well as the spatial pattern at home and host locations. The estimation models and results are presented in Section 4, which also offers robustness checks. Section 5 summarizes our findings and present concluding remarks.

2.2 Literature Background and Hypotheses

2.2.1 Chinese OFDI: host location choice

Hymer (1960) argues that firms internationalize when their potential returns in a foreign market are sufficient to overcome LOF, which refers to the additional costs of operating in foreign countries (Zaheer, 1995). Following this basic argument, the location strategies of Chinese MNEs have been widely studied with respect to two aspects: the benefits and resources in host locations and the costs in relation to cross-national distances. Chinese firms started to invest abroad after 2000 and their OFDI has sped up after the implementation of the 'Going Abroad' policy and 'Belt and Road' Initiative of the Chinese government (Buckley, 2010; Sutherland et al., 2020).

Most early studies on Chinese OFDI focused on the benefit side – using spatial patterns of OFDI to infer investment motives (e.g., Buckley et al., 2006; Zhang & Daly, 2011; Kang & Jiang, 2012; Kolstad & Wiig, 2012). Chinese MNEs are found to share some common features with Developed-market Multinational Enterprises (DMNEs), such as their profit-driven nature, reflected by extensive investments in countries with large markets (Deng, 2004; Ramasamy, 2012; Kolstad & Wiig, 2012). On the other hand, scholars have also emphasized various specific motives and location choice rationales such as less sensitivity to labour costs (Deng, 2004), higher tolerance towards instable institutional environments (Cheung & Qian, 2008, Buckley et al. 2007), as well as stronger motivations for seeking strategic-assets and natural resources (Kolstad & Wiig, 2012).

Besides host country features, location choice is also influenced by LOF (Zaheer, 1995). LOF comes from three major sources — 'Unfamiliarity Hazards', 'Discrimination Hazards' and 'Relational Hazards' which are all closely related to Chinese MNEs (Zhou & Guillen, 2017). As late movers in the early stage of internationalization, EMNEs lack enough knowledge and foreign market information, so they suffer from the 'Unfamiliarity Hazards', where there are large information asymmetries and costs associated with searching and mobilizing local resources and markets (Caves, 1971). 'Discrimination Hazards' means that foreign firms are treated unequally due to lack of legitimacy, and they are not accepted by the local consumers and authorities (Henisz & Williamson, 1999). Chinese MNEs often have to overcome negative impressions such as the 'Made in China' label which describes Chinese products as low-quality (Lattemann et al., 2017), or the fact that Chinese MNEs are accused of being controlled by the Chinese government, threating the 'national security' of host countries, as seen in the case of Huawei. Third, 'Relational Hazards' refers to difficulties in establishing ties with the local actors (Eden & Miller, 2004). It is difficult for EMNEs, as newcomers, to tap into local networks for collaboration. When LOF costs exceed the potential benefits in a host country, the OFDI turns out to be unprofitable. LOF costs increase with the cross-national distances to host countries (Hymer, 1960). Due to distinct home market conditions, Chinese firms are also sensitive to large gaps in culture, managerial practices, institutional environment, industrial structure and economic development stage (Blomkvist & Drogendijk, 2013; Ren & Yang, 2020). These gaps become more significant given that Chinese firms still lack FSA to compete in foreign markets on their own.

2.2.2 Host location choice and home country advantages

IB scholars try to explain the specific location choice rationales above by attributing them to the home market conditions and location-specific advantages within China (Luo & Wang, 2012; Gaur et al., 2018). The distinct characteristics of the home market influence firms' investment motives and the perception of cross-national distances, thus changing the expected benefits and costs in certain host locations and making the strategy of Chinese MNEs different from that of DMNEs.

First, the strong preference for strategic-assets, natural resources and lower sensitivity to labour costs and institutional weaknesses is due to low-cost and resource-intensive manufacturing sectors in China (Deng, 2004); the lack of core technologies which requires OFDI as the springboard for catching up in short time (Luo & Tung, 2007); and the support from the Chinese government which remedies the risk of institutional weaknesses (Zhang & Jiang, 2016). These home country features differ from those of developed economies and shape the specific investment motives and location strategies of Chinese MNEs.

Second, political or business relations play a crucial role in overcoming cross-national distances and thus influence internationalization decisions and location strategy of Chinese MNEs (Deng, 2012). First, they can obtain knowledge and market information through indirect learning from internationalization experiences of others, such as suppliers, clients, competitors and value chain leaders, which helps to avoid high risks associated with subsequent internationalization. (Banerjee et al., 2015). In addition, they also use relations with government institutes or other firms to become insiders in overseas markets. Empirical evidence shows that having political ties with the Chinese government makes Chinese MNEs more likely to invest in countries with friendly diplomatic relationships with China, which helps reduce investment uncertainty, especially in countries with high political risks (Li & Liang, 2012; Zhang & Jiang, 2016). Chinese OFDI is also influenced by organizational connections: some Chinese firms invest in a host country to follow their peer firms (De Beule et al., 2018; Jiang et al., 2020), or follow the overseas locations of foreign firms if these foreign firms have subsidiaries in China and have collaboration with local firms. In this way, Chinese MNEs turn to be insiders in international production networks (Hertenstein, 2017). Moreover, Chinese OFDI is also found to follow overseas Chinese communities – they have strong tendency to rely on ethnicity-based social and business networks to tap into the local markets (Karreman et al., 2017).

These studies, although having linked host locations with the home country by connections and networks that span across borders, are limited to analyses at the country level, assuming that distance, relations, and resource availability are constant and have the same impacts on all Chinese firms. This neglect of subnational heterogeneity makes it difficult to understand what home location advantages are really available to firms and their impact on subsequent internationalization strategies. There are significant geographic variances within the home country, in terms of economic development, innovation system, institutional conditions and resource endowments (Boschma & Frenken, 2009; Dellestrand & Kappen, 2012; Goerzen et al., 2013; Sun et al., 2015). Moreover, the cross-national distances may be precepted differently by firms with different subnational origins (Castellani et al., 2014). Especially, in the case of China, differences may be very significant, not only in resources and institutional environment but also in local openness and external connectivity at the subnational level (Zhou et al., 2002; Ma et al., 2013; Liu et al., 2014).

Some studies go beyond the national level to explain OFDI origins at finer subnational locations, finding that spatial differences create heterogenous contexts within which firms make OFDI decisions. They mainly test the impact of different local institutional environments among Chinese provinces. Most studies find a facilitating role of advanced institutions in promoting OFDI (Wan & Hoskisson, 2003; Sun et al., 2015); in addition, higher marketization degree, better access to financial support and openness through friendship cities are found to facilitate direct investments abroad by local firms, while unfavourable institutions deter it (Liu et al., 2014; Ma et al., 2016; Sun et al., 2015). In contrast, some others find that under the condition of unfavourable institutional conditions, for example, when institutional dimensions are progressing at different paces, local firm will escape abroad to avoid institutional conflicts and frictions (Shi et al., 2017). However, these studies on home region heterogeneity have yet to systematically explore its impacts on investment strategies of MNEs, including location choices. This paper studies how home region influences location decisions by focusing on one important feature of home regions, i.e., their global connectivity.

2.2.3 Global connectivity of subnational locations and Chinese OFDI

Locations (regions, cities, or industrial clusters) are economically or socially linked with each other by multi-dimensional linkages and interwoven in a global network of interactions and interdependency. The EG literature has been systematically exploring connectivity at the subnational level, such as global city networks (Smith & Timberlake, 2001; Taylor et al., 2002) and industrial cluster linkages (Mudambi et al., 2017; Turkina & Van Assche, 2018). Connectivity is multi-dimensional. First it is measured by the connections of infrastructure, in terms of air traffic accessibility (Rimmer, 1998; Smith & Timberlake, 2001) and information communications through postal, telephone and internet connections (Warf, 1995; Graham & Marvin, 2000; Moss & Townsend, 2000). Advancement in infrastructure facilitates the increasing inter-regional flows of commodities, capital, information, individuals and firms (Rivas, 2007). Moreover, connectivity also takes the form of social and organizational linkages, such as cross-border diasporas and cultural proximity (Saxenian, 2006; Gambardella et al., 2009). FDI of MNEs has been regarded as 'global pipelines', the most important global connectivity channel (Bathelt et al., 2004). Embedded in multiple locations, EMNEs work as trans-local pipelines to gain access to complementary knowledge and resources and transfer them within the firm organization (Meyer et al., 2011). Taylor (2002) argues that the network of global cities is generated by the hierarchical office network of advanced producer-service MNEs: following research further explores the importance of MNE connectivity for the innovation performance of cluster firms (Lorenzen & Mudambi, 2013), as well as development trajectory and resilience of regions and clusters (Sturgeon et al., 2008; Leamer & Storper, 2014; Iammarino & McCann, 2017; Crescenzi & Iammarino, 2017).

The EG research has thus provided a solid understanding of global connectivity at the subnational level. Some other studies have adopted a more integrated framework arguing that different dimensions of connectivity are deeply intertwined and interplay with each other (Boschma, 2005; Iammarino & McCann, 2006; Crescenzi et al., 2016; Castellani et al., 2021). However, in the current literature, it is still not fully clear how different dimensions of connectivity coevolve and how the formation of new connectivity is influenced by prior ones. Although the importance of connectivity through MNE are well recognized by both EG and IB, it is yet to know how this connectivity is built (Bathelt & Li, 2020).

In this paper, I argue that existing global connectivity at subnational level works as an important channel of OFDI, facilitating local firms to invest in closely connected locations. Firms are social constructs embedded in direct and indirect economic, social and cultural relations of particular places (Agnew, 2001; Bathelt & Glückler, 2003; Boggs & Rantisi, 2003; Bathelt et al., 2004). Home regions with wide and intensive global connectivity have better access to external knowledge and relational assets (Taylor & Walker, 2002; Alderson & Beckfield, 2004; Alderson et al., 2010), providing firms originating and embedded in these regions with early access to important information on, for example, consumer preferences, institutional environments, or potential partners in specific foreign locations through the global connectivity. Connectivity may constitute a firm's international advantage in OFDI and lead companies to invest in those countries where mutual understandings and relations have already been built.

The information and relational assets from global connectivity are bounded to certain geographic spaces, and because that tacit knowledge is based on face-to-face interaction and labor mobilities, they decay sharply with distance (e.g. Jaffe, 1989); relational assets are based on the long-term trust and common norms, values and customs embedded in local networks (Granovetter, 1985). Therefore, they are only available to insiders. For example, although many foreign MNEs have located their subsidiaries in coastal areas of East China and have spillovers to the Chinese firms (Cheung & Ping, 2004), these spillover effects are highly localized. Firms in Middle or West China have much less access to them, so it is difficult for such firms to obtain information on foreign countries or get access to the international networks of foreign MNEs. Similarly, the ethnicity-based relational assets are limited to groups of people sharing the same cultures and ethnic ties within certain subnational areas. For example, firms in other provinces are outsiders to the exclusive Cantonese communities; compared with them, local firms from Guangdong Province have easier access to large overseas Guangdong (Cantonese) communities in the US and Europe. Therefore, the effects of global connectivity are highly localized and have strong impact on the local firms.

In this paper, I focus on the influence of three major dimensions of global connectivity –

international trade, cross-border R&D collaboration as well as international friendship cities. All these three dimensions help to lower the LOF in certain countries and influence the location choice of Chinese MNEs.

1.Trade connectivity

International trade links producers, suppliers and buyers located in different regions on the same global value chain (Nadvi & Halder, 2005). First, the existence of large-scale import and export between a Chinese region and a certain foreign country reflects the industrial complementarity between two locations. There exists a large number of upstream and downstream partners and potential markets in the host country. And this opportunity could be internalized and more effectively exploited through cross-border investment (Dunning, 1980). Second, upstream and downstream companies in the global value chain exchange information frequently through import and export and obtain knowledge feedbacks from each other, including production technologies and production processes (Gereffi et al., 2005; Pietrobelli & Rabellotti, 2011). At the same time, trade leads to intensive communications with foreign companies or consumers, helping Chinese firms quickly update market demands, consumer preferences, and institutional conditions in which their trade patterns operate (Fernandes & Tang, 2014). This reduces the Unfamiliarity Hazards and information asymmetry, helping local Chinese companies in identifying, evaluating, and exploring new market opportunities in the foreign countries. Therefore, local Chinese companies have higher potential returns from OFDI in the target country. The first hypothesis is as follows:

H1: Chinese MNEs are more likely to invest in countries with high trade connectivity to their home region.

2. Innovation connectivity through international R&D collaboration

National and regional systems of innovation have become connected in global innovation networks (Carlsson, 2006; Narula & Guimón, 2010). Connections among innovative regions reduce the spatial constrains of tacit knowledge (Amin & Cohendet, 2004). International R&D collaboration represents one of the most important channels to transfers both codified and tacit knowledge between inventors in different locations (Fleming et al., 2007; Alnuaimi et al. 2012).

Increasing collaborations have been observed between China and developed economies which have different comparative advantages in the R&D activities (Chen et al. 2013; Branstetter et al., 2013). This helps technologically lagging regions to get access to frontier knowledge from distance locations (Chen et al., 2013; Giuliani et al., 2016). Frequent and effective R&D collaboration between home and foreign locations means their R&D communities have formed a common language, shared basic understanding and mutual compatibility (Henn, 2012). Local firms may be better aware of conditions of innovation systems in the foreign locations connected to their home regions and are able to obtain more information about foreign countries' technologies advantages in specific technology domains or local institutional environment related to innovation. This may help to alleviate the Unfamiliarity Hazards and encourage local firms to invest in those locations: this is especially important for Chinese MNEs who show strong strategic assets-seeking motive (Luo & Tung, 2007). Moreover, R&D collaboration represents long-term, reciprocal relations which are based on high level of mutual trust. The trust can also be leveraged by the local firms in network building and thus reduce the Relational Hazards in the following OFDI. Therefore, our second hypothesis is as follows:

H2: Chinese MNEs are more likely to invest in countries with high innovation connectivity to their home region.

3. Social connectivity through friendship cities

'Friendship cities', also known as 'Twin cities', are an informal diplomacy program and social relationship conducted at the subnational level. The program was initiated after the World War II responding to the need of overcoming hostility and consolidating peace (Jayne et al., 2011). This program has been developed by historical, economic, cultural or ideological connections (Baycan-Levent et al., 2010; Jayne et al., 2011). As an important international civic interaction channel, friendship city relationship is believed to produce proximities across distance (Clarke, 2008), facilitate flows of global mobility through people-to-people movements, social interactions, shared activities and reciprocal exchanges (Zelinsky, 1991; Urry, 2007). Since the Opening policy in 1978, Chinese cities has been actively participating in building friendship city relationships (Zhang et al., 2020). Local firms, authorities as well as the inhabitants in a Chinese city are connected to certain foreign locations and are able to obtain more information through frequent social interactions under the framework of friendship city. This helps local Chinese firms to overcome Unfamiliarity Hazards and be better prepared for future investments in such cities or the corresponding countries. On the host side, those social interactions help to promote the understanding and positive attitudes towards China, especially to certain Chinese cities with which they have friendship relationships. These positive attitudes lead the investors originated from those Chinese cities to be seen as more legitimate in the eyes of foreign customers, suppliers, employees, partially eliminating the Discrimination Hazards in OFDI. Thus, the third hypothesis is:

H3: Chinese MNEs are more likely to invest in countries with close social connections through friendship city relationship to their home region.

2.3 Data and descriptive analysis

2.3.1 Data

I use the following data to test the above hypotheses.

1.OFDI information during 2000-2015, obtained from the Name List of the Overseas Direct Investment Projects Statistics of the Chinese Ministry of Commerce. It includes detailed information about the OFDI projects undertaken by Chinese firms, such as the approval time, name and location of the investing firm, investment destination, business description texts, etc.

2.I use patent data to identify R&D collaborations between Chinese regions and foreign countries. Following existing studies, it is measured by the co-invention information reported in patents (Castellani et al., 2021). From the US Patent and Trademark Office dataset (USPTO) during the research period 2000-2015, I identify the co-patenting between foreign inventors with Chinese inventors. The nationality and location of each inventor is identified by their address. The co-invention is defined as a patent who has at least one inventor whose address is within China and also has at least another one whose address is in a foreign country. If one patent includes inventors from more than one Chinese province or multiple foreign countries, then this patent is regarded as co-inventions for all province-country pairs involved.

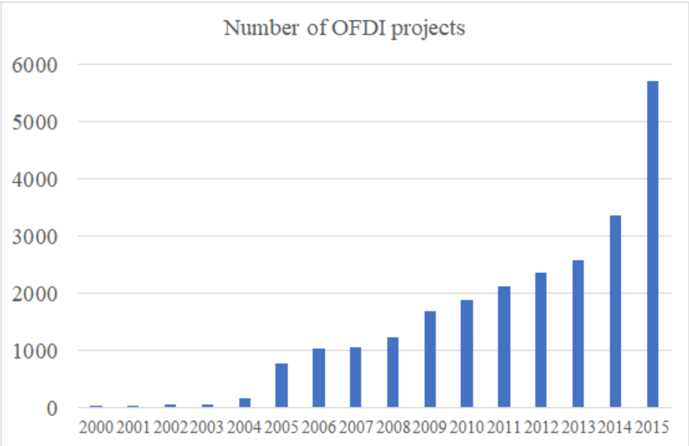
3. The friendship city relationships between Chinese cities and foreign cities are obtained from the 'International friendship city list 1973-2015' of China International Friendship Cities Association. This statistic records the names of Chinese and foreign cities as well as the initial time the relations are established.

4. Trade information comes from China Customs Database. It covers every trade deal between China and foreign countries. I aggregate the import and export value by Chinese province - foreign country pair in each year.

2.3.2 Chinese OFDI- trends and spatial patterns

Figure 2-1 shows the annual OFDI number in our sample. Before 2005, investment projects were less than 100 but jumped suddenly to 800 and kept a stable increase during the period 2005-2014. The year 2015 witnessed another jump in the total OFDI project number which increased suddenly to 5800, nearly doubled the number of the previous year. This can be attributed to the shock from the Belt and Road Initiative launched in 2014, since which the Chinese central government has become more supportive of OFDI. This general trend shows that Chinese OFDI is negligible in terms of project numbers before 2004 but increased very quickly in the following 10 years. From 2016, Chinese OFDI has been found to surpass that of Inward FDI flows (MOFCOM, 2017).

Figure 2-1 Annual Number of Chinese OFDI Projects



Data Source: Chinese OFDI Name List from Commerce Department

I further investigate the geographic distribution of Chinese OFDI by destination area as shown in the second column of Table 1. Most investments go to Northern America, South-eastern Asia, Eastern Asia, and Sub-Saharan Africa where the project numbers are above 2000. Europe as a whole attracted more than 3,000 OFDI projects and more than half are in Western Europe. Eastern Europe, Southern Europe and Northern Africa attract far less Chinese investments, which are all below 500.

OFDI projects with different motives show different destination preferences. The third to sixth columns in Table 2-1 show the share of four investment motives in total project numbers by different destination macro-regions: R&D, Trade, Production and Natural Resources. The motive is identified through keyword searching in the business description text in the Commerce Ministry OFDI Name List. The details of this method are introduced in Appendix A.2. The shares of all motives do not sum to 100% because some projects have multiple motives. OFDI with a trade motive shows shares significantly higher than others, being over 70% in all the regions except Australia and New Zealand, indicating that trade is a major objective for Chinese OFDI. On the contrary, the shares of the other three motives vary with different host regions. That of R&D investment is higher than 20% in advanced economies with strong innovation capabilities, including Northern America, Western Europe, Northern Europe as well as Southern Europe, while this share in other regions is much lower. The share of production OFDI is very high in three macro-regions within Asia, South-eastern Asia, Southern Asia and Central Asia. This may be due to their low labour costs and proximity to China which helps Chinese MNEs to coordinate production more effectively, reflecting the regionalization trend of Global Value Chain (Gereffi & Fernandez-Stark, 2011). Moreover, this share is also high in Africa. For the natural resource exploitation OFDI, not surprisingly Sub-Saharan Africa, Latin America & Caribbean and Central Asia have significant higher shares because of their abundant unexploited natural resources. Different shares among world areas clearly indicate that investments with four motives have specific location preferences.

Table 2-1. Spatial distribution of Chinese OFDI by macro region: project numbers and share by investment motive (2000-2015)

Macro Regions	OFDI Project Numbers	R&D	Trade	Production	Natural Resource
Northern America	5542	20.68%	71.87%	18.08%	3.61%
South-eastern Asia	3494	7.13%	74.99%	46.68%	18.06%
Eastern Asia	2761	13.73%	76.02%	27.96%	8.76%
Sub-Saharan Africa	2271	5.94%	75.08%	37.69%	22.85%
Western Europe	1621	21.16%	79.83%	21.78%	0.99%
Western Asia	1117	7.88%	79.05%	14.95%	2.95%
Australia and New Zealand	1063	8.37%	65.57%	19.29%	15.62%
Southern Asia	894	11.41%	76.85%	38.37%	5.59%
Latin America and the Caribbean	785	7.13%	79.62%	27.01%	20.13%
Central Asia	753	7.30%	77.29%	44.75%	15.94%
Northern Europe	640	26.25%	71.72%	21.09%	2.19%
Southern Europe	402	20.90%	82.09%	27.61%	0.25%
Eastern Europe	360	10.56%	77.78%	31.94%	4.72%
Northern Africa	241	5.39%	79.67%	43.15%	8.30%

Data Source: Chinese OFDI Name List from the Ministry of Commerce

Then I focus on the subnational locations of origin of Chinese MNEs, as shown in Figure 2-2, provincial OFDI project numbers show significant spatial patterns. Most OFDI projects are conducted by some coastal provinces, Shanghai, Jiangsu, Shandong, Zhejiang and Guangdong which are more developed and more open to trade. There are also many OFDI projects originating from the capital, Beijing. Some economically lagging inland provinces such as Tibet, Qinghai, Gansu and Guizhou have nearly no OFDI. At the same time, some border provinces in the north and southwest, especially Heilongjiang, Xinjiang and Yunnan also have higher OFDI numbers because of their proximity to the neighbouring countries.

Figure 2-2 OFDI project numbers by Chinese provinces (2000-2015)

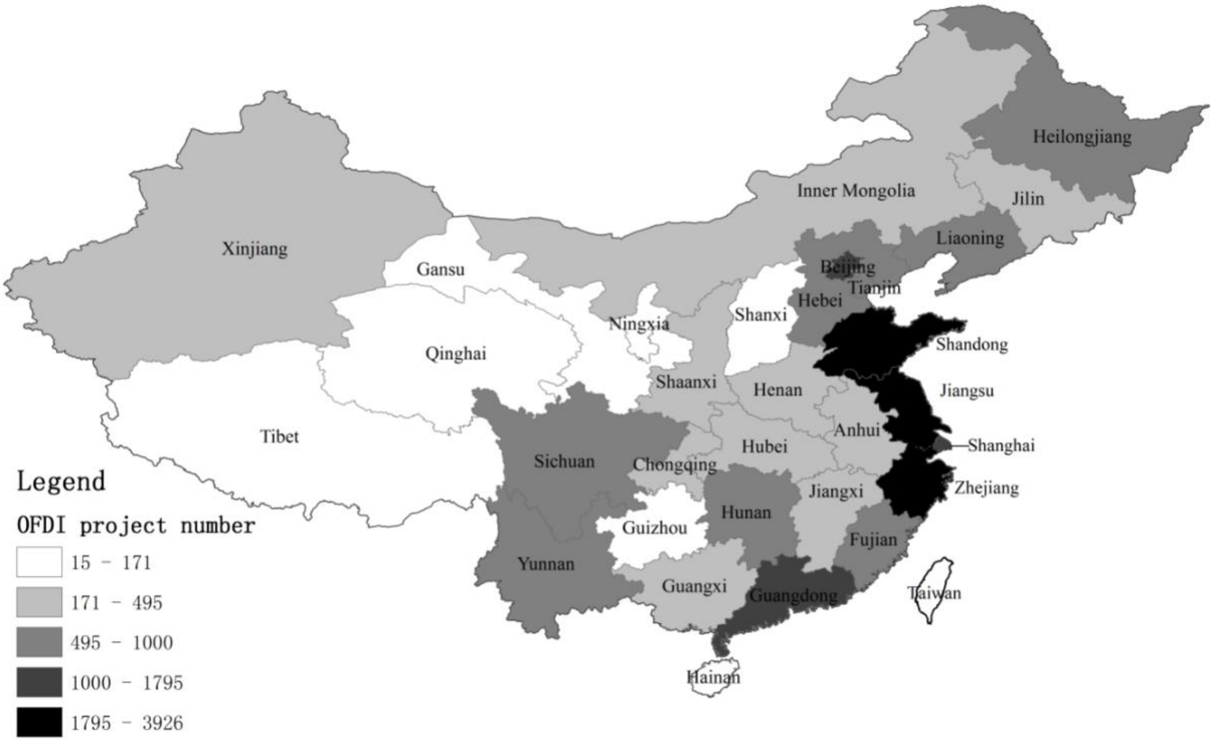


Figure 2-3. Top three OFDI destinations for the 31 Chinese provinces (2000-2015)

At the same time, MNEs originating from different subnational locations within China have different OFDI destination preference. Figure 2-3 shows the top three OFDI destinations for each of the 31 provinces during the research period. As the largest destination of Chinese OFDI, the US is in the top three destinations for most Chinese provinces. At the same time, there exists huge spatial heterogeneity of OFDI destination. Some provinces invest more in their neighbouring countries. For example, Russia is the top destination of provinces in the North East; Mongolia is the top destination for Inner Mongolia; the OFDI from south western provinces goes significantly to ASEAN countries, especially neighbouring countries like Vietnam, Laos, Myanmar and Cambodia. Eastern provinces invest intensively in Korea and Japan. Besides geographic proximity, we can also observe the influence of ethnic or religious ties in the location choice of firms in different provinces. For example, Ningxia, the Autonomous Province of Hui people (a major Muslim ethnicity of China) invests a lot in the United Arab Emirates; Fujian, which shared the same Hokkien dialect with Taiwan[1], substantially invests in the latter. To the best of our knowledge, this subnational spatial difference in OFDI origin-destination preference has not been studied in the literature on Chinese OFDI.

2.3.3 Global connectivity of home regions

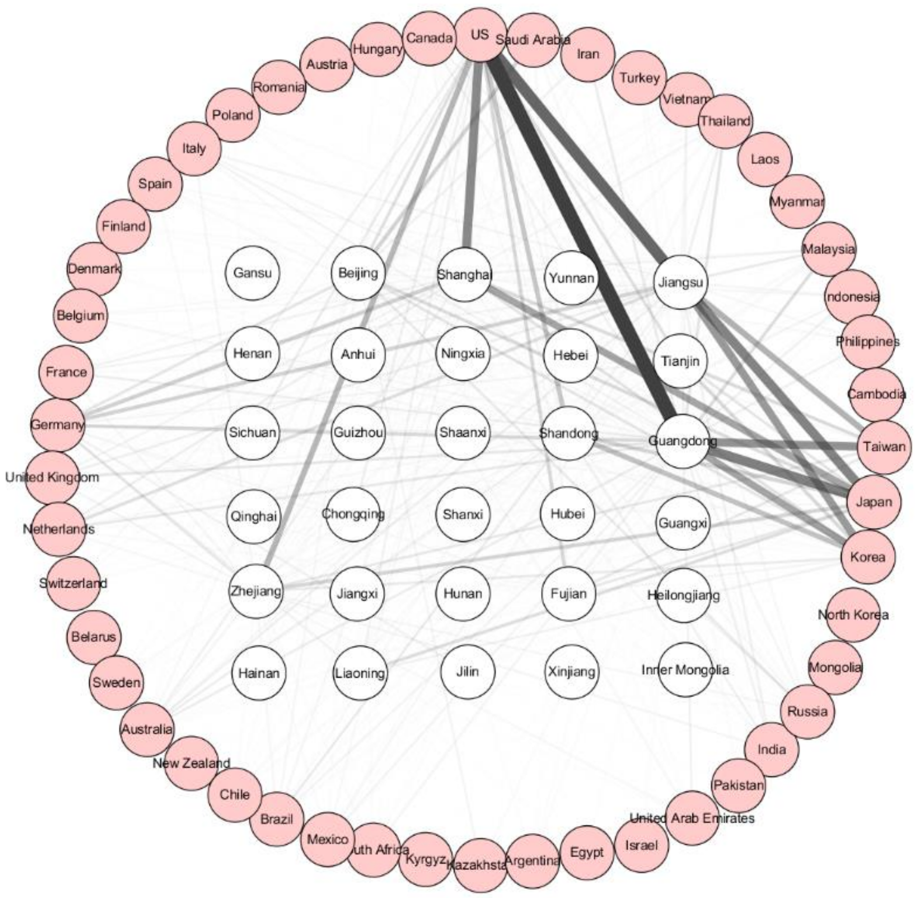
Next, network analysis methods are used to illustrate the three dimensions of connectivity between each country and Chinese province during the study period[2]. Among them, trade connectivity is represented by the sum of export and import value cumulated between 2000-2015; innovation connectivity is represented by the sum of all co-invented patents, and friendship cities are represented by all existing friendship relations between all provinces and foreign countries until 2015. To allow comparison between different networks, these three dimensions of connectivity are all standardized to a score within 0 to 1 through dividing by their highest value. The width of edges in Figures 2-6 is proportional to the connectivity scores.

[1] Taiwan (ROC) is considered by the Chinese government as part of China, but it is economically and politically independent from the mainland, so in this paper it is analysed as a foreign location.
2 For the sake of simplicity, only the top 50 foreign countries with the strongest connectivity with China are listed. These countries, in total, account for more than 92.1% of trade value, 99.7% of patent co-inventions as well as 90.6% of friendship cities with China.

Trade connectivity

As the world factory, China has wide trade relationships with foreign countries. Figure 2-4 shows that trade links are highly concentrated between a few Chinese provinces and foreign countries. Guangdong is the centre of the trade network: its trade with the US is significantly higher than that of any other province-country pair. At the same time, it also has strong trade relations with Japan and Taiwan. Jiangsu also maintains close trade ties with these three foreign countries. In addition, the relationships between Zhejiang and the US, and Shanghai and Germany are also very strong. The above-mentioned provinces are mostly southern coastal provinces. Since the Reform and Opening in 1978, those regions were firstly designated as open areas, and within them exporters and foreign investors received more favourable treatment (Zhou et al., 2002). In comparison, other provinces are less open or opened later. This contributes to big difference in the external trade connectivity.

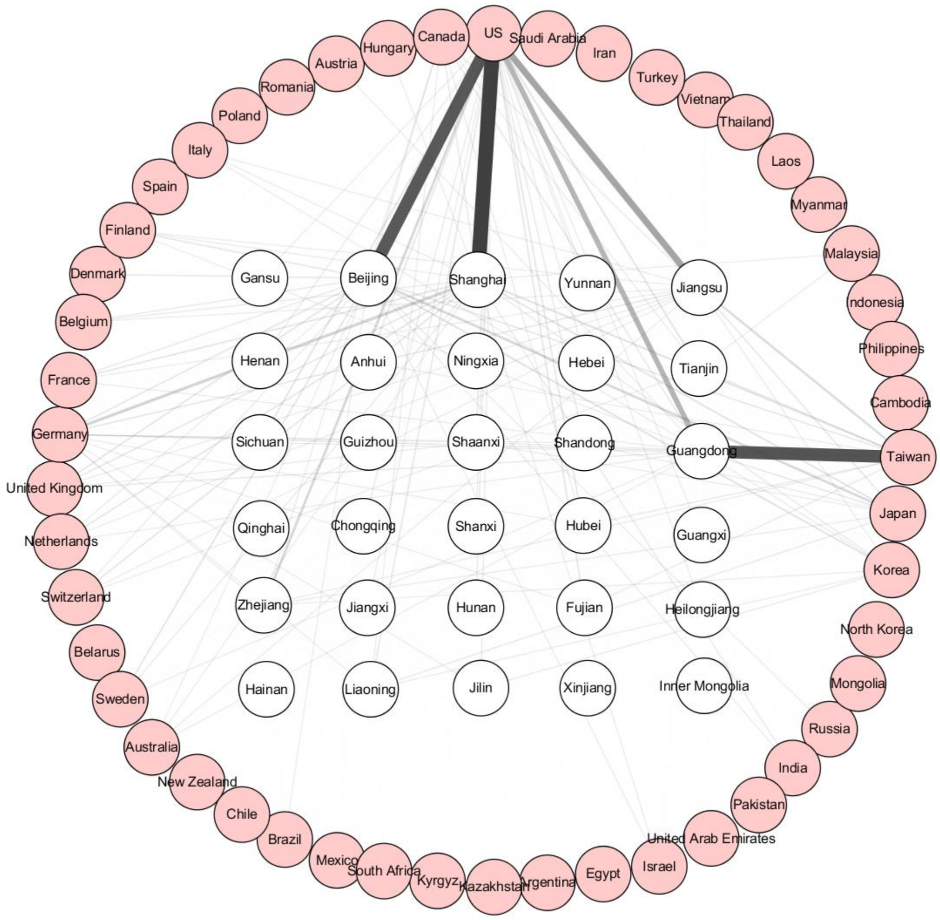
Figure 2-4. The international trade network, cumulative trade value 2000-2015 between Chinese Provinces and foreign countries



Innovation connectivity

More and more firms in emerging markets are participating in international R&D collaborations, which could provide them an opportunity to catch up with advanced economies. Among emerging markets, China's international R&D collaboration has increased significantly. find that USPTO patent applications by Chinese inventors have increased by 10 times over the past two decades and one-third are related to joint inventions with foreign partners (Ma et al., 2009; Chen et al., 2013). As shown in Figure 2-5, innovation connections are highly concentrated in China's three major innovative regions - Beijing, Shanghai and Guangdong. Beijing and Shanghai have established very close collaboration relations with the US, while Guangdong is closely connected to Taiwan. At the same time, the US also has close ties with Jiangsu and Guangdong, and Germany links to Shanghai. In contrast, other province-country pairs have only very sparse co-inventions. These results indicates that innovation collaboration, as a high-level external connection, is highly concentrated between China's most innovative regions and a few innovation centres of the world.

Figure 2-5. The innovation network, number of USPTO co-invented patents during 2000-2015 between Chinese provinces and foreign countries

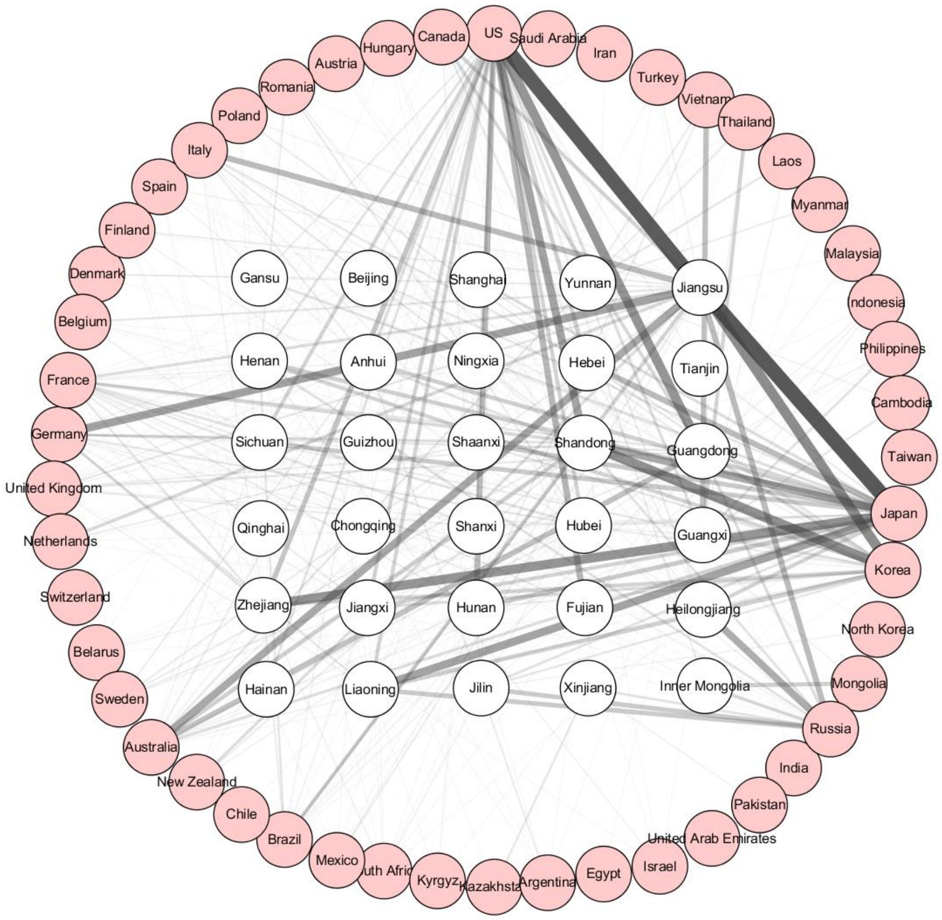


Friendship city networks

It can also be seen from the friendship city network in Figure 2-6 that Jiangsu has the strongest global connectivity and has established many friendship city relations with the US, Japan, Australia, Germany, Italy, and Germany. In addition, Shandong, Zhejiang, Guangdong, Heilongjiang, and some other provinces also have linkages with cities in certain foreign countries. Some of the relationships reflect geographical and historical ties. For example, Liaoning has close ties with Japan, partly because of the strong economic and industrial influence from the latter: Liaoning used to be the major economic centre of Manchukuo during the Japanese occupation period in the World War II. Secondly, due to geographical proximity, Shandong has a strong friendship relationship with South Korea; the same applies to the North East provinces of Heilongjiang and Jilin with Russia; Guangxi, which is on the south western border, with the neighbouring South East Asian countries, such as Vietnam, Thailand, and

Cambodia. At the same time, some friendship city relations also reflect ethnic ties. For example, the Inner Mongolia Autonomous Region has only established friendship with cities in Mongolia, while Guangdong Province, with large amount of immigration in the US since the late Qing Dynasty, has close friendship with cities in the latter.

Figure 2-6. The number of friendship cities between Chinese Provinces and foreign countries



In summary, the network analysis shows that at the subnational level, the network structure differs significantly among the three types of connectivity. Innovative connectivity measured by patent co-invention is the most centralized, it is largely concentrated between a few Chinese provinces and foreign countries. This reflects the highly agglomerated nature of innovation activities, and as a high-level connection, co-invention only happens between the most innovative centres. The trade network is also concentrated between China's eastern coastal regions and western developed countries. In comparison, social connectivity measured by the friendship city network is more scattered, and the relationships reflect complex historical and cultural ties and geographic proximity. At the same time, in each network, the global connectivity of various provinces within China is significantly different, not only in its intensity, but also with respect to its geography. For example, although the US is China's largest trading partner, it still shows significant variation across provinces. Some provinces have much larger trade volume with countries other than the US, such as Shandong with South Korea, Liaoning with Japan, and Heilongjiang with Russia. At the same time, the connection intensity of the same province also varies with the type of connectivity. For example, Guangdong's largest trading country is the US, but at the same time, its patent co-inventions with Taiwan are the highest. In the next section, I use an econometric model to study how this different connectivity affects the local firms' OFDI.

2.4 Econometric analysis

2.4.1 Model and variables

According to the OFDI Name Lists, there are 197 countries/regions having received Chinese MNEs in the research period. Some host countries were excluded from our data sample. First, financial centres such as Hong Kong, Macau, Virgin Islands, Cayman Islands are dropped as they are not counted as final destinations of OFDI and it is hard to identify their exact nature. Second, countries with less than 10 Chinese OFDI projects are deleted. The model thus come up with 125 host countries. The details are listed in Appendix A.1.

This paper utilizes a gravity model to test the determinants of FDI between Chinese subnational regions and foreign countries and evaluate the influence of global connectivity. The gravity model has been widely used in research on FDI and international trade (e.g., Benassy-Quere et al., 2007, Daude & Stein, 2007), on the basis of the assumption that trade, investments or other flows between cities, countries and continents depend positively on the size of the economies and negatively on the distance. Using the gravity model, I include variations on three dimensions as shown in equation 1. The regression units of my panel are 3,875 pairs between 31 Chinese provinces and 125 host countries during 2000-2015. All independent variables in the model enter with one year lag.

$$OFDI_{i,j,t} = \beta_0 \cdot Connectivity_{i,j,t-1}^{\beta_1} \cdot Home\ region\ features_{i,t-1}^{\beta_2} \cdot Host\ country\ features_{j,t-1}^{\beta_3}\ \mu_{i,j} \quad (1)$$

where $OFDI_{i,j,t}$ denotes the number of OFDI projects conducted by firms from Chinese province i to host country j in year t. $Connectivity_{i,j,t}$ is the degree of connectivity between region i and country j in term of trade value, number of USPTO co-invented patents, and number of friendship cities. The trade and co-invention are measured as flow in year t-1, while the friendship city is measured as stock from 1973 until year t-1, because once a friendship is built, there will be a long-term impact and interactions. I select the home region-specific, host country-specific factors by referring to the existing literature on Chinese OFDI to ensure the validity of our estimation. β_2 and β_3 capture the propensity to send FDI from home regions and attracting FDI by host countries, respectively. All the data sources and descriptive information of variables are summarized in Table 2-2.

Table 2-2. List of variables, data sources and descriptive information

	Variable	Data Sources	Unit	Observations	Mean	Min	Max
Dependent	OFDI project number	OFDI Name List of the Ministry of Commerce	Number	62,000	0.387	0	273
Host country features	Country GDP	World bank WDI	Million USD	59,551	456848.4	483.064	1.67e+07
	Country GDP per capita	World bank WDI	Thousand USD	59,551	14.0702	0.194	111.968
	Country patent per capita	World bank WDI	Number/Million people	61,008	93.377	0	3278.941
	Total natural resources rents	World bank WDI	Percent	59,613	10.265	0	82.529
	Country political stability	WGI indicator	Score	60,543	-0.1449	-2.97	1.76
Home region features	Province GDP	Chinese Provincial Yearbook	Million RMB	58,125	118795.7	1392.43	728126.5
	Province GDP per capita	Chinese Provincial Yearbook	Thousand RMB	58,125	5065.224	548.0002	19403.58
	Province patent per capita	Chinese Provincial Yearbook	Number/Million people	58,125	680.172	5.376	7927.747
	Province	NERI	Score	62,000	5.793	-0.3	10.92

	marketization degree						
Connectivity	Export	Chinese custom dataset	Million USD	62,000	209.431	0	102288.9
	Import	Chinese custom dataset	Million USD	62,000	186.153	0	65448.32
	Co-invention	USPTO	Number	62,000	0.5398	0	1184
	Friendship cities	Friendship city association of China	Number	62,000	0.364	0	35

For home regions, I first incorporate provincial *GDP* as well as *GDP per capita* to control the regional economic scale and development level. Technology ability is important for firms to internationalize, I include the technology capabilities of Chinese provinces, measured by patent application numbers. The data for the above variables was obtained from the Chinese National Statistics Bureau. Moreover, following recent empirical studies on Chinese OFDI that argue the importance of home region marketization degree for OFDI (Liu et al., 2014; Sun et al., 2015), the institutional variance among 31 provinces is measured by the annual marketization grades assessed by the National Economic Research Institute of China (NERI) (Fan et al., 2011).

I also control for host country features according to the different location advantages attracting OFDI (Dunning, 1987). Host country data is obtained from World Bank dataset. First, I control for the market scale, measured by the constant GDP. Second, country labour cost is included in the model as Chinese firms are relocating their production line, especially for some traditional industries to countries with low labour costs (Ren & Yang, 2020). Due to the lack of detailed salary data for every host country, the *GDP per capita* is used to capture average labour costs. Third, I control natural resource endowments by *'Total natural resources rents'*, which are "the sum of oil rents, natural gas rents, coal rents (hard and soft), mineral rents, and forest rents in the percentage of country's annual GDP". Fourth, patent number is used to measure the abundance of strategic assets in the host country. I also control the institutional stability of host countries which is found to influence MNEs' entry willingness and entry mode selection (e.g. Buckley et al. 2007; Cheung & Qian, 2009; Ramasamy et al. 2012; Ascani et al., 2016). It is measured by the index Political Stability in the Worldwide Governance Indicators

(WGI). The correlation matrix among independent variables is shown in the Appendix Table A 2-2. Although there are some strong correlations among control variables, such as country GDP and country patent numbers, the correlations with main regressors, 3 dimensions of connectivity are acceptable.

In the regression, I take the z-score standardization form for both dependent and independent variables with means of zero and standard deviations of one. The regression results are interpreted as how many standard deviations of OFDI number increase with one standard deviation increase of independent variables. In this paper I use multiple estimation methods: starting with pooled cross section models with different fixed effects to control for invariant home and host features. Then main empirical results are interpreted on the basis of a panel model with province-country pair fixed effect. This pair fixed effect can capture the potential invariant relationships between home region and host country which can be confounding factors to our variables of interest (like the distance).

2.4.2 Result analysis

The results using different regression methods are presented in Table 2-3. Columns 1 and 2 are two pooled cross section models, the former only control the year fixed effect while the latter also includes province and country FE. Column 3 shows the result of panel model with pair fixed effect. For the variables of interest, the three dimensions of global connectivity, we observe that export has significantly positive correlation with OFDI in all the four estimations, while import is negative and insignificant in the fixed effect panel model and significantly negative in the pooled cross section models. These results indicate a positive influence of trade connectivity, but only for export. Therefore, the hypothesis 1 is only partially verified.

The coefficients of the innovation connectivity and friendship cities are significantly positive and robust among all model settings. These results confirm hypotheses 2 and 3 suggesting that if a country has stronger innovation collaborations and more friendship city relationships with a Chinese province, it is more attractive for the investment of Chinese MNEs originating from that province. Our regression results show that R&D collaboration has a strong correlation with OFDI — it is a reliable channel encouraging OFDI, which is in line with the findings of Castellani et al. (2021) that R&D collaboration of US metropolitan areas is conducive to attracting IFDI. Moreover, R&D collaboration may play an increasingly important role, as both international patenting and international R&D alliances are rapidly increasing for China (Chen et al., 2013; Su, 2017). The result of friendship cities illustrates the strong positive influence of civic interactions and social connectivity on Chinese OFDI. This finding is in line with (Zhang et al., 2020), which argues that the number of international friendship cities and the variety of countries engaged tend to encourage local firms to invest abroad. Our results find this cross-nation friendship not only increases the investment willingness of local firms, but also influence the OFDI location choice.

Table 2-3. Results for full OFDI sample with three regression settings

VARIABLES	(1) Pooled Cross section OFDI	(2) Pooled Cross section OFDI	(3) FE Model OFDI
Trade connectivity (import)	-0.0167***	-0.0151***	-0.00331
	(0.00473)	(0.00465)	(0.00664)
Trade connectivity (export)	0.406***	0.381***	0.522***
	(0.00496)	(0.00487)	(0.00692)
Co-invention	0.443***	0.420***	0.533***
	(0.00513)	(0.00496)	(0.00567)
Friendship cities	0.149***	0.157***	0.389***
	(0.00476)	(0.00486)	(0.0130)
Country GDP	0.115***	1.902***	1.039***
	(0.00575)	(0.0546)	(0.0461)
Country GDP per capita	-0.0292***	-0.189***	-0.264***
	(0.00456)	(0.0474)	(0.0374)
Country Patent	-0.0880***	0.271***	0.220***
	(0.00578)	(0.0256)	(0.0207)
Total natural resources rents	0.0196***	0.0342***	0.00219
	(0.00356)	(0.0108)	(0.00819)
Country Political Stability	0.00383	0.0433***	0.0462***
	(0.00443)	(0.0108)	(0.00863)
Province GDP	0.0429***	0.131***	0.0978***
	(0.00829)	(0.0140)	(0.0103)
Province GDP per capita	-0.00257	0.0371***	-0.0263***
	(0.00610)	(0.0136)	(0.00717)
Province Patents	0.0422***	0.00756	-0.0203***
	(0.00717)	(0.00940)	(0.00714)
Province	-0.00519	0.00100	0.0196***

marketization degree			
	(0.00584)	(0.0156)	(0.00742)
Constant	0.0299***	0.0238***	0.0200***
	(0.00799)	(0.00352)	(0.00272)
Country FE	N	Y	N
Province FE	N	Y	N
Pair FE	N	N	Y
Observations	50,995	50,995	50,995
R-squared	0.502	0.547	0.507
Number of province-country pairs	-	-	3,689

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Concerning the control variables of host country characteristics, *GDP* exerts a positive and statistically significant effect on OFDI for all three model, suggesting the market scale is essential determinants of Chinese OFDI, reflecting the market-seeking motive of Chinese MNEs (Kang & Jiang, 2012). On the contrary, *GDP per capita* shows a negative impact. The *Country Patent* is significantly positive for the FE model in column 3, which is consistent with the argument that Chinese MNEs have strong motives to seek strategic assets (Luo & Tung, 2007). The *Institutional Stability* is also significantly positive, indicating that Chinese OFDI projects are attracted to host countries with better institutional environment, the same with the location preference of western MNEs and other studies on Chines OFDI: well-developed host country institutions increase the likelihood of entering that country and help compensate the shortage of international experience for Chinese investors (Lu et al., 2014). For the home region features, OFDI is more likely to originate from provinces with larger economic scale. In contrast, the coefficients of provincial *GDP per capita* and *Patent numbers* are negative, implying that market size is more important than economic structure in fostering OFDI. The marketization degree has a positive impact in the fixed effect panel model, our empirical results are in line with the institutional-fostering view— OFDI of emerging market is facilitated by favourable local institutional environments (e.g. Deng & Zhang, 2018).

2.4.3 Investment motive heterogeneity

In addition to the full sample model, following related research, including Castellani et al. (2013); Zhou & Guillen (2017); Crescenzi et al. (2016); and Castellani et al. (2021), I further exam the heterogenous impacts on OFDI with different motives. Dependent variables are numbers of investments for trade, production, R&D as well as nature resources respectively, in the form of z-score standardized values. As shown by models 5-8 in Table 2-4, OFDI with four motives differ in the sensitivity to different connectivity. For trade connectivity, import value is negative in the full sample model 3 but turns to be positive in the production and resource models. And its coefficient for the resource model is higher than that of the production model. This may be because these two types of investment are closely related to imports of products and raw materials, especially, natural resource imports account for a large proportion of China's total imports. In addition, export facilitates investments with all motives except natural resources, and it shows higher impacts in the trade and production models. Similarly, co-invention connectivity has the highest impact on R&D investment. Interestingly, friendship city shows a significant positive impact for all motives, and the coefficients are very close. These results show that some dimensions of connectivity promote OFDI with specific motives, such as import for natural resource investment and co-invention for R&D investment. Friendship city, on the contrary, is universal and has very similar impacts on all motives. Moreover, the impacts of some control variables vary with investment motives. For example, host market size, measured in term of Country GDP has the highest coefficient for trade model, while the negative effect of *Country GDP per capita* is stronger for production investments which seek low labour costs comparing with China. At the same time, the variable, *Total natural resources rents* is only significant for the resource investments which involve huge capital inputs and thus are also sensitive to the *Country political stability*.

Table 2-4. Results for OFDI with four motives, fixed effect regression

VARIABLES	(5) FE Model Trade	(6) FE Model Production	(7) FE Model R&D	(8) FE Model Resource
Trade connectivity (import)	-0.0278***	0.0354***	-0.0677***	0.0589***
	(0.00647)	(0.00827)	(0.00744)	(0.0101)

Trade connectivity (export)	0.637***	0.546***	0.653***	-0.00412
	(0.00674)	(0.00862)	(0.00776)	(0.0105)
Co-invention	0.402***	0.222***	0.635***	0.134***
	(0.00553)	(0.00707)	(0.00636)	(0.00860)
Friendship cities	0.239***	0.299***	0.298***	0.240***
	(0.0127)	(0.0162)	(0.0146)	(0.0198)
Country GDP	0.936***	0.632***	0.534***	0.456***
	(0.0449)	(0.0574)	(0.0517)	(0.0699)
Country GDP per capita	-0.267***	-0.278***	-0.160***	-0.0415
	(0.0365)	(0.0466)	(0.0419)	(0.0567)
Country Patent	0.239***	0.137***	0.201***	0.0521*
	(0.0201)	(0.0257)	(0.0232)	(0.0313)
Total natural resources rents	0.0123	0.00165	-0.00725	0.0681***
	(0.00799)	(0.0102)	(0.00919)	(0.0124)
Country Political Stability	0.0365***	0.0637***	0.0160*	0.0868***
	(0.00841)	(0.0107)	(0.00968)	(0.0131)
Province GDP	0.116***	0.250***	0.0292**	0.247***
	(0.0101)	(0.0129)	(0.0116)	(0.0156)
Province GDP per capita	-0.0373***	-0.0776***	-0.0178**	-0.0142
	(0.00699)	(0.00893)	(0.00804)	(0.0109)
Province Patents	-0.0249***	-0.0336***	-0.00894	-0.0680***
	(0.00696)	(0.00890)	(0.00801)	(0.0108)
Province marketization degree	0.0166**	0.0368***	0.00796	-0.0277**
	(0.00724)	(0.00925)	(0.00833)	(0.0113)
Constant	0.0199***	0.0272***	0.00946***	0.0275***
	(0.00266)	(0.00339)	(0.00306)	(0.00413)
Country FE	N	N	N	N
Province FE	N	N	N	N
Pair FE	Y	Y	Y	Y
Observations	50,995	50,995	50,995	50,995
R-squared	0.498	0.300	0.498	0.046
Number of province-country pairs	3,689	3,689	3,689	3,689

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

2.5 Conclusion and discussion

IB scholars have long studied how MNEs organize their global value chains and operations by choosing suitable investment destinations with specific Location Advantages (e.g. Buckley, 2007). However, our knowledge of the influence of the locations of origin of EMNEs at the subnational level is still limited. As globalization processes accelerate, regions show deep interdependence with each other through various external economic, technological, and social connections. On this background, this paper places OFDI activities in an open and spatially interdependent framework. I build the theoretical framework by connecting IB studies with the global connectivity literature in EG, arguing that local firms originating from regions with wide connectivity can leverage cross-border linkages and access overseas information and networks before investing abroad, which adds to their internationalization advantages in closely connected foreign locations. In this way, spatial behaviours of MNEs are not only determined by host locations' features but are also deeply embedded in the network structure of flows between home and host.

The case of China enables us to empirically test the influence of global connectivity, not only because of its huge subnational heterogeneity, but also because Chinese firms did not start to invest abroad until other connectivity has already existed. The spatial differences of connectivity work as a specific local condition, making Chinese MNEs from different origins choose diverse host locations. The empirical model investigates OFDI projects from 31 Chinese provinces to 125 host countries during 2000-2015. Our results show this FDI flow is jointly shaped by the pull factors in host counties, push factors in home regions as well as prior connectivity between these two locations. Connectivity between home and host is proven to have a strong influence on Chinese OFDI, while such an influence varies with the type of connectivity and investment motives. I find significant facilitating roles for prior patent co-inventions and friendship city relationships, while the influence of trade is ambiguous, with a positive effect for export but a negative one for import.

This paper contributes to the location perspective studies in IB. Differently from existing literature on the home country advantages (Rugman & Li, 2007; Gaur et al., 2018) and on cross-national distances (Kang & Jiang, 2012; Zhou & Guillen, 2016), the subnational level can give a deeper analysis of spatial differences, which is especially important for large countries with vast geographic heterogeneity. By analysing at this finer level, this paper argues that the widely-discussed home country advantage is not homogenously accessible to all firms within the national boundary. Second, the discussion on home regions' global connectivity is especially important for understanding the internationalization mechanisms of EMNEs. The conventional

FDI path of MNEs in developed countries is depicted in the Uppsala model as using the advanced ownership advantages and achieving global expansion through experimental investments gradually, starting from near locations to distant ones (Johanson & Vahlne, 1977). EMNEs, as new players in the global arena, have lower firm specific ownership advantages compared with their western counterparts, however they adopt more aggressive OFDI strategies into some distance locations (Ren et al., 2012; Clegg et al., 2016). Our findings suggest that existing external connectivity of home regions remedies the lack of firms' international experience, helps alleviate the LOF and lead them to certain distant locations.

Our findings offer practical implications. This research reveals that the location choice of Chinese OFDI is jointly determined by location bounded resources and regional connectivity. Decision makers should keep in mind that abundant host country resources itself does not ensure the success and profitability of OFDI. Because of LOF, foreign companies also need close connectivity to get access to those resources. One effective way is leveraging the global connectivity of home regions. If regions lack capability to build global connectivity by themself, they may need to strengthen the interregional networks and cooperation within China and use other regions' global connections.

Second, Chinese OFDI is found to have strong effects on the host countries, in terms of capital accumulation, employment and productivity growth, especially in developing countries (Crescenzi & Limodio, 2020; Fu & Buckley & Fu, 2020). This paper provides implications for the policy makers that an effective way to attract Chinese OFDI is to leverage the current connectivity with China or build new networks. Connectivity is not established only at the national level, such as formal diplomatic relationships (Sun & Liu, 2019), but also happens at the subnational level, such as civic interactions organized by the local authorities and public or technology exchanges by the innovation communities. Those linkages also help to attract Chinese firms from the connected locations.

Several limitations of this study need to be noted, leading to avenues for further investigation. First, because of the deep interdependence between OFDI and some unobservable factors, such as other global connectivity types, the econometric models suffer from potential endogeneity. I recognize that it is difficult to argue that our results can capture the causal relationships between them. Future research should pay attention to the exogenous shocks, such as policy changes impacting certain global connectivity dimensions but not OFDI decisions in order to further understanding their relationship. In addition, because of data availability, this research uses the OFDI project number as the proxy for OFDI. However, OFDI projects from different home regions may significantly differ in investment sizes - those from large firms located in Beijing and Shanghai may be larger than others from peripheral provinces. Moreover, besides the 3 dimensions of connectivity discussed in this paper, some other connectivity is also important for OFDI location choice, especially the prior connectivity through inward FDI. However, there are no available and complete statistics on the inward FDI by Chinese provinces and 125 foreign countries in my sample. The next chapter uses the representative countries as a small sample to study the effect of Inward FDI on OFDI innovation performance of CMNEs. Future studies with further disaggregated data, possibly allowing for comparisons of the influence on the home region through more global connectivity channels, will hopefully provide more evidence on this topic.

Appendix

A.1 List of sample countries/regions

List of 125 host countries and Chinese OFDI project numbers during 2000-2015:

United States(4884), Russia(1457), Japan(1030), Australia(943), South Korea (867), Vietnam(857), Germany(833), United Arab Emirates(685), Canada(658), Indonesia(646), Laos (635), Thailand(489), Cambodia(438), United Kingdom(438), Mongolia(406), Malaysia(402), India(377), Nigeria(311), Netherlands(310), Kazakhstan(301), France(275), Myanmar(272), Taiwan(258), Italy(256), Brazil(231), South Africa(212), Korea, Dem. People's Rep.(200), Uzbekistan(178), Philippines(174), Ethiopia(170), Zambia(167), Bangladesh(162), Kyrgyz Republic(152), Pakistan(146), Tanzania(140), Saudi Arabia(135), Ghana(132), Mexico(123), Kenya(123), Spain(122), New Zealand(120), Egypt, Arab Rep.(117), Turkey(113), Tajikistan(99), Chile(95), Angola(95), Iran, Islamic Rep.(92), Sweden(88), Zimbabwe(85), Mozambique(83), Congo, Dem. Rep.(83), Poland(83), Algeria(74), Belgium(73), Sri Lanka(68), Uganda(68), Sudan(65), Switzerland(65), Ukraine(64), Peru(63), Romania(62), Hungary(57), Argentina(55), Seychelles(50), Nepal(49), Namibia(43), Colombia(43), Mauritius(42), Israel(41), Luxembourg(40), Ecuador(38), Denmark(36), South Sudan(36), Morocco(36), Finland(36), Cameroon(35), Czech Republic(34), Bolivia(34), Mali(34), Madagascar(33), Fiji(33), Belarus(32), Cuba(32), Togo(32), Venezuela (31), Liberia(30), Guinea(29), Western Samoa(29), Botswana(29), Congo, Rep.(28), Bulgaria(28), Equatorial Guinea(28), Sierra Leone(27), Qatar(27), Ireland(25), Austria(25), Gabon(25), Turkmenistan(23), Libya(23), Benin(22), Papua New Guinea(22), Senegal(21), Georgia(21), Côte d'Ivoire(19), Brunei Darussalam(19), Mauritania(18), Jordan(18), Norway(17), Azerbaijan(17), Samoa(16), Uruguay(16), Portugal(14), Bahrain(14), East Timor(13), Syrian Arab Republic(13), Oman(11), Cyprus(11), Niger(11), Yemen, Rep.(11), Malawi(10), Serbia(10), Djibouti(10), Chad(10), Guyana(10)

List of 67 excluded countries/regions

New Caledonia, Guatemala, Saint Lucia, Puerto Rico, Bosnia and Herzegovina, Moldova, Somalia, Belize, Monaco, French Guiana, Dominica, Kiribati, Nicaragua, Bahamas, Guinea (Bissau), Palau, Comoros, Palestine, Burkina Faso, Armenia, Iceland, Marshall Islands, Island, San Marino, Cape Verde, Dominican Republic, Republic of the Marshall Islands, Grenada, Congo, Estonia, Republic of Macedonia, Latvia, Federated States of Micronesia, Gambia, Serbia and Montenegro, Montenegro, Slovenia, Paraguay, Tonga, Croatia, British Anguilla, Barbados, Antigua and Barbuda, Slovakia, Burundi, Central African Republic, Jamaica, Lesotho, Lebanon, Eritrea, Bosnia and Herzegovina, Lithuania, Trinidad and Tobago, Maldives, Tunisia, Albania, Afghanistan, Malta, Suriname, Vanuatu, Rwanda, Kuwait, Costa Rica, Iraq, Bermuda, Cayman Islands

A.2 Identification of Investment Motives

The investment motives are classified according to Dunning's classification: Technology and R&D (strategic asset-seeking), Production (efficiency-seeking), Trade (market-seeking), Resource (natural resource-seeking) (Dunning, 1987). The OFDI motive is identified by searching keywords in the variable "Investment business" which is a text format description of the expected activities in host countries reported in the investment name list. The keywords used to classify investment motives are listed in Table A 2-1. below. Some investment projects involve multiple motives.

Table A 2-1. Keywords Used for Investment Motive Identification

Investment motive	Key words identification
R & D/ Technology	"R & D", "Technology Introduction" Research and Development, "Product Development", "Research", "Design"
Trade	"Import and Export", "Trade", "Sales", "Contact Customers", "Market Expanding"
Production	"Production", "Manufacturing", "Processing"
Resource	"Mineral", "Mining", "Nature resource" "Exploitation", "Exploration", "Natural Gas", "Crude Oil", "Wood"

Note: Some key words have several synonyms in Chinese. All the synonyms are used to identify the investment motive.

Table A 2-2. Correlation matrix of independent variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1.Country GDP	1												
2.Country GDP per capita	0.3191	1											
3.Country Patent	0.7733	0.2307	1										
4.Total natural resources rents	-0.1624	-0.1937	-0.1289	1									
5.Country Political Stability	0.1496	0.6176	0.1462	-0.2085	1								
6.Province GDP	0.0139	0.015	0.0033	-0.0084	-0.0044	1							
7.Province GDP per capita	0.017	0.0184	0.0041	-0.0069	-0.0058	0.5431	1						
8.Province Patents	0.01	0.0103	0.0023	-0.0141	-0.0023	0.841	0.5059	1					
9.Province marketization degree	0.0049	0.0069	0.0019	0.0108	-0.0048	0.5857	0.5227	0.5283	1				
10.Trade connectivity (import)	0.2411	0.0985	0.3299	-0.0341	0.0587	0.1761	0.1761	0.1797	0.153	1			
11.Trade connectivity (export)	0.3911	0.1137	0.3349	-0.061	0.0562	0.2041	0.1315	0.2213	0.147	0.5418	1		
12.Co-invention	0.267	0.0591	0.1891	-0.0255	0.028	0.0431	0.0814	0.0532	0.0505	0.2664	0.5066	1	
13.Friendship cities	0.5208	0.2136	0.5958	-0.1371	0.1328	0.1533	0.0673	0.1452	0.1208	0.4386	0.4967	0.1549	1

Chapter 3. The Impact of Outward FDI on the Firm Innovation Performance: The Influence of Inward FDI

3.1 Introduction

Existing literature on the internationalization of multinational enterprises from emerging economies (EMNEs) is based on two basic arguments about their special motivation and mechanism. First, EMNEs are depicted as lacking ownership advantages and firm specific resources as descripted in the classical International Business theories, such as the OLI paradigm and in particular the Resource Based View (Hymer,1960; Dunning,1988; Barney,1991). They internationalize through leveraging general advantages embedded in the home country context, for example, government support, domestic production capability and market size, membership of business groups as well as prior linkages with multinationals from developed economies (DMNEs) (Mathews, 2002; Luo & Han, 2010; Yiu, 2011; Bhaumik et al., 2016; Gaur & Ding, 2018). These home advantages work as substitutes for firm-specific advantages and facilitate the internationalization of EMNEs. The second argument is that EMNEs internationalize to acquire and augment new resources, especially strategic assets which are not available at home (Luo & Tung, 2007; Rui & Yip, 2008; Meyer et al., 2009). Empirical studies find that by investing abroad, EMNEs improve their R&D expenditure, patent applications and productivities and narrow the technology gaps with DMNEs in a relatively short time (Fu et al., 2017; Li et al. 2018; Piperopoulos et al., 2018; Howell, 2020). However, there exists a prominent missing link between these two basic arguments - it is not fully understood whether and how these specific home advantages hinder or help EMNEs achieve their resource augmentation motivation.

DMNEs have spatially restructured their global value chain and relocated many operations, including production, marketing and even some R&D activities to emerging countries (Nolan, 2001; Dicken, 2010). This makes the exposure to foreign MNEs to be an important home country feature for EMNEs. Many are found to experience "inward internationalization" and "outward internationalization" in sequence. Before investing abroad, they have already established various connections with foreign business networks in the home country. This "inward internationalization" is found to influence their subsequent outward FDI, including the investment motivations, location choice, and entry mode (Luo, 2007; Gu & Lu, 2011; Hertenstein, 2017). The two-way transnational investments are recognized as important catching-up opportunities for EMNEs - on the one hand, FDI from advanced economies is a major source of external knowledge and has spillover effect on local firms - on the other hand, EMNEs use internationalization as a springboard to acquire strategic assets and establish their competitiveness in their home market and globally (Luo & Tung, 2007, 2018; Rui & Yip, 2008;

Deng, 2009; Luo & Bu, 2018; Kumar et al., 2019). However, given such deep interdependency between inward and outward FDI and their prominent roles in technology upgrading for EMNEs, the interaction between these two internationalization processes has been less explored due to significant methodological problems associated with disentangling them empirically.

How do IFDI and OFDI jointly shape the innovation path of EMNEs? Do prior linkages to foreign investors influence the innovation benefits of EMNEs in their subsequent OFDI? And what types of IFDI linkages with Chinese firms (between-firm and intra-firm; inter-industry and intra-industry; geographic proximity and industrial relatedness) lead to higher influence on OFDI-led innovation gains?

To answer these important but unanswered questions, this paper investigates the influence of IFDI on OFDI-led innovation gains and try to understand the interdependency between inward and outward FDI and their joint impacts on the innovative performance of Chinese MNEs. China has rapidly changed its international investment position. It has long been one of the largest FDI recipient country since 1990s. At the same time, Chinese outward FDI accelerated since 2000 and exceeded FDI inflows in 2016, turning China to be a net investor (Liu et al. 2005; MOFCOM, 2017). Against this backdrop, many Chinese firms have built various linkages with subsidiaries of DMNEs in China, such as supply and demand relationships, joint ventures (JV) and original equipment manufacturer (OEM) before investing abroad (Zhang & Song, 2001; Sodhi & Tang, 2013). By doing so, they not only get access to advanced technologies, but also obtain international management practice, production standards, market information as well as a better awareness of institutional and cultural contexts of foreign countries (Child & Yan, 2001). The extensive two-way FDI flows make China a suitable case to study the aforementioned research questions.

Empirically, first I use a sample of Chinese manufacturing firms (with annual sales higher than 5 million RMB) to measure the causal effect of IFDI on innovation performance, measured by the patent applications in SIPO. The OFDI activity is regarded as a "treatment" on Chinese firms. I divide the firm sample into two groups, the treated group, firms becoming MNEs (conducting their first OFDI) during 2005-2011, and the control pool firms, that is firms having no OFDI during the research period or before, from which the counterfactual control firms are selected through PSM. Then the OFDI treatment effect is measured by comparing the innovation performance change between OFDI firms and counterfactual firms which indicates what would have happened to the first group's innovation performance if they had not conducted OFDI.

Second, I focus on the influence of IFDI on this effect. Foreign firms have different channels of interaction with Chinese firms, which has heterogenous influence on the direction and intensity of OFDI innovation gains. In this paper, I look at the influence of two connection modes widely discussed in the literature (Aitken & Harrison, 1999): 1. within-firm effect through foreign equity participation; 2. between-firm spillovers through geographic proximity and industry links. Through the first channel, foreign companies build strategic alliance and joint ventures with Chinese firms and share various resources, such as technologies, managerial experience, and production know-how. For the second one, spatial proximity with foreign investors helps Chinese firms to learn through imitation, competition and collaboration in the value chains and business networks. Moreover, I further test how this between-firm influence on the OFDI-led innovation gains varies with intra/inter industry relationship, industry relatedness as well as country of origin of IFDI.

This paper makes the following theoretical and empirical contributions to the literature. First, intensive inward FDI of foreign MNEs reflects the economic, industrial, and institutional features of emerging markets. Studying its impact on subsequent OFDI innovation gains provides insights on the special contexts in which EMNEs internationalize. By doing so, I argue that the EMNEs' home country advantages not only influence the OFDI decision and strategy but also their consequences.

Second, this paper broadens the understanding of the relationship of inward-outward FDI and internal-external internationalization (Banerjee et al., 2015). Existing literature only discusses the impacts of IFDI and OFDI on firm performance separately, ignoring that the different internationalization stages, particularly in emerging economies such as China may display deep interaction and continuity between the IFDI linkages and OFDI engagement (Li et al., 2012; Li et al., 2017; Chen et al., 2020). It is important to analyse their joint impacts in both international business and innovation studies. This paper makes an explorative attempt and find that IFDI leads to a far-reaching "indirect" effect - magnifying the innovation gains in the subsequent OFDI of EMNEs, and that this effect is contingent on the relationship between foreign and domestic firms.

Third, existing studies find a positive correlation between OFDI and innovation for EMNEs (Li et al., 2016; Fu et al., 2018; Piperopoulos et al., 2018; Howell et al., 2020). This paper further explores the dynamics of this OFDI-led innovation changes as time goes on. I find this effect is continuous and gradually increasing – OFDI activities not only change the innovation capability of Chinese investors right after the investment abroad, but also reshape their long-term innovation paths. Moreover, nearly all firm-level studies on this topic rely on small firm samples from listed Chinese companies (Wu et al., 2016; Piperopoulos et al., 2018; Howell et al., 2020) or survey data in specific geographic areas or sectors (Fu et al., 2018; Zhou, 2019), which may be not representative of all EMNEs. I use a new sample of China firms by merging three data sources to provide more empirical evidence on OFDI innovation gains.

The paper is structured as follows. The next section introduces the literature background and develops the hypothesis. Section 3 describes the firm samples, data processing and econometric models. The estimation results are presented in Section 4. Section 5 checks the robustness via alternative model settings and a new matching using the different OFDI timing as the treatment. Finally, Section 6 offers discussions and conclusions.

3.2 Literature background and hypothesis development

3.2.1 Outward FDI and innovation performance of Chinese MNEs

Accessing strategic resources and transferring back to parent firms and the home country are important motivations for Chinese multinational enterprises (CMNEs). Through OFDI, they get access to diversified knowledge bases and innovation-conducive environments which are often not available at home. This enables CMNEs to acquire not only codified knowledge, but also tacit know-how via spatial and social proximity: by embedding in the innovation system of host economies, CMNEs may tap into the pool of talents, ideas and connect to the local network of innovative actors, such as, universities, suppliers, competitors, and service providers (Uzzi, 1997; Cantwell & Iammarino, 2001; Meyer et al., 2009; Ghauri & Park, 2012). This strategic asset-seeking feature is reflected in many aspects of their OFDI. It is found that Chinese investors prefer host countries with rich technological endowments (Buckley et al., 2007; Lu et al., 2014). Moreover, CMNEs adopt special entry modes and integration strategies to take better advantage of external knowledge (Anderson & Sutherland, 2015; Ai & Tan, 2018). After acquiring external knowledge, CMNEs have strong incentives to transfer it back to China and integrate it with their own R&D resources and technologies (Erkelens et al., 2015). By doing so, they are able to reinforce their competitiveness in the home market which is their highest priority (Rugman & Li, 2007).

On the other hand, CMNEs face obvious constrains when seeking knowledge abroad, due to the lack of absorptive capability and liability of foreignness. There still exist significant technological gaps between China and advanced countries. Except for some national champions who have established global technology leadership, such as Huawei, Lenovo or Geely, the majority of CMNEs are still lagging behind their western counterparts in frontier technologies, marketing techniques, and managerial experience (Li, 2007; Luo & Tung, 2007; Fu, 2015). The lack of prior knowledge and too large technology gaps will limit their absorptive capability and prevent CMNEs from acquiring and integrating valuable strategic assets (Cohen & Levinthal, 1989; Cassiman & Veugelers, 2006; Fu et al., 2018).

In addition, China is distinctive in terms of economic development, institutional and cultural contexts as well as firms' management practice (Boisot & Child, 1996; Child & Tse, 2001). When Chinese firms go abroad, they often encounter a significant level of Liability of Foreignness (LOF) (Zaheer, 1995). First, national differences cause psychological distance, rising the transaction cost and difficulties in local adaptation (Johanson & Vahlne, 1977; Meyer et al., 2011). As a transition economy, China has many institutional voids, such unsound intellectual property rights, poorly functioning capital and labour markets, which profoundly shapes the routines of CMNEs. For example, the dependency on close personal relationships, which is different from the formal and law-based business practice in developed counties (Boisot & Child, 1996; Chen & Chen, 2004). Second, CMNEs often suffer from legitimacy and credibility deficits (Cuervo-Cazurra & Genc, 2008; Ramachandran & Pant, 2010). The fiscal and administrative supports from the government endow CMNEs with special advantages in the home market and facilitate their internationalization. However, the government involvement, in turn, is a disadvantage or stigma in the overseas operation, especially for firms with state ownership or those in core high technology sectors (Madhok & Keyhani, 2012; Amighini et al., 2013; Cuervo-Cazurra & Li, 2020). The factors above impede the formation of trust and collaboration between Chinese investors with local actors in the host locations and negatively influence learning through OFDI.

Some recent empirical studies explore the innovation-enhancing effects of Chinese OFDI at both firm and regional levels. Most of the results confirm that OFDI is followed by an improvement in the innovation performance and this correlation is contingent on three aspects: heterogeneous capabilities of the investing firms, and characteristics of both investment destinations and of home subnational regions. First, higher in-house R&D, clear strategic orientation and previous exportation experience increase the innovation gains from OFDI (Fu et al, 2018). Second, CMNEs benefit more from investments in advanced locations with strong innovative capacities, highly specialized suppliers, and demanding consumers (Piperopoulos & Wu &Wang, 2018). Moreover, learning through OFDI is contingent on the specific geographic and industrial contexts. Using regional data, Li et al, 2016 find that Chinese provinces with stronger absorptive capabilities, less intense competition in the local market and inward FDI learn more from OFDI. Therefore, the following hypothesis is here formulated:

H1：Outward FDI enhances the domestic innovation capabilities of Chinese firms.

3.2.2 The influence of inward FDI on Chinese OFDI-led innovation gains

IFDI is very important for the industrial and economic development in emerging markets. Through FDI, foreign firms deeply interact with local firms through demonstration, competition and human capital turnover (Zhang et al., 2014). The abundant literature on FDI spillover in China indicates consistently that FDI influences economic growth, productivity, employment and profoundly changes the society and environment (e.g. Wei & Liu, 2006; Yao, 2006; Baek & Koo, 2009; Jiang, 2010). In this paper, I further argue that IFDI enhances the innovation gains of OFDI. Specially, connecting to foreign firms in the home market works as a preparatory process for the subsequent internationalization of Chinese firms by 1. improving absorptive capabilities; 2. gaining internationalization experiences; 3. building the institutional familiarity with foreign countries. Due to these three influences, Chinese firms can better explore and augment strategic assets abroad.

First, with the knowledge spillovers from foreign firms, Chinese firms strengthen their technological competitiveness, which narrows the gaps with the frontier technologies and improves the absorptive capabilities when operating in foreign countries (Hale & Long, 2011). CMNEs become more able to find innovation opportunities and valuable technologies, assimilate and integrate them into their existing knowledge stock. Second, CMNEs obtain information of foreign countries and internationalization experience through "indirect learning" from foreign firms in China, which are necessary for the success of OFDI (Johanson & Vahlne 1977; Barkema & Drogendijk, 2007). The Uppsala model argues that MNEs from developed countries learn incrementally and directly through operating in different foreign locations (Johanson & Vahlne,1977; Banerjee et al., 2015). On the contrary, as late movers, CMNEs and other EMNEs are faced with fiercer competition and limited periods of time to catch up. They need to conduct aggressive OFDI in unfamiliar countries for strategic assets. Therefore, EMNEs cannot learn directly and incrementally only by their own experience but also through acquiring the experience and location specific information from successful MNEs around them, such as, leaders, partners, or competitors (Banerjee et al., 2015). By doing so, they alter their practices according to the expectations of foreign countries and lower the adaptation cost of operating and seeking knowledge in foreign locations. Therefore, the "indirect" learning from prior connections with foreign firms in the home country make Chinese firms easier to acquire external knowledge in OFDI. Third, inward FDI co-evolves with the local institutional environment, foreign investors are not only influenced by the host country environment but also help to reshape the national, regional, or economic institutions (Cantwell & Dunning & Lundan, 2010). FDI accelerates the marketization process and improves the business transparency in the host locations (McMillan & Carl, 1993). In addition, foreign firms are also able to bring international production, employment and environmental standards. Those are especially important for the transitional economies, like China or Eastern European countries in the early 1990s, which suffer from institutional voids (Meyer, 2003). The improvements in the institutional environment facilitate the organizational changes of domestic firms and then make CMNEs more familiar with the institutional contexts in foreign countries, alleviating the barriers in acquiring foreign knowledge.

Research has focus on the mechanism of FDI spillover by emphasizing the relationship between foreign and domestic firms. It was classified by the pioneer work of Aitken & Harrison (1999) as: 1. within-firm effect through foreign equity participation; 2. between-firm effect through spatial proximity and economic relationship. And then the between-firm effect is also found to differ between intra and inter-sector relationships (e.g. Kugler, 2006; Jordaan, 2008; Liu & Wang & Wei, 2009). Following these arguments, this paper explores whether the influence of IFDI on OFDI-led innovation also has different channels and depends on the connection modes between foreign capital and Chinese firms, as detailed below.

3.2.2.1 The within-firm channel - foreign equity participation

International joint venture (JV) is a common entry mode for foreign firms in emerging markets. As an equity-based strategic alliance, JV combines skills and capabilities among different partners, creates mutual learning opportunities and common interests. Compared with other alliance modes, such as contract-based licensing, or market-based transactions, JV is recognized as a more effective mode for the transfer of knowledge which have strong tactic nature and uncertainty (Kogut,1988). In addition, JV is based on the resource complementarity, partner firms work with less transactional costs and aim for a win–win situation (Inkpen, 1998).

In the Chinese context, foreign firms are encouraged by the Chinese government to establish JVs with their Chinese counterparts. Especially for certain sectors, for example, automobile, foreign firms have long been forbidden to have wholly- owned subsidiaries in China through acquisition or greenfield investments (Peng, 2000). Because of the common interest nature of JV, the capability improvement of Chinese firms does not conflict with the interests of its foreign partner. As a result, they get quick access to many tangible and intangible resources, including financial capital, technologies, human resources, as well as the knowledge of the market conditions in foreign countries (Tsang, 1999; Das & Teng, 2000). Moreover, as firm reputation is transferable between partner firms in strategic alliance (Dollinger et al., 1997; Nielsen, 2007), JV partnership with well-known global firms at home helps Chinese firms to create better business images globally, thus they can improve their legitimacy and credibility when operating abroad. At the same time, the equity control in JV makes sure that the Chinese ownership still hold the initiative in internationalization decisions. Therefore, JV with foreign companies endows Chinese firms with various valuable resources which help to acquire foreign knowledge through OFDI and increase their own innovation capabilities.

H2: Relative to wholly domestic-owned firms, Chinese firms with foreign equity participation (JVs) obtain higher innovation through OFDI.

3.2.2.2 The between-firm channel through geographic proximity and sectoral relatedness

In addition to the within-firm interaction through equity participation. The FDI literature also emphasizes between-firm knowledge spillovers through geographic proximity and sectoral relatedness (Jaffe & Trajtenberg, 1996; Sjöholm, 1996; Maurseth & Verspagen, 2002). Because of the spatial boundaries for tacit knowledge diffusion, the majority of between-firm FDI spillovers happen predominantly locally. Especially, China occupies a massive geographical space with strong market fragmentation between regions (Poncet, 2005), making the interactions between foreign and domestic firms difficult to happen over long distance. Empirical studies have captured the spillover effect at the local province or city level, Chinese firms are found to have deep interactions with their neighbouring foreign firms (Madariaga & Poncet, 2007; Liu et al., 2009; Ouyang & Fu, 2012; Wei & Liu &Wang, 2012; Ning & Wang, 2016). Similarly, I argue innovation gain through OFDI is also influenced by the localized interactions with foreign firms in the home cities.

Moreover, the between-firm interaction of IFDI on OFDI-elated innovation gains is contingent on the different relationships with foreign firms. First, firms in the same industry are most directly impacted by IFDI through demonstration and competition effects (Görg & Greenaway, 2001; Liu et al., 2009; Monastiriotis & Alegria, 2011; Crescenzi & Gagliardi & Iammarino, 2014). Demonstration effects in the same sector provide most relevant technologies and market and help them in the subsequent OFDI. On the other hand, due to direct competition, foreign companies tend to prevent the knowledge spillovers to domestic competitors in the same sector, which gives Chinese firms stronger incentives to make better use of existing technologies or acquire strategic assets abroad to counterbalance the foreign firms' technological advantages in domestic market (Jacobs et al., 2014). Second, FDI spillovers also happen across sectors, depending on the industrial relatedness through supply-demand relationship. Because of the complementarity, inter-sector spillover effects are found to be stronger than same-sector effects (Kugler, 2006; Jordaan, 2008). IFDI in different sectors may also facilitate OFDI-related innovation. Value chain linkages with foreign MNEs in the home market not only help technology upgrading and increases the absorptive capabilities of Chinese firms, but also provide international ties by fostering trusts and embeddedness in the global production networks (Hertenstein et al., 2017). This network relationship is "borderless" and can be duplicated from China to foreign locations, helping to mitigate the LOF and improve the OFDI performance (Hertenstein et al., 2017). On the contrary, IFDI in less related industry may not have effective interactions and has no impact on their OFDI consequences.

Based on the analysis above, I come to the two hypotheses:

H3: Chinese firms who collocate with more foreign firms in their home cities will have higher innovation gains after OFDI.

H4: Both intra and inter-sector linkages with foreign firms positively influence the OFDI innovation gains of Chinese firms and the inter-sector influence mainly happens through input and output relationships with IFDI in related sectors.

3.2.2.3 The "country-of-origin" effect

There is significant heterogeneity in terms of economic situation, technological structure, business culture and institutional contexts among countries (Hofstede, 1991; Carvalho et al., 2015). These national differences make FDI from different origins significantly differ in spillover effects in the same host location (Meyer & Nguyen 2005; Iammarino et al., 2008). Similarly, the influence of IFDI on OFDI innovation may be also specific to MNE origins.

Although MNEs operate globally, they are still deeply influenced by the "national effect" of their origins and have many resources and characteristics inherited from and bounded to their home countries. First, MNEs' overseas operation in emerging markets is closely related to exploiting and modifying their existing technological assets and adapting to local demands of host countries (Johanson & Vahlne, 1977). Subsidiaries acquire the technological assets from their parent firms which are often embedded in the home country's innovation system. Those assets often reflect their origin country's comparative advantages in certain technology domains (Criscuolo et al., 2005). This country-specific characteristic will be also included in the knowledge spillovers in emerging markets and passed on to local EMNEs. Second, there are distinct national systems of business and managerial practice embedded in countries' culture and institutions, shaping the global practices of MNEs. This "organizational imprinting" continuously influences the strategies, governance structures and R&D systems of MNEs (Bartlett & Ghoshal, 1989; Pauly & Reich 1997; Noorderhaven & Harzing, 2003; Elango & Sethi, 2007). Those country specific practices may also be imitated by the partners and neighbouring firms in host countries. In addition to technologies and managerial experience, other intangible resources and knowledge that domestic firms can obtain from foreign firms, such as the market information, social network, industry standards or reputation, are also bounded to the origin of the foreign investor to different extents. Therefore, the resources from foreign companies are imprinted with origin country characteristics and then passed on to Chinese firms, which may have a better matching in the countries where IFDI originated. Then I come to the final hypothesis:

H5: The innovation capabilities of Chinese firms engaged in OFDI towards a certain country are more strongly influenced by the exposure to IFDI originated from that country.

3.3 Data and methodology

3.3.1 Data sources

The empirical analysis is based on a new firm level dataset constructed by linking the following three data sources, as listed in Table 3-1.

I rely on the Annual Manufacturing Enterprises Survey ("firm dataset" for short) from China's National Bureau of Statistics which is widely used in firm-level research on China. This dataset covers all manufacturing firms whose annual sales exceed RMB 5 million since 1998 and includes three major accounting statements – balance sheet, cash flow statement and income statement, and has been widely used in this research area (e.g. Li & Liu &Yuan &Yu, 2017). The data used in this paper ranges from 2004 to 2010.

Second, the OFDI information used in my paper comes from China's Ministry of Commerce. This covers information of non-financial OFDI conducted by Chinese firms, for which it is compulsory to report the detailed project information to the Ministry of Commerce in order to get the currency exchange permission. This dataset is the most complete project-level data source for Chinese OFDI, and it has been used in previous empirical studies (e.g. Deng, 2007; Cui & Jiang, 2009; Amighini et al., 2014). It includes the investor firm name, investment destination, investment description, as well as the original province of more than 40,000 Chinese OFDI projects from 1983 to 2015.

Third, I obtain patent information from the patent dataset of State Intellectual Property Office of China (SIPO). It includes complete information of all patent applications in SIPO from 1985 until now. The detailed variables are application date, IPC classification, applicant names and addresses, inventors' names, etc. This patent dataset includes three types of patenting activity: invention, utility model as well as external design. I only use the invention patents because inventions are directly related to technology advancement and have more novelty and economic value (Dang & Motohashi, 2015). The majority of the related literature uses USPTO or EPO because of data availability and some criticism on the credibility of Chinese patent data. However, the SIPO data has important advantages over USPTO or EPO data in the case of research which focuses on China. First, it is the only patent data which can be matched with other micro-level official databases of China. Second, SIPO includes a much larger number of Chinese patents: because it is more expensive to patent abroad than at home, only a small proportion of Chinese firms who are larger, younger, more export-oriented will do so (Eberhardt et al., 2011), and the technologies patented abroad are those with high economic value. This means that the USPTO or EPO dataset would omit a considerable proportion of Chinese firms who only patent domestically to be competitive and innovative in the home market. In this paper, I use the patent application number to measure the innovation performance of Chinese firms.

Table 3-1. Main Data Sources

Data Source	Period	level	Information
Annual Manufacturing Enterprises Survey of China's National Bureau of Statistics	2004-2010	Firm level	Balance sheet, cash flow statement and income statement, ownership structure
State intellectual property office of China (SIPO)	1990-2018	Patent level	Technology class, address of applicant names, application date; main classification
Name list of China's outward foreign direct investment	1983-2014	Project level	Name of parent firm, destination, investment motivation

3.3.2 Sample and data processing

I obtain the sample through the following data processing steps.

First, there is inaccuracy in the firm dataset due to some non-standardized financial statements and report errors. Following Li & Liu (2017) and Feenstra et al. (2014), I exclude firms whose important characteristics, such as total sale, gross industrial output, export value is missing. Second, since this paper focuses on the OFDI and innovation behaviours of Chinese MNEs, I exclude firms whose dominant registered capital is foreign-owned. Those firms are the subsidiaries of foreign MNEs rather than Chinese firms, and their transnational investments are conducted directly by their headquarters rather than by those subsidiaries in China.

Then to identify the innovation performance of Chinese firms, I link the firm dataset and SIPO by merging the firm names with the applicant names[3]. Some recent studies have made attempts to link these two disaggregated datasets (He et al., 2016; He et al., 2018). They found potential challenges because of name variations, name changes and recoding errors – the same entity may use different names in two datasets. Second, the innovations of some firms may be not patented or not patented domestically in the SIPO. Moreover, for some firms in business groups, their patents may be assigned to other organizations such as their headquarters, a division, a factory, or a branch office (He et al., 2016). All these limitations make it impossible to identify the innovation capabilities of some firms by SIPO. To solve this problem, in the firm sample I include firms that can be identified in the SIPO database – firms whose name appears at least once among all applicants during 1990-2018. By doing so, I exclude firm whose

[3] Before merging, I delete the useless suffix (such as “Co”, “Ltd”, “Corp”, etc.) which could cause matching failure.

innovation performance cannot be successfully identified through patent information, while at the same time, I also exclude the firms who have never applied patents in SIPO due to limited innovation capability. This does not cause selection bias in my analysis because here I focus on the difference between OFDI firms and counterfactual non-OFDI firms, rather than the absolute patent numbers – the filtering is equally applied to both treatment and control groups.

Then, the firm sample above is linked with the OFDI name list to obtain the treated firm sample (firms conducting their first OFDI during the research period) and control pool sample (firm who have never invested abroad until the end of research period). After the above cleaning, I find 1,150 Chinese firms with OFDI, representing two million employment and 1.5 trillion RMB output one year before their first OFDI. The control pool includes 291,990 non-investing firms. With a ratio between treated group and control pool of 1:254, there is a large control pool from which to select the counterfactual control firms for each treated firm.

Table 3-2. New CMNEs emerged

OFDI Year	New CMNE Numbers Matched	Total New CMNE in OFDI Namelist	Matched Percentage	Total Employment	Industry Output (Million RMB)
2005	101	822	12.3 %	194,230	77,943
2006	129	1,043	12.4%	220,924	104,122
2007	122	1,081	11.3%	210,335	143,523
2008	146	1,293	11.3%	438,674	267,642
2009	212	1,786	11.9%	292,281	448,053
2010	214	2,163	9.9%	211,841	150,798
2011	189	2,517	7.5%	490,020	360,520
Total	1,113	10,705	10.4%	2,058,305	1,552,605

3.3.3 Econometric models

It is difficult to test the relationship between OFDI and domestic innovation activities because of endogeneity. First, firms who have some specific characteristics such as better productivities and larger scales are more likely to invest abroad, and those features may also influence their innovation performance. This self-selection bias makes the OFDI firms incomparable to the non-OFDI firms. Second, firms with better domestic innovation performance may also be more prone to investing abroad, which causes a reverse causality problem. These endogenous issues make the simple estimations invalid. Following previous studies (Hamilton & Nickerson, 2003; Cozza et al.; Li et al., 2017; Crescenzi et al., 2020; Howell et al., 2020), I combine Propensity Score Matching (PSM) with a Difference in Difference estimation (DID) to assess the causal effect of OFDI on innovation. The PSM method pairs an OFDI firm with a non-OFDI firm (or several firms) with otherwise similar characteristics. By doing so, I create the counter factual of what would have happened if my focal new CMNEs had not conducted OFDI; this group of untreated firms are to some extent comparable to the treated group in the DID model.

In the matching, first I estimate firms' OFDI propensity using a probit regression. The predetermined firm characteristics at year T-1 are used as covariates to explain the treatment OFDI in T 0. The OFDI propensity of each firm is estimated using the equation 1:

$$\Pr(OFDI_{i,t0}) =$$

$$F(X_{i,t-1}) = \beta_1 \text{Total\_Sale}_{i,t-1} + \beta_2 \text{ Firm\_Age}_{i,t-1} + \beta_3 \text{Net\_Profit}_{i,t-1} + \beta_4 \text{Export\_Value}_{i,t-1} + \beta_5 \text{Goverment\_ Subsidy}_{i,t-1} + \beta_6 \text{ State\_share}_{i,t-1} + \beta_7 \text{Foreign\_share}_{i,t-1} + \varepsilon_{i,t} \quad (1)$$

$X_{i,t-1}$represents firm i's characteristics determining whether this firm would invest abroad in the treatment period. I set the function F by referring to empirical studies about the driving factors of Chinese OFDI (Luo, 2012; Wang et al., 2012). Exiting literature uses different theoretical frameworks to explain OFDI decisions. The Resource-based view argues that OFDI is determined by ownership advantages - firm's own resource or strategy-based characteristics (Penrose, 1956; Bain, 1956; Hymer, 1976). I measure it by firm age, firm scale (total sale value), profitability and export experience. According to the institutional-based view, OFDI decision is influenced by formal and informal institutions (Meyer & Peng, 2005). Given the deep intervention of the government in the Chinese economy, these impacts are important forces in the internationalization decision of Chinese enterprises (Luo et al, 2010). I measure the influence of institutional environment by ownership structure (state share and foreign share in the total registered capital) and support from government policy (the amount of government subsidy). Third, both OFDI and innovation activities are also influenced by industry specific dynamics (Porter, 1980), which makes firms in different sectors not comparable. Therefore, in the matching, counterfactual firms are selected within each 3-digit sector and in the same year.

In this way, the OFDI propensity score is estimated, the nearest-neighbour matching method is employed to find out the counterfactual firms. They are selected by year and sector and then pooled together to be the untreated group. 1,113 out of 1,150 treated firms are successfully matched with a control firm. Firms which failed to be matched are dropped from the sample because of the violation of the balance condition hypothesis (Li & Liu et al., 2017).

After obtaining the control group, I analyse the impact of OFDI on innovation through two methods. First, I calculated the average treatment effect on the OFDI treatment firms (ATT). In equation 2, ATT_{t+k} compares the treated with the control group and calculates the difference in patent application numbers, while equation 3 calculates different innovation trends measured by the difference in patent number changes for each year between two groups, denoted byATT_{t+k}^{Trend}. These two indicators measure the difference in innovation performance in terms of absolute number and relative trend, respectively.

$$\mathrm{ATT}_{t+k} = \frac{1}{N}\sum_{i}^{n}(\mathrm{Patent}_{i,t+k}^{\mathrm{Treatment}} - \mathrm{Patent}_{i,t+k}^{\mathrm{Control}}) \quad (2)$$

$$\mathrm{ATT}_{t+k}^{\mathrm{Trend}} = \frac{1}{N}\sum_{i}^{n}((\mathrm{Patent}_{i,t+k}^{\mathrm{Treatment}} - \mathrm{Patent}_{i,t+k-1}^{\mathrm{Treatment}}) - (\mathrm{Patent}_{i,t+k}^{\mathrm{Control}} - \mathrm{Patent}_{i,t+k-1}^{\mathrm{Control}})) \quad (3)$$

Second, based on the comparable firm sample obtained above, following Crescenzi et al. (2020), I further perform the DID model to more precisely estimate the OFDI effect adding firm, time and treatment period fixed effects:

$$\mathrm{Patent}_{i,t} = \beta_0 + \sum_{k=T-5}^{T+5} \partial_0^k \mathrm{Period}_k + \sum_{k=T-5}^{T+5} \partial_1^k \mathrm{OFDI}_{i,c,t-1} * \mathrm{Period}_k + \mathrm{Year\ FE} + \mathrm{Firm\ FE} + \varepsilon_{i,t} \quad (4)$$

$OFDI_{\ i}$ is a dummy variable for treatment, measuring whether a firm becomes an MNE during the period considered. $Period_{\ k}$ is the dummies of event time, measuring k years after the OFDI which runs from 5 year before OFDI to 5 years after. The parameter of interest is shown in the ∂_1^k , which indicates the difference in innovation capabilities between treated and control group k year after the OFDI. Year and firm fixed effects are used to absorb the time trends and firm heterogeneities.

3.4 Results

3.4.1 Matching results

I test the balancing condition after matching by checking the bias between treated and untreated groups, as shown in Table 3-3. It shows that before the matching, there are significant difference between treated firms and untreated firms in nearly all covariates except the share of state-owned capital, indicating that there is systematic difference in firm characteristics before OFDI and the two groups are incomparable. On the contrary, after matching, these biases are largely eliminated, and the difference is insignificant.

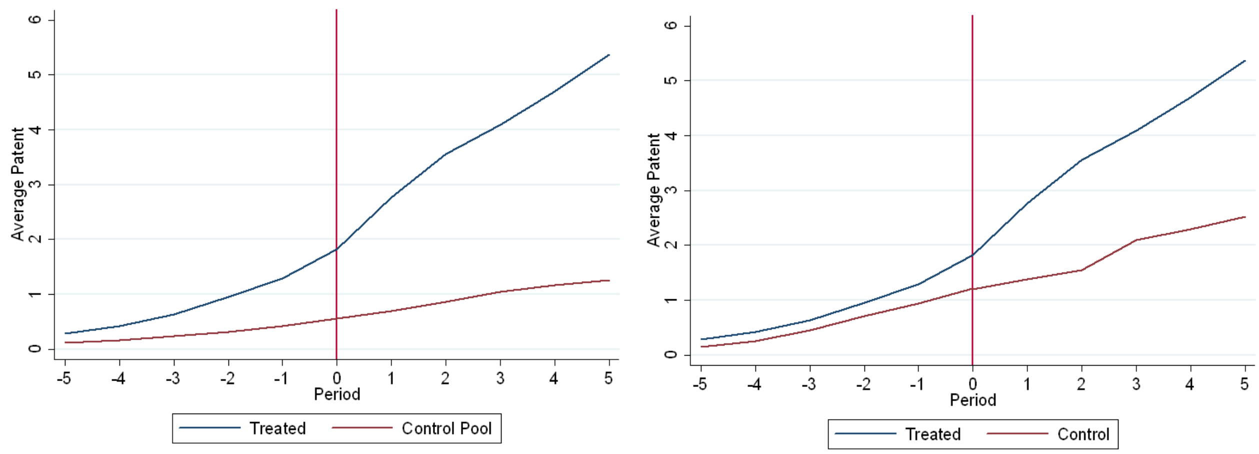
However, the balance in observed covariates is not sufficient to eliminate endogeneity because of unobservable factors simultaneously influencing OFDI and patent application. I further check through comparing the patent growth path. Figure 3-1 shows the average patent number difference before and after matching. Before matching, OFDI firms are more innovative than non-OFDI firms with distinct patent growth path and their difference occurs before the OFDI. In comparison, after matching, the pretreatment innovation between year T-5 to year T-1 of two groups show a generally parallel trend. The difference only started from T 0 OFDI year. And the average patent number of the two groups begins to diverge and the gap is gradually widening, in the year T+5, the average patent application of OFDI firms is twice the number of non-OFDI firms. Following Crescenzi et al. (2020), I do not match firms using their pretreatment innovation performance, if there are important unobservable variables influencing both OFDI and innovation, the innovation trajectories of the two groups could already be very different before treatment. The parallel trend of application number is a strong indication that before OFDI there is no systematic difference in the innovation capability changes between treated and untreated firms and the matched firms are the comparable counter facts of OFDI firms. Therefore, the potential endogeneity is largely controlled, which is further supported by the DID model results below.

Table 3-3. Balancing test, before and after matching

	Before Matching				After Matching			
Variables	N=1,150	N=291,990			N=1,113	N=1,113		
	Treated	Control	Difference	T-statistics	Treated	Control	Difference	T-statistics
Industry Output (Thousand RMB)	1227832	318383	909448***	13.28	1196711	1233377	-36666	-0.1562
Net Profit (Thousand RMB)	95381	24459	70921***	4.853	92535	74521	18013	0.8675
Export (Thousand RMB)	200024	28453	171570***	18.64	196,550	163,155	33395	0.9517
Subsidy (Thousand RMB)	1405	561.4	843.8**	2.154	1455.4	1618.8	163.32	-0.2887
State-owned Share	0.08512	0.08381	0.001305	0.0559	0.08504	0.05093	0.0341	1.1885
Foreign-owned Share	0.1402	0.08491	0.0553***	3.167	0.14162	0.18506	-0.0434	-0.7795
Liability (Thousand RMB)	863783	231773	632009***	12.632	809860	869380	-59519	-0.368

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Figure 3-1. Average patent number of treated and untreated group before and after matching

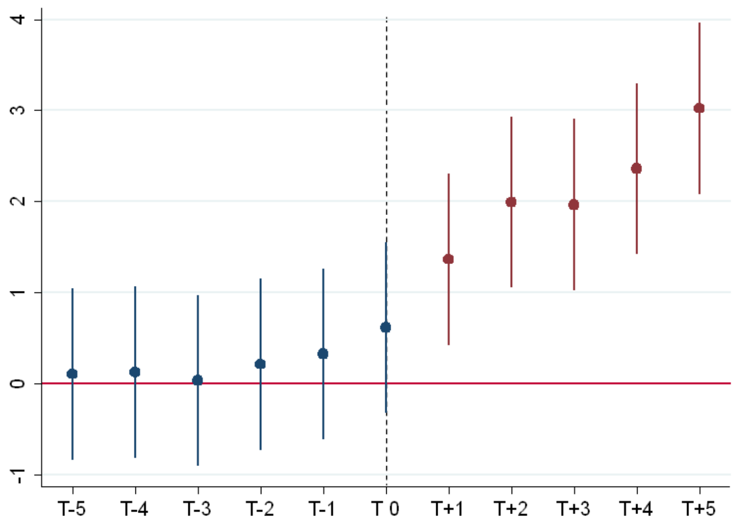


3.4.2 Causal effect of OFDI on innovation performance

Column 1 and 2 in Table 3-4 show the results of patent number difference, ATT_{t+k}; and the difference in year-by-year patent number change, ATT_{t+k}^{Trend}, between OFDI firms and control firms. I observe a significant difference in patent application numbers in column 1. OFDI firms applied for more patents than control firms and this difference already existed before OFDI but is very small and increased significantly after treatment. The trend results in column 2 show that before OFDI there is no significant difference in the patent growth trend between two groups, but after they invest abroad, the growth of the OFDI firms turns to be significantly faster than the counterfactual non-investing firms. These findings indicate that the two groups of companies have a certain difference in the absolute number of patents before the investment, but they maintain a parallel trend, while the innovation paths diverged after OFDI and OFDI firms experienced higher growth.

Column 3 in Table 3-4 and Figure 3-2 show the results of the difference-in-differences estimates, ∂_1^k. Before treatment, patent application numbers are not significantly different between treated and untreated firms, controlling for firm and time fixed effects. However, one year after the OFDI, patent application numbers of treated firms start to be significantly higher than those of the untreated firms, and this gap keeps increasing with time from 1.368 more patents in T+1 to 3.026 in T+5. During the five years since OFDI, on average, OFDI firms applied for 10.72 more new patents than their non-OFDI counterfactual firms.

Figure 3-2. Difference in Difference result: treatment effect of OFDI on treated firms



Vertical lines show the 95% confidence intervals. Point estimates that are statistically significantly different from zero (p = 0.05) are shown in red, insignificant point estimates in blue.

Table 3-4. OFDI treatment effect during T-5 to T+5 years

Time	(1) ATT_{t+k}	(2) ATT_{t+k}^{Trend}	(3) DID model results	
T-5	0.143***	0.111**	∂_1^{T-5}	0.107
	(0.0489)	(0.0462)		(0.477)
T-4	0.167**	0.023	∂_1^{T-4}	0.128
	(0.0729)	(0.695)		(0.477)
T-3	0.0637	-0.103	∂_1^{T-3}	0.0352
	(0.105)	(0.697)		(0.477)
T-2	0.259*	0.196	∂_1^{T-2}	0.216
	(0.149)	(0.123)		(0.477)
T-1	0.370*	0.111	∂_1^{T-1}	0.328
	(0.190)	(0.120)		(0.477)
T 0	0.653***	0.283*	$\partial_1^{T\ 0}$	0.618
	(0.237)	(0.1320)		(0.477)
T+1	1.379***	0.725***	∂_1^{T+1}	1.368***
	(0.339)	(0.241)		(0.477)
T+2	2.004***	0.625**	∂_1^{T+2}	1.995***
	(0.441)	(0.290)		(0.477)
T+3	1.969***	-0.035	∂_1^{T+3}	1.967***
	(0.575)	(0.297)		(0.477)
T+4	2.353***	0.383*	∂_1^{T+4}	2.365***
	(0.669)	(0.241)		(0.477)
T+5	3.027***	0.674*	∂_1^{T+5}	3.026***
	(0.861)	(0.375)		(0.477)
Observation	1,113	1,113	Constant	1.115***
				(0.201)
			Period FE	Yes
			Year FE	Yes
			Firm FE	Yes
			Observations	34,308
			R-squared	0.437

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

3.5 The influence of IFDI on OFDI-led innovation

3.5.1 Results of the within-firm channel

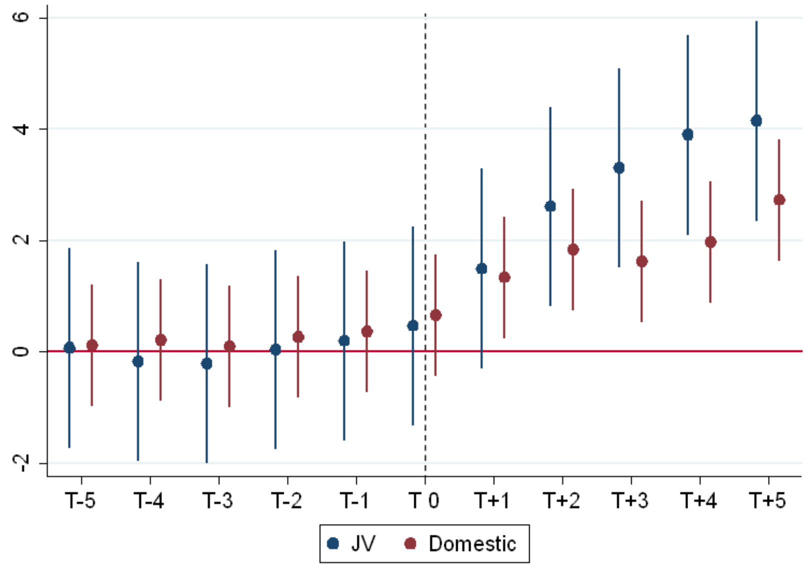
Then for studying the influence of within firm influence (foreign capital participation) on the treatment effect, I divide the whole treated sample as well as their corresponding control firms into two subgroups: 255 firms and corresponding controls with foreign registered capital (JVs) and 888 firms with only domestic registered capital. One potential concern is there may exists some systematic difference between JVs and domestic firm which make their innovation path have already been different before treatment. Therefore, I check the comparability between two groups through testing the balancing condition, as shown in Table 3-5. There is no significant difference for all variables except government subsidy. Moreover, the results of $Patent_{T-1}$ and $Patent_{T-1}$-$Patent_{T-5}$ indicate that two groups of firms have similar innovation capability one year before OFDI as well as similar innovation paths from T-5 to T-1. These results suggest no systematic difference between two groups, and they are comparable to each other. Column 2 and 3 in Table 3-6 and Figure 3-3 report the OFDI treatment effect on two groups. Before T 0, the coefficient ∂_1^k of OFDI is not significant for both groups, indicating no significant difference between the patent application numbers with non-OFDI companies. After treatment, this coefficient gradually increases and the effect on joint venture group is larger than that on domestic firms in all years. The column 3 shows the statistics of T-test for coefficient difference, I observe significant different at year T+3 and T+4. Chinese enterprises with foreign equity obtain greater innovation gain after investing abroad.

Table 3-5. Balancing tests, joint ventures and domestic firms

Variables	Mean (888 Domestic)	Mean (255 JV)	Difference	T-statistics
Industry Output (Thousand RMB)	1287461	838552.8	448908.1	1.208
Net Profit (Thousand RMB)	96042.16	78693.67	17348.49	0.4231
Export (Thousand RMB)	186755	235208.7	-48453.65	0.787
Subsidy (Thousand RMB)	1659.771	649.288	1010.483*	1.6247
State-owned Share	0.0991	0.0293	0.0698	1.013
Liability (Thousand RMB)	871106	568146.7	302959.3	1.3218
$Patent_{T-1}$	1.361	1.035	0.325	1.305
$Patent_{T-1}$-$Patent_{T-5}$	1.038	0.871	0.167	0.700

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Figure 3-3. Difference in Difference result: treatment effect of OFDI by joint ventures with foreign equity and domestic firms



Vertical lines show the 95% confidence intervals. Estimates for joint ventures with foreign equity are shown in blue, estimates for domestic firms are in red.

Table 3-6. DID model results by joint ventures and domestic firms

Variables	(1) JV	(2) Domestic firms	(3) Treatment effect difference between two groups
∂_1^{T-5}	0.0667	0.118	-0.0513
	(0.909)	(0.552)	(1.182)
∂_1^{T-4}	-0.173	0.207	-0.38
	(0.909)	(0.552)	(1.182)
∂_1^{T-3}	-0.213	0.100	-0.313
	(0.909)	(0.552)	(1.182)
∂_1^{T-2}	0.0400	0.262	-0.222
	(0.909)	(0.552)	(1.182)
∂_1^{T-1}	0.196	0.361	-0.165
	(0.909)	(0.552)	(1.182)
$\partial_1^{T\,0}$	0.467	0.655	-0.188
	(0.909)	(0.552)	(1.182)
∂_1^{T+1}	1.493	1.336**	0.157
	(0.909)	(0.552)	(1.182)
∂_1^{T+2}	2.613***	1.834***	0.779
	(0.909)	(0.552)	(1.182)
∂_1^{T+3}	3.302***	1.621***	1.681*
	(0.909)	(0.552)	(1.182)
∂_1^{T+4}	3.898***	1.966***	1.932**
	(0.909)	(0.552)	(1.182)
∂_1^{T+5}	4.147***	2.730***	1.417
	(0.909)	(0.552)	(1.182)

Constant	0.561	1.567***	
	(0.358)	(0.213)	
Period FE	Yes	Yes	
Year FE	Yes	Yes	
Firm FE	Yes	Yes	
Observations	5,400	20,988	
R-squared	0.386	0.445	

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

3.5.2 Results of the between-firm channels

A reduced form of DID model is used to study the influence of between-firm channels by examining whether OFDI leads to higher innovation performance if the Chinese investors collocate with more foreign firms in the home cities before internationalization. The regression sample includes all OFDI firms and their corresponding control firms. As shown in formula 3, the dependent variable $\Delta P_{i,t+k}$ is the difference in patent application numbers from one year before OFDI to k years (k = 1, 3, 5) after the treatment for firm i. $X_{i,t-1}$ denote the firm-level factors one year before OFDI which may influence the innovation performance changes, those factors include all the covariates used in the PSM as well as the initial innovation capability before becoming MNEs. Moreover, $X_{c,t-1}$ is the characteristics of the home city c, including the total patent numbers, industry output and employment which may also influence firm's innovation dynamics as environmental factors. Besides, the model also includes the fixed effects of year, sector to control the time trends, and unobservable and industrial features.

$$\Delta Patent_{i,t+k} = \beta_0 + \beta_1 OFDI_i + \beta_2 IFDI_{i,c,t-1} + \beta_3 IFDI_{i,c,t-1} * OFDI_i + \beta_4 X_{i,t-1} + \beta_5 X_{c,t-1} + Year\,FE + Sector\,FE + \varepsilon_{i,t} \quad (3)$$

the variable $IFDI_{i,c,t-1}$ is the sum of registered foreign capital (including both the capital in wholly owned foreign firms as well as the foreign-owned capital in joint ventures) at the home city c of Chinese firm i. The influence of IFDI is captured by the cross terms between the OFDI with $IFDI_{i,c,t-1}$. I expect a higher $IFDI_{i,c,t-1}$ potentially increases the local spillovers from foreign firms and increase the innovation effect of OFDI. Then, I divide $IFDI_{i,c,t-1}$ into two parts. The first, $same\ sector\ IFDI_{s,c,t-1}$ is the foreign capital in the same 3-digit sector s with firm i, and second, $cross\ sector\ IFDI_{s,c,t-1}$ measures the foreign capital intensity in other sectors. Moreover, to further explore this cross-sector influence through supply and demand ties, I use the variable $related - sector\ IFDI_{s,c,t-1}$ to measure the interaction with local foreign firms through supply and demand relatedness, as shown in the formula 4 below.

$$Related\ sector\ IFDI_{s,c,t-1} = \sum_{k=1}^{K} IFDI_{k,c,t-1} \times Relatedness_{s,k} \quad (4)$$

$Relatedness_{s,k}$ measures the share of input/output of sector s from/into sector k[4]. A higher relatedness means two sectors have stronger demand and supply dependency. Therefore, $Related - sector\ IFDI_{s,c,t-1}$ sums up the foreign capital intensity in different sectors weighted by this input-output relatedness, capturing the effects due to the presence of foreign companies in the upstream of downstream of the same supply chain in the home cities. In this paper, $Related\ sector\ IFDI_{s,c,t-1}$ is the sum of both forward related FDI (output linkages) and backward related FDI (input linkages). All the independent variables are standardized before regression.

Table 3-7 shows the results. The first three columns show the treatment effect in year T+1, T+3 and T+5. Outward FDI has significant and positive impact on firms' innovation performance and this impact increased with time. I also notice that the coefficient of treatment is not substantially changed no matter which variables are introduced into the model, and it is very similar to the result of the DID model in Table 3-4. Therefore, the treatment effect of OFDI on innovation performance is quite robust. In column 4-6, the total capital of foreign firms in the home cities of Chinese firms and its cross-term with the treatment are included into the model. The results show the total inward FDI is negative but its cross-terms with OFDI are significant in T+1 and T+3, indicating that foreign capital in the home city has competition effects on domestic firms in innovation, on the other hand, it helps Chinese firms to benefit more in their OFDI. And this effect decays with time. In column 7-9, I interact the treatment, OFDI with the IFDI in the same sector and different sector IFDI respectively. The result shows the cross-term of same sector FDI is significantly positive in all three years. This indicates that if a Chinese firm is located in a city with a large IFDI intensity in its own sector, it is likely to acquire more knowledge than other Chinese investors. Exposure to same-sector foreign investments magnifies the innovation-enhancing effect of outward FDI. On contrary, the cross term of cross-sector FDI is insignificant in all times, which means that more local foreign firms in other sectors have no impact on Chinese firms' OFDI innovation gains. These results seem to be contradictive to the inward FDI spillover studies which argue that between-sector knowledge spillover is more likely to happen because of larger complementarity and less competition (Kugler, 2006; Jordaan, 2008). This may because that other-sector IFDI includes both related sectors which has strong complementarity and interactions with domestic firms and also other unrelated firms having limited interaction or even negative impacts and the influence of the former cannot be shown. I further use the variable related-sector IFDI to exam this mechanism, as shown in the columns where 10-12 interact OFDI with related sector FDI at the control of same sector FDI intensity. I find that the cross-term is significant positive in

4 Following Liu et al (2009) It is calculated from the 2002 and 2007 versions of input-output tables from National Statistic Bureau of China.

all three years after OFDI. This confirms the importance of prior supply-demand relationship with local foreign firms in subsequent knowledge seeking of OFDI – the cross-sector influence only happens through related sectors. In summary, I do find evidence about the influence of inward FDI on the OFDI effect which is more prominent through same-sector spillovers and supply chain relatedness between different sectors.

Table 3-7. The IFDI influence on OFDI innovation gains through between-firm channels

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Variables	T+1	T+3	T+5	T+1	T+3	T+5	T+1	T+3	T+5	T+1	T+3	T+5
Treatment effect												
OFDI	0.994***	1.550***	2.399***	0.174	0.810	1.659*	0.407	1.173**	2.318**	0.483	1.136**	1.871**
	(0.295)	(0.509)	(0.803)	(0.357)	(0.620)	(0.981)	(0.335)	(0.585)	(0.924)	(0.309)	(0.542)	(0.857)
Total IFDI				-1.002**	-1.616*	-1.503						
				(0.507)	(0.881)	(1.393)						
OFDI×Total IFDI				0.837***	0.705*	0.708						
				(0.208)	(0.362)	(0.573)						
same-sector IFDI							-0.174	-0.332	-0.551	-2.73***	-0.764	0.621
							(0.218)	(0.381)	(0.601)	(0.735)	(1.290)	(2.039)
OFDI×same sector IFDI							0.827***	0.705*	1.459**			
							(0.212)	(0.371)	(0.585)			
other-sector IFDI							-0.809	-0.454	-1.557			
							(0.503)	(0.877)	(1.384)			
OFDI×other-sector IFDI							0.274	0.0429	-0.772			
							(0.218)	(0.381)	(0.602)			
Related-sector IFDI										2.546***	0.423	-0.946
										(0.757)	(1.329)	(2.101)
OFDI×related-sector IFDI										1.176***	0.815**	1.005*
										(0.191)	(0.336)	(0.531)
Firm Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	-0.0500	1.023**	2.071***	0.0963	0.745	1.925*	-0.0155	1.036	0.920	0.744**	1.465***	2.605***
	(0.274)	(0.474)	(0.747)	(0.410)	(0.712)	(1.126)	(0.464)	(0.809)	(1.278)	(0.297)	(0.521)	(0.824)
Observations	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,140	2,140
R-squared	0.134	0.228	0.206	0.139	0.228	0.206	0.148	0.230	0.210	0.158	0.230	0.208

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

3.5.3 Results of "country-of-origin effect" of IFDI

Further, I pay attention to the "country-of-origin effect" and use a sample of firms who have OFDI to test the influence of inward FDI from OFDI destinations on their innovation gains. The information on the origins of IFDI is very difficult to obtain at the Chinese subnational level, so it is rarely discussed in the existing literature. I obtain this information from the annual statistics of 31 Chinese provinces which include the provincial-level investments from the major IFDI source countries. I focus on countries which are the major sources of IFDI into China, at the same time, they are also the main OFDI destinations for the firms in my sample. The firm distribution among countries is shown Table A 3-1 in the Appendix, from which we can see that more than 50% of the sample firms targeted these countries in the first OFDI. I use yearly IFDI flows from those major origin countries into 31 Chinese provinces as the weights to estimate the city-level foreign investments from different origin countries and then decompose $IFDI_{\ i,c,t-1}$, the total IFDI flow in the home city c of Chinese firm i, into two terms, 1. *IFDI from the OFDI destination country* of firm i, 2. *IFDI from other countries.* Consistent with the equation (3), I control for other factors that affects the firm's innovation capability changes, including firm variables (covariates used in the PSM), the patent numbers before OFDI, regional variables, and the industry and year fixed effects. In addition, because the model focuses on the spatial characteristics of investment, I also control the fixed effect of the investment destination country to control the difference in innovation capability of different destinations. The results are shown in the Table 3-8. Both *IFDI from destination country* and *IFDI from other counties* are significantly positive in year T+1 and the coefficient of destination country IFDI is larger and more significant, while in 3 years after OFDI, both become insignificant. In year T+5, *IFDI from destination country* turns to be positive and significant again and *IFDI from other counties* remains positive but insignificant. The above results show that IFDI originating from OFDI destination has significantly stronger impact on the innovation improvement after OFDI. The hypothesis 5 is verified.

Table 3-8. Results of IFDI influence on OFDI innovation gains through "country-of-origin effect"

	(1)	(2)	(3)
Variables	T+1	T+3	T+5
IFDI from OFDI destination country	2.529**	1.606	6.756*
	(1.104)	(2.168)	(3.630)
IFDI from other countries	1.569*	0.373	3.138
	(0.849)	(1.667)	(2.791)
Firm Control Variables	Yes	Yes	Yes
City Control Variables	Yes	Yes	Yes
Destination FE	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Constant	1.169	0.309	1.530
	(1.034)	(2.030)	(3.399)
Observations	522	522	522
R-squared	0.197	0.229	0.247

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

3.6 Robustness checks

1. I check the validity of the findings presented above by alternative matching strategies. First, I add more covariates into my matching model, such as number of employees, fixed assets, current assets, short-run investment and long-run investment, etc. The results are shown in the column 1 of Table A 3-2 in the Appendix. Second, I adopt the 1:3 matching and find three corresponding control firms with similar characteristics, as shown in the column 2. Results indicate that the effect of OFDI on firm innovation performance is robust to different PSM settings.
2. Besides, the major concern related with the matching is the comparability between the treatment group and control group: OFDI firms may have other unobservable systematic differences to non-OFDI firms, which are hard to control. I further address this concern using a new matching within the treatment group. I only focus on the OFDI firms and change the treatment from the OFDI dummy to the timing difference of their first OFDI. Firms becoming MNEs in 2005, 2006 and 2007 are treatment group and those investing 3 years later are used as control pool. I assume that the OFDI timing is relatively random among MNEs during the research period. If OFDI indeed leads to innovation improvement, the early investors should experience patent increase earlier than those investing late. The DID results are shown in Table A 3-2 and Figure A 3-1. The coefficient of treatment is still significant at T+1 (at 10% percent) and T+3 but the value is smaller. This result helps to further alleviate the endogeneity concern.
3. Using different matching settings, the other robustness check is about the influence of foreign equity participation on OFDI innovation benefits, as shown in Table A 3-3. Under alternative matching settings, the OFDI treatment effect on the joint ventures is always higher than that on domestic firms.
4. For the influence through between-firm channels, I assume the interaction between foreign firms and Chinese firms happens within the same city, while studies on the spatial diffusion effect of IFDI find that IFDI spillover may have cross-regional effects at larger geographic scope (Lin & Kwan, 2016) Therefore, the interaction with Chinese firms may also happen between neighbouring cities within the same province. To check this possibility and the robustness of my results, I then change the observation scale of IFDI to province. The results are shown in the Table A 3-4, where I see that the cross term of provincial level IFDI with the treatment OFDI is significantly positive but only in T+1 year. Moreover, the cross term of same sector IFDI is significantly positive in all periods and that for IFDI in other sector is not. The results are generally similar to the city level analysis, indicating that the co-locating with foreign firms in the same province also increase the OFDI innovation gains – the influence of IFDI through between-firm channel is robust to alternative spatial scales.

3.7 Conclusion

In this study, I explore the innovation-enhancing effect of outward FDI for Chinese MNEs and the important role played by inward FDI. I also investigate the underlying mechanism of this IFDI influence. By comparing a sample of 1,113 Chinese manufacturing firms which become MNEs during 2005-2011 and the corresponding counter factual firms, I observe significant impact of OFDI on the subsequent innovation performance in terms of domestic patent application. I test two important channels through which the IFDI influence happens: 1. the within-firm channel through foreign equity participation in the Chinese firms; 2. the between-firm channel, measured by co-locating with Chinese firms in their home cities and industrial relatedness through supply and demand ties.

To the best of my knowledge, this paper is the first empirical study that systematically exams the role of IFDI in firms' innovation gain through OFDI. I attempt to make the following contributions to the literature:

First, my findings enrich the IB literature and provide a more complete understanding of emerging markets and EMNEs by linking the home country contexts with the internationalization consequences. The special economic, industrial, and institutional features in the home country are found to be supplementary to the lack of firm specific advantages and influence EMNEs before and during internationalization (Mathews, 2002; Luo & Han, 2010; Yiu, 2011; Bhaumik et al., 2016; Gaur & Ding, 2018). Specifically, scholars have included inward internationalization activities with foreign investors in the EMNE internationalization framework to better understand the OFDI activities without strong ownership advantages (Gu & Lu, 2011; Hertenstein, 2017; Li et al., 2017). However, this stream of literature mainly focuses on IFDI's impact on the internationalization motivation and strategy of EMNEs, little is known about their impact upon post-investment performance. This study fills this research gap by showing that IFDI, as an important home country context, has strong impacts on the innovation gains after OFDI.

Second, the theoretical analysis and empirical findings provide a more thorough picture of the relationship of inward–outward FDI in the dynamic contexts of emerging markets. "investment development path model" of Dunning (1981) argues that for emerging markets, relative positions of inward and outward FDI change with time. Countries gradually shift between different investment stages – as economic development and ownership advantage accumulation of domestic firms, OFDI flows exceed those of IFDI and finally turn the country to be a net outward investor (Dunning, 1981; Dunning, 2003). This paper provides micro mechanism to this important model - there exists strong continuity and interactions between inward and outward FDI. These two-way investments are linked at the pivot, EMNEs, who are both recipients of IFDI and implementer of OFDI. EMNEs use both in sequence and leverage former to make better use of the latter to achieve resources augmentation. From accepting IFDI to conducting OFDI, EMNEs are changing their positions in the global production network from passively integrating into DMNE-led value chain towards actively building their own and become the global lead firms themselves (Pananond, 2013; Lee et al., 2018). And this, in turn, changes the internationalization stages of their home countries - the firm specific advantages and home country contexts co-evolve with each other under the IFDI-OFDI nexus.

Third, this paper contributes to the literature on FDI spillover effect. The empirical finding shows that IFDI not only has "direct" innovation impact on emerging market firms through demonstration, competition, or labour turnovers (Wei & Liu, 2006; Crespo & Fontoura, 2007), but also works as a platform through which EMNEs become better prepared for the subsequent internationalization to achieve their strategic assets-seeking motivation. Besides, different from studies based upon firms' interaction with the overall IFDI (Li et al., 2012; Li et al., 2017; Chen et al., 2020), I deeply study the mechanism by distinguishing heterogeneous channels of IFDI' influence on the OFDI-led innovation, in terms of equity participation, collocation and supply-demand ties. Moreover, In response to the "country of origin effect" view in the FDI spillover studies which argues that MNEs reflect the characteristics of the national business systems of their home country (Ferner, 1997; Ferner et al., 2014). IFDI originated from a certain country has stronger influence on innovation benefits if Chinese firms invest in that country.

These finding have important implications for CMNEs that want to increase their international performance and technological competitiveness, as well as for other EMNEs that could learn from the Chinese experience. Before investing abroad, companies can establish linkages with foreign companies in their home countries and home regions at low cost in order to make better use of the OFDI opportunities which are often more costly and risky (Li et al., 2017). For companies that want to acquire technology through foreign investment, some countries could be given priority, if prior external linkages have already been built through interacting with IFDI originated from those countries.

I also acknowledge that this paper has several limitations, which provides opportunities for future research. First, both the inward and the outward FDI are significantly influenced by the Chinese national policies. The Chinese government implements various location-based and industry-based regulations on transnational investments. Those policies have been co-evolving with the foreign firms in China over time and may have changed the relationship between domestic and foreign firms (Zhou et al., 2002; Deng, 2009). Therefore, future research should pay attention to how the special institutional context and its dynamics change this influence of inward FDI. Besides, my firm sample is based on the Chinese manufacture firms, it is important to further explore whether the findings presented here can be extended to other sectors, such as service, infrastructure as well as other countries with different economic and institutional conditions.

3.8 Appendix

Table A 3-1. The firm distribution by the first OFDI destinations

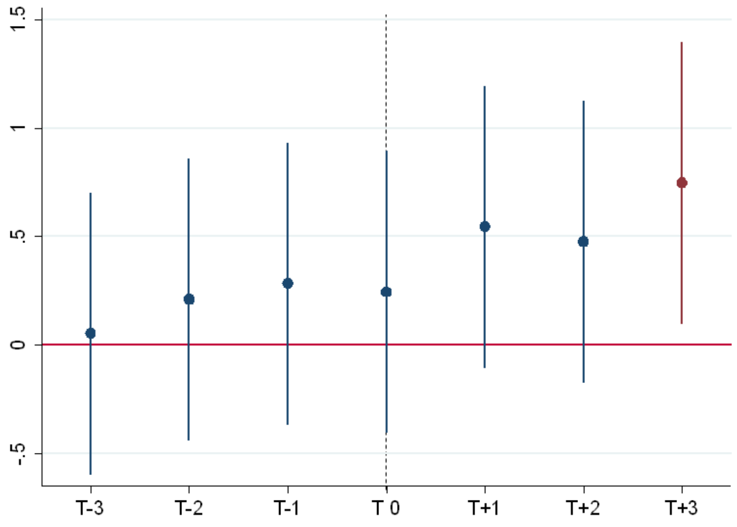
Country	Number of firms		
United States	189	Italy	16
Germany	62	France	11
Russia	35	Turkey	10
Japan	34	South Africa	10
Korea	33	Taiwan	8
Canada	25	Spain	6
United Kingdom	23	Switzerland	5
Singapore	22	Denmark	2
Australia	17	New Zealand	1
Netherlands	17	Total	526

Table A 3-2. Robustness check I

Variables	(1) Changing covariates	(2) 1:3 Matching	(3) Matching using OFDI time difference
∂_1^{T-5}	0.0734	0.0147	-
	(0.424)	(0.425)	-
∂_1^{T-4}	0.110	-0.157	-
	(0.424)	(0.425)	-
∂_1^{T-3}	0.116	-0.132	0.0550
	(0.424)	(0.425)	(0.330)
∂_1^{T-2}	0.414	0.0987	0.212
	(0.424)	(0.425)	(0.330)
∂_1^{T-1}	0.630	0.356	0.286
	(0.424)	(0.425)	(0.330)
$\partial_1^{T\ 0}$	0.929**	0.715*	0.246
	(0.424)	(0.425)	(0.330)
∂_1^{T+1}	1.609***	1.388***	0.547*
	(0.424)	(0.425)	(0.330)
∂_1^{T+2}	1.987***	1.956***	0.478
	(0.424)	(0.425)	(0.330)
∂_1^{T+3}	2.162***	2.027***	0.748**
	(0.424)	(0.425)	(0.330)
∂_1^{T+4}	2.811***	2.583***	-
	(0.424)	(0.425)	-
∂_1^{T+5}	3.253***	3.119***	-
	(0.424)	(0.425)	-
Constant	1.157***	1.443***	0.561
	(0.163)	(0.120)	(0.358)
Period FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Observations	27,492	54,672	4,928
R-squared	0.389	0.387	0.371

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Figure A 3-1. Difference in Difference result: matching within CMNEs, using OFDI timing as the treatment



Vertical lines show the 95% confidence intervals. Point estimates that are statistically significantly different from zero ($p = 0.05$) are shown in red, insignificant point estimates in blue.

Table A 3-3. Robustness checks II

	(1) Changing covariates		(2) 1:3 Matching	
Variables	JV	Domestic firms	JV	Domestic firms
∂_1^{T-5}	-0.00866	0.0940	-0.137	0.0531
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T-4}	0.0823	0.117	-0.339	-0.112
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T-3}	0.0390	0.136	-0.0231	-0.160
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T-2}	0.195	0.469	0.212	0.0689
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T-1}	0.619	0.632	0.442	0.333
	(0.849)	(0.485)	(0.671)	(0.505)
$\partial_1^{T\,0}$	0.831	0.953**	0.608	0.740
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T+1}	1.766**	1.569***	1.434**	1.375***
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T+2}	2.199***	1.933***	2.046***	1.932***
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T+3}	3.052***	1.937***	2.587***	1.885***
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T+4}	4.108***	2.483***	3.556***	2.336***
	(0.849)	(0.485)	(0.671)	(0.505)
∂_1^{T+5}	3.026***	3.309***	3.430***	3.291***
	(0.849)	(0.485)	(0.671)	(0.505)
Constant	0.968***	1.202***	1.337***	1.463***
	(0.333)	(0.187)	(0.194)	(0.143)
Period FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Observations	5,544	21,948	11,088	43,584
R-squared	0.335	0.399	0.336	0.393

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Table A 3-4. Robustness checks III

Variables	T+1	T+3	T+5	T+1	T+3	T+5
OFDI	0.998***	1.547***	2.328***	0.934***	1.506***	2.294***
	(0.295)	(0.511)	(0.804)	(0.290)	(0.510)	(0.803)
Total IFDI_province	-0.0316	0.132	0.192			
	(0.254)	(0.439)	(0.691)			
OFDI×Total IFDI_province	0.848***	0.626	0.119			
	(0.295)	(0.511)	(0.803)			
same-sector IFDI_province				0.0328	-0.0505	-0.301
				(0.265)	(0.466)	(0.735)
OFDI×same sector IFDI_province				2.147***	1.491***	1.538*
				(0.325)	(0.571)	(0.900)
other-sector IFDI_province				-0.0114	0.174	0.333
				(0.267)	(0.469)	(0.739)
OFDI×cross-sector IFDI_province				-0.370	-0.212	-0.722
				(0.330)	(0.580)	(0.914)
Constant	0.0728	1.196**	2.218***	0.166	1.250**	2.241***
	(0.287)	(0.496)	(0.780)	(0.283)	(0.498)	(0.784)
Firm Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
City Control Variables	Yes	Yes	Yes	Yes	Yes	Yes
Sector FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,170	2,170	2,170	2,170	2,170	2,170
R-squared	0.082	0.171	0.154	0.116	0.176	0.156

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Chapter 4. The Material Basis of Modern Technologies - A Case Study on Rare Metals

4.1 Introduction

Natural resources are the material basis for industry development and economic growth. As a special group of resources, rare metals (RMs), also known as minor metals, are becoming more and more prominent in high-tech industries, and are regarded as "technology metals" with great criticality at the innovation frontier (Grandell et al., 2016; Ali, 2019). Different from major and base metals (e.g., copper, iron, and aluminium) RMs are like the "vitamins" or "spices" for the industry - only used in very small quantities, but providing unique and essential chemical, electrical or mechanical properties. They fundamentally improve the functionalities of materials leading to extensive applications in a variety of high-tech products, such as semiconductors, catalysts, engines, turbines, batteries, as well as medical equipment and weapons (e.g. Hampel & Kolodney, 1961; Lavareda et al., 2006; Fizaine, 2013; Gunn, 2014). Innovation, especially cutting-edge technological innovation, has formed a deep dependence on these minor but crucially important materials.

On the other hand, RMs are facing significant supply risks, which have received special attention from both the academia and government agencies (e.g. US National Research Council, 2008; European Commission, 2010; Humphries, 2010; Hayes & McCullough, 2018). The potential supply risks come from different sources: depletion due to mineral scarcity, geographical concentration of deposits, political stability of producing countries, geopolitical risks in global RM trade as well as the low recycling rates (Haxel, 2002; Radetzki, 2008; Narine, 2012; Izatt et al., 2014; Lederer & McCullough, 2018). Such risks may constrain the industrial development and innovation of modern technologies. For example, solar energy industry and relevant technologies are expected to be seriously affected by fluctuations in the supply of gallium (Ga) and indium (In) (Gunn, 2014). Despite such criticalities and the potential impacts on frontier technologies, neither innovation research nor economics literature have paid enough attention to rare metals.

Against this backdrop, in what follows we attempt to explore the following crucial but unanswered questions: 1. To what extent do different technological areas depend on various rare earth metals and what have been the dynamics of RM-based technologies? 2. Do changes in the RMs' supply affect the innovation output of the RM-based technologies?

To answer these questions, we first use the USPTO patent data to systematically explore the technological dependence on RMs by identifying the RM keywords in the patent text. We then rely on a panel model of 2,187 Technology-RM pairs over the period 1976-2015 to assess the impact of RM supply, measured by the annual global metal production, on the innovation performance of RM-based technologies, measured by patent numbers. A major challenge in estimating this effect is the reverse causality that technology developments, in return, affect metal production. For miners and metal producers, increasing technology importance changes their anticipated profits of exploring, extracting, and processing minerals and metals and thus influence their production decisions. To address these endogeneity concerns, we develop an instrument variable and capture the exogenous variance of RM supply from the metal companionability and co-production relationship between rare metals and their geological host, the base metals (Nassar et al., 2015; Sprecher et al., 2017).

Our paper contributes to the literature in various respects. First, we enhance the understanding of the driving forces of innovation and the endogenous technological development under the influence of changing supply conditions of natural resources. As a "creative destruction" process, innovation leads to production paradigm shifts and new combination mode of production factors (Schumpeter, 1949), which change the modes and efficiency in utilizing different natural resources. Mainstream economics argues that technological innovation makes it possible to substitute scarce and expensive resource with capital, man-made goods, or other relatively abundant and cheap resources (Solow, 1974; Stiglitz, 1974; Rosenberg, 1976). In this way, technology solves or ameliorates the resource scarcity, enabling society to overcome natural supply constraints and achieve sustainable development. However, such a "technology optimism" overlooks the endogeneity of technologies – innovation itself may be reversely influenced by resource supply conditions. It is less clear whether and how natural resource availability in return affects technology dynamics. Moreover, the strong assumption on substitutability neglects the resource heterogeneity and the criticality of some non-renewable resources with limited substitution possibilities (Graedel, 2015). In this paper we argue that because of their unique technological characteristics and relatively low substitutability, the rarity and supply risks of RMs may become the potential constrains for the advancement of frontier technologies.

Second, this paper also contributes to the resource criticality studies by broadening the understanding of the rare metals. Existing literature on RMs mainly focuses on material flow analysis and supply chain management (e.g. Kim & Davis, 2016; Sauer & Seuring, 2017); criticality assessment (e.g. Hayes & McCullough, 2018); international regulations, as well as the corresponding behaviours and responsibilities of firms (Diemel & Cuvelier, 2015; Hofmann et al., 2015). However, although regarded as "technology metals", RMs have rarely been systematically studied from an actual technological perspective. It is widely recognized in the literature that modern technology is strongly dependent on those metals, and possible supply risks may cause big shocks to technological change, particularly in high-tech industries (Eggert, 2010). However, it is still unknown how deep this dependency is and how big these shocks would be. Following Diemer et al. (2021), this paper makes an explorative attempt to quantitatively and comprehensively measure the technological dependence on RMs through patent text mining. Using the rich USPTO patent information, we adopt a cross-technology focus, allowing us not only to explore the dependence on RMs but also to measure the heterogeneity among various technological areas.

The paper is organized as follows: Sections 2 reviews related literature and establishes the theoretical foundations; Sections 3 explains the selection rationale and data sources of rare metals and technologies as well as the text mining methods, whilst Section 4 calculates the technological dependence on RMs at the different scales of technology classes; Section 5 and 6 estimate the impact of RM supply on the innovation output of RM-based technologies and test the robustness; Section 7 concludes providing further research directions.

4.2 Literature review

4.2.1 Technology dynamics and natural resource availability

Different streams of literature have analysed the interdependency between technological dynamics, natural resource availability and economic growth. In the neo-classical growth frameworks technology is believed to determine the relationship between natural resources and economic growth. Solow (1974), Dasgupta and Heal (1974) as well as Stiglitz (1974) use one-sector optimal growth models with non-renewable resources as input to explain the compatibility between natural resource constraints and economic development. They came to the optimistic conclusions that with exogenous technologies as the fundamental driving force, positive long-run growth can be achieved in the presence of non-renewable natural resources. Technological progress and capital accumulation compensate for the negative effects of the fading natural resource input. However, this exogenous perspective has been criticized on the grounds that some critical natural resources may in return influence technological progress itself (Barbier, 1999). The endogenous relationship between natural resource availability and technology development is further studied by resource and ecological economists under the framework of New Growth Theory. Barbier (1999) modified the Romer-Stiglitz model by allowing resource scarcity as a constraint condition for innovation and found that it may offset the long-run rate of innovation outcomes. Groth and Schou (2002) further introduced non-renewable natural resources as essential inputs and came to the conclusion that scarce resources make it difficult to have stable endogenous growth. Bretschger (1999; 2005) focused on the supply condition of innovation in a multi-sector model setting, assuming non-renewable resources as the essential inputs in the research sector. He found that resource prices increase lower the expectations on the direct return on innovation and causes problems in long term technological progress. At the same time, the resource supply condition leads to structural changes among sectors and have a deep influence on both technology trajectory and economic development.

A parallel stream of literature related to this topic looks at the driving forces of technological innovation. On the one hand, the "technology-push" perspective emphasizes that science and technology play the key role in innovation rates and create new technology paradigms (Mowery & Rosenberg, 1979). On the other hand, other studies use a "demand-pull" perspective to identify the effect of the final market conditions, potential demand of the users, and of the economy and society as a whole on the performance and direction of technological innovation (Von Hippel, 1994; Acemoglu, 2002; Franke & Shah, 2003). Innovators adjust their efforts catering to the changing market conditions for commercialization (Rosenberg, 1969; Christensen & Bower, 1996). Under the same endogenous view, "induced innovation hypothesis" literature argues that the rate and direction of technological progress are determined, to a significant extent, by dynamics in supply of production factors, such as natural resources as well as the changing policy conditions (Hicks, 1932; Schmookler, 1962). Specific factor supply conditions determine the optimal combination mode of resources and such optimal mode changes as the technology progress adjusting the meta-production functions according to the dynamics of resource availability (Dosi, 1988).

Many empirical studies have tested this important hypothesis. Early contributions mainly focused on the agriculture sector by comparing the US with Asian countries (Hayami & Ruttan, 1970; Kawagoe et al., 1986; Olmstead & Rhode, 1993; Thirtle et al., 2002). They viewed agricultural growth and related technology development as a dynamic factor substitution process. The increase in the land resource and decline in the land price relative to labour cost encourage the substitution of land for labour, which stimulates innovation in mechanical technologies. In comparison, limited land supply induces innovation in high yielding fertilizer and biological technologies. Moreover, recent studies use the case of new energy technologies to further test this hypothesis arguing that the supply shortage and price increase of conventional energy inputs stimulate the development of green energy technologies (Goulder, 1999; Cheon & Urpelainen, 2012; Bayer et al., 2013; Aghion et al., 2016). In his pioneering article, Popp (2002) found that anticipated energy prices strongly predicted patents designed for green and sustainable energies across a range of industrial sectors. In the same vein, Lin & Chen (2019) found higher electricity price makes renewable energy more competitive and stimulates innovation in renewable energy technologies to reduce the reliance on electricity generation. This inducement effect on green energy innovation is further strengthened by properly designed energy policies and environmental standards which help to integrate the spillover effect of green energy technologies into market mechanism (Popp, 2001; 2002; Johnstone et al., 2010; Lindman & Söderholm, 2016; Böhringer, 2017).

In summary, existing economics and innovation literatures have provided some important explanations to the co-evolution between natural resources and technological progress. Nonetheless, the substitution relationship between capital and natural resources and that among different resources are always assumed to be the key mechanisms in the theoretical models above. In classical economics models, the substitution elasticity between exhaustible resources and capital or man-made inputs is assumed to be bigger than unity (Solow, 1974), which is proved to be unrealistic considering the material balance restriction (Common & Perrings, 1992; Costanza & Daly, 1992; Cleveland & Ruth, 1997). At the same time, for some specific critical resources, like the case of rare metals, this strong substitution assumption may not hold at all (Graedel et al., 2015). Although the challenge to substitution from key irreplaceable natural resources has been considered by some economics theoretical models (e.g., Bretschger, 2005), to our knowledge there is still no research providing empirical evidence.

In addition, existing empirical studies only focus on limited sectors and technological domains, with important omissions (Watari, 2020). Moreover, they fail to explore the detailed inducement mechanisms of heterogenous resources. Dosi (1988) argues that inducement to innovation may come from various channels such as: 1. abundance of particular inputs like energy and raw materials; 2. major shocks in prices/supplies; 3. scarcities of critical inputs. However, natural resources have been mainly regarded as general inputs ignoring that they may enter the core growth of some high-tech and R&D-intensive industries as "critical inputs" (Bretschger, 2005). As a special group of natural resource, the RM case represents non-renewable, technologically critical, and irreplaceable materials, providing new insights for the literature on natural resource and technology. Here we argue that the supply of such specific natural resources not only indirectly "induces" innovation but also works as the critical material basis and directly "determines" the technological frontier dynamics.

4.2.2 Rare metals: technological criticality and supply risks

With the advancement of science, the range of useful and available chemistry elements for human societies have been gradually expanding on the periodic table. For example, the types of elements used in computers have increased from 11 in 1980s to 15 in 1990s, and to 60 in the 2010s (Zepf & Achzet, 2015). At the same time, various elements are also combined by different modes leading to the emergence of new industrial materials (Eggert, 2010). In recent years unique electrical, thermal, chemical, and optical properties of RM materials have been discovered, meeting the demands of cutting-edge technologies. Those RM-based technologies have led to substantial function improvements in existing products and also resulted in the creation of new products. High-tech products and the technological frontier show a strong dependence on rare metals.

There are two major technology paradigm shifts highly relying on RM materials. First, scholars highlight the importance of RMs in clean and green energy technologies (Grandell et al., 2016). Almost all core technologies in this green shift, including solar electricity, wind power, fuel cells, hydrogen production and storage, electric cars and energy efficient-lighting are heavily dependent on different kinds of RMs (Grandell et al., 2016; Zhou et al, 2016). Second, against the backdrop of the shift towards industry 4.0, revolutionary technology breakthroughs in information, communication and artificial intelligence technologies have significantly increased the complexity and sophistication of electronic equipment – faster and smarter devices with greater computing capabilities are invented as the physical infrastructure for digitalization, automatization, and global connectivity. This has also raised demands for various RMs as essential inputs in advanced electronic components, such as lithium (Li) and cobalt (Co) in batteries, gallium (Ga) and germanium (Ge) in integrated circuits, tantalum (Ta) in capacitors, molybdenum (Mo) in transistors as well as indium (In) in the displays (Eggert, 2010; Gunn, 2014).

Unlike other natural resources, the application of RMs in specific areas of technology is difficult to be replaced by other materials due to their unique properties (Leader, 2019). Engineering and natural science research indicates that for some RMs, "no suitable substitutes can be found no matter what price is offered without performance and function being seriously compromised" (Graedel et al., 2015 p. 6299). The research and development of useful possible substitutes often require very long research cycle and high costs, which makes market-ready substitutes for many rare metals rarely available (European Commission, 2012). Moreover, the possible substitutes of a certain RM are often some other RMs which are also facing supply constraints, for example, the replacement of cobalt with neodymium in permanent magnets (Ku, 2018). Many studies have found that future production of some high-tech products will be constrained by the potential supply shortage of RMs. For example, the drastic increase in critical metal prices makes green energy products difficult to compete economically with the incumbent energies, which leads to a negative impact on the adoption and development of clean energy technologies (Leader et al., 2019).

Over the last decades, RM markets were impacted by crises in the supply chain. The high demand and criticality in high-tech industries further increase the risk of extreme price spikes or even material unavailability (Moss & Tzimas, 2013). These supply risks come from different stages of the RM value chain, from upstream mineral mining to metal production (smelting, refining and heat processing) and then to global trade. For some RMs, the ore extraction is concentrated in a small number of locations and connected to issues of conflicts and serious violation of human rights. This geographical concentration of sources makes the ore supply very vulnerable to natural disasters, wars, social and political instability (Menzie et al., 2011; Diemer et al., 2021). Rising RM values often trigger more conflicts in the unstable mining countries, which causes further interruptions in mineral mining (e.g., Berman et al., 2017). For example, in 1976, the political upheavals in Zambia made the global cobalt (Co) production fell by 20% with a price jump from $5.40/lb to $25/lb (Radetzki, 2008). Furthermore, because of the global expansion of mineral and metal value chains, production of RMs has gradually shifted to emerging countries (especially, China). The spatial divergence of production and consumption leads to a tremendous increase in the global RM commodity trade which is accompanied by more risks (Haxel, 2002; Narine, 2012; Lederer & McCullough, 2018). The trade of some critical metals is also impacted by trade conflicts or political events which lead to market panics and sharp price increases (Mancheri, 2015).

The supply and availability of RMs change the innovation motivation of researchers. Innovation is a risk-taking investment: innovators allocate efforts among technology areas according to the expected profits of innovations. Fluctuations in the supply chain significantly affect the production of rare metals, which then affects their availability in downstream industries and their demand (Schoolderman & Mathlener, 2011). Sufficient supply of RMs increases the production scale and market size of products using RM-based technologies, therefore rising the probability of application and commercialization of relevant technologies, making it more profitable to invest in such technologies (Acemoglu, 2002). On the other hand, insufficient production or disruption in RM supply may reduce the returns of R&D on RM-based technologies and make their application more costly. This changes the innovation motivation of scientific research institutions and corporate researchers in areas that rely heavily on RMs.

Based on the above background, our main research hypothesis is as follows:

Hypothesis: The increasing supply of a certain rare metal positively impacts the innovation output of technology areas which are highly dependent on it.

4.3 Data and methodology

4.3.1 Selection of RMs and global production dynamics

There is no standard definition for rare metals in the literature, but there is a clear understanding on what defines them. These metals have two characteristics: first, they are of technological importance, being demanded by the frontier technologies and industries; second, they are rare, reserved and used in significantly smaller quantities compared with the base metals, such as iron, aluminium, and copper. In this paper we select RMs by referring to the existing literature on "critical rare metal/minerals", "technology metals", "green energy metals", as listed in Table 4-1. It is important to note that we did not include precious metals, such as gold, silver and platinum group metals which are also rare and technologically important, but they are more intensively used as currency or jewelleries rather than industries. Moreover, we did not include rare earth group metals[5]: although the latter are crucially important and widely investigated by related literature (Humphries, 2010; Hensel, 2011; Zhou et al., 2016), their production information is not available for individual elements.

Table 4-1. List of selected RMs and examples of related literature

Rare metals	Related Literature
Bismuth (Bi)	Moss et al. (2011); Hein et al. (2013); Hagelüken (2014)
Cadmium (Cd)	Moss et al. (2011); Valero et al. (2018)
Cobalt (Co)	Humphries (2010); Campbell (2020)
Gallium (Ga)	Anctil & Fthenakis (2013); Frenzel et al. (2017)
Germanium (Ge)	Harper et al. (2015); Frenzel et al. (2017)
Indium (In)	Elshkaki & Shen. (2011); Grandell et al. (2016); Frenzel et al. (2017)
Lithium (Li)	Liu et al. (2019); King & Boxall (2019)
Molybdenum (Mo)	Leader et al. (2019); Zhu et al. (2020)
Selenium (Se)	Elshkaki, & Shen (2019); Grandell et al. (2016)
Tantalum (Ta)	Humphries (2010); Kim et al. (2019)
Tellurium (Te)	Woodhouse et al. (2013); Valero et al. (2018)
Vanadium (V)	Moss et al. (2013); Gunn et al. (2014)
Zirconium (Zr)	Moss et al. (2011); Zhu et al. (2020)

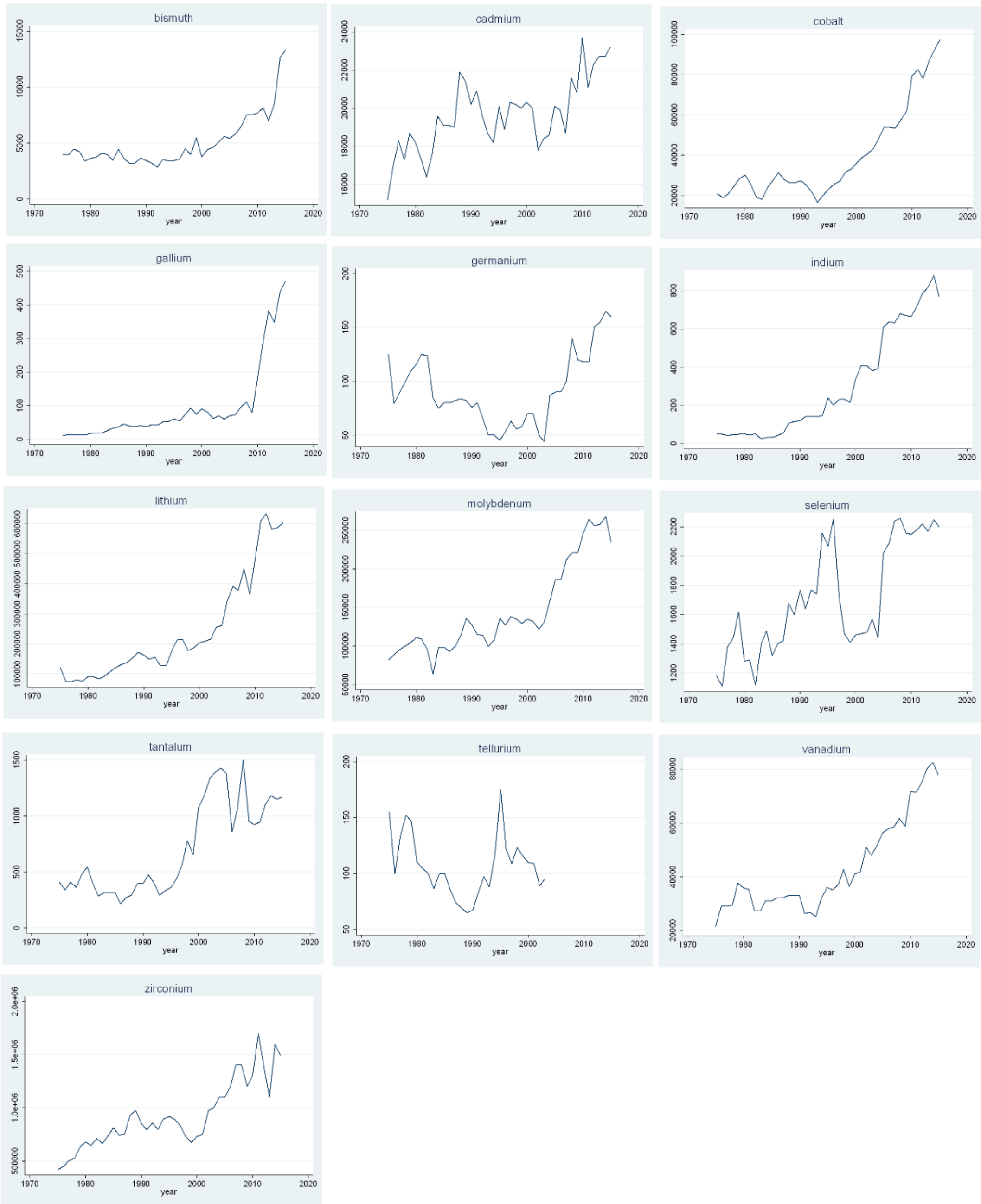
Note: Two elements, selenium and tellurium are metalloids rather than metals. However, they have some similar characteristics and applications with metals, therefore they are analyzed together with other metals in the literature (i.e. Elshkaki & Shen, 2019; Zhu et al., 2020; Watari et al., 2020).

We obtained the global production data of these 13 rare metals during 1975-2015 from the United States Geology Survey database of historical statistics for mineral and material commodities. Figure 4-1 below shows the annual production of 13 RMs, in unit of ton. In general, the production of most metals has risen with fluctuation and, especially after 2000, the upward trends accelerate. At the same time, the supply dynamics of different metals show

[5] Rare earth elements are a group of 17 elements: La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu plus Sc and Y.

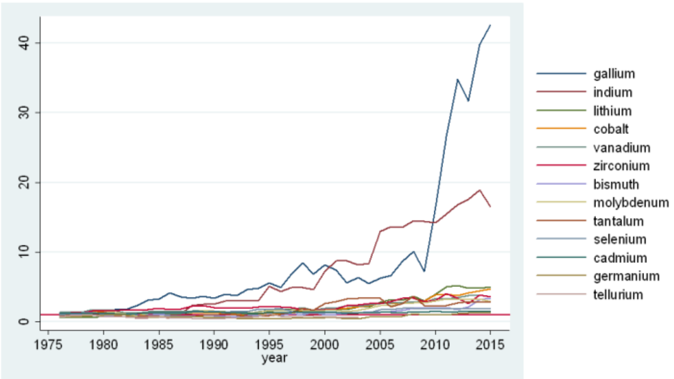
significant differences. The production of cadmium, tantalum, and selenium fluctuates greatly, while for cobalt, lithium, vanadium, indium, and bismuth the trend is relatively stable, showing a nearly monotonical increase. At the same time, we also observe that some macro events have common impacts on the supply of all metals. For example, around 2010, affected by the financial crisis, almost all metals showed different degrees of production decline.

Figure 4-1 Annual production of 13 RMs, 1975-2015 (Unit, ton)



Due to many differences – the chemical property, reserve amount in nature, as well as diversified applications in industry – there is a vast variation in the demand and volume production among the 13 metals. For example, in 2015 the production of zirconium was 400 times that of gallium. This makes the comparison in terms of absolute production quantities among the metals meaningless. Therefore, for each metal we standardize every year production data by taking a ratio over the amount of production in 1975, the initial year, so that we can compare relative production changes between metals in four decades (Figure 4-2). Gallium and indium have the fastest growth: by 2015, their production was 40 times and 20 times higher than the initial amount in 1975, respectively. In addition, the production of lithium and cobalt has also increased rapidly, both nearly five times. On the other hand, the growth of cadmium, germanium and tellurium is very limited.

Figure 4-2.Production changes for 13 RMs, 1975-2015 (ratio relative to 1975)



4.3.2 Patent data and global technology dynamics

This paper uses patents granted by the United States Patent and Trademark Office (USPTO) over the period 1976-2015 to measure the global technology dynamics of the RM-based technologies. Despite of some limitations of patent data, such that many innovations and inventions are not patented, patent statistics are still believed to be a reasonable measurement for innovation, especially in high technology industries (e.g., Pavitt, 1985; Griliches, 1990; Patel & Pavitt, 1995; Fifarek et al., 2008).

There are in total 5,310,050 granted patents in the USPTO during the research period. The IPC code is used by USPTO for technology classification at five different technology levels - section, class, subclass, groups and subgroups. Besides IPC classification, we also use "WIPO technology classification" to analyse the RM intensity of different technology areas. This taxonomy was developed by Schmoch (2008) and gradually updated since then. It assigned 653 IPC classes into 35 technology **fields** which are further aggregated into five main technology

sectors - Chemistry, Electrical engineering, Instruments, Mechanical engineering, and Others.[6] This classification is developed under three major principles. First, it achieves a size balance among different technology sectors and fields by avoiding very large or very small fields. Second, the content of the different fields is distinct from each other avoiding the overlapping between technologies. Moreover, it covers all 4-digit IPC technology classes.[7] The balanced patent size, within-sector homogeneity and across-sector differences make it a useful classification in cross-sector comparison. Therefore, it has been widely used by patent analyses (e.g., d'Agostino et al., 2013; Balland et al., 2019).

4.3.3 Identification of RM-based technologies

The identification of rare metals in the patent databases is carried out by text-mining, searching for the name of the relevant metal elements in the patent text (e.g., Fifarek et al., 2008; Diemer et al., 2021). In this paper, we use the "brief summary text", the first part of the patent description text[8]. It includes the key information disclosed by the inventors, such as technology details about the function and application of the invention, and the materials it uses to achieve its function. We note that mentioning a material in the patent text could have different reasons. It could be due to technologies produced directly from basic and applied research for that material, or innovations in applied technologies for which that material is an essential component (Fifarek et al., 2008). Moreover, it may also relate to obtaining, saving or recycling of that material.

In this paper, we focus on the technologies "relying on" RM materials or employing them as inputs. To do so, we exclude two groups of technologies: 1. those potentially related to mining technologies (39,437 patents in the class E21) which include technologies about mining minerals, and 2. Metallurgy technologies (56,306 patents in classes C21-C30) which include those for producing, refining, smelting as well as recovering and recycling of metal and metalloids. Our final sample for the analysis includes 5,214,307 patents.[9] If a patent mentions the RM keywords in the summary of description text, we consider the innovation as resulting from the properties of the specified RM materials and the patent as RM-based. However, we recognize that this method has some other potential limitations. For example, it fails to identify the degree of dependency on RMs: for two patents, which both mention a RM, one may use it as a necessity, while for the other RM may not play a major role in the innovation. Nevertheless, in this paper we are concerned mainly about the relative proportion of RM-based patents in

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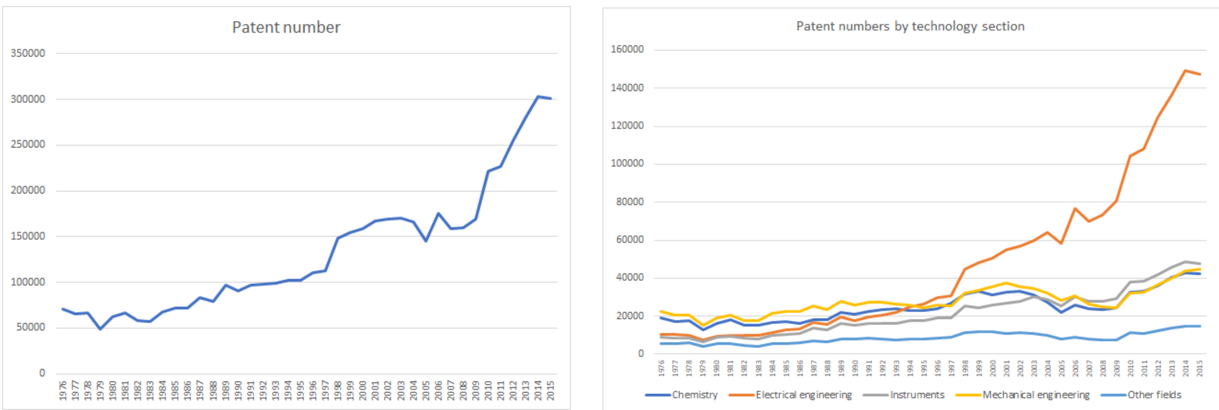
[6] The latest 2019 version Technology Concordance Table linking IPC and WIPO classification is in Appendix, Table A 4-1.
[7] IPC 4-digit codes in the patent documents are reclassified by this standard. Different sectors have technologies in multiple digit IPC classes. For example, the sector chemistry has 17 4-digit classes from class *A (Human Necessities)* in IPC, 30 from *B (Performing Operations; Transporting)*, 87 from *C (Chemistry; Metallurgy)* and 18 classes from other classes D, E, F, G, H.
[8] Available at https://patentsview.org/download/data-download-tables
[9] For a detailed description of the patent sample see Table A 4-2 in the Appendix.

different aggregated technology categories and their temporal trends, rather than individual patents. We assume that if a technology field has a higher proportion of RM-based patents, then this field has a higher dependency upon RM materials.

4.3.4 General innovation dynamics in USPTO

Using USPTO patent information, we describe global technology changes during the observed period. The left side of Figure 4-3 shows the total number of patents, which has gradually increased, especially after 2009. The right side outlines the structural dynamics of technology development by the five sectors, which has experienced different growth paths. The Mechanical engineering and Chemistry sectors have the highest number in the early years when the other sectors were significantly lower. However, in the 1990s the pattern of patents distribution experienced significant changes. The growth of Electrical engineering patents began to accelerate and exceeded the Chemical sector in 1994, reflecting the technological paradigm shifts towards ICTs. After 2000, patents number of Chemistry and Mechanical engineering as well as Instruments experienced almost the same growth trajectory, with a decline during 2000-2008 then bouncing back. Patents in Instruments maintained a steady growth during the period, while patents in other sectors kept a low level. Figure A 4-1 in the Appendix shows the distribution of granted patents in 35 fields. The distribution in the Chemistry sector is relatively even, and the Pharmaceutical field has the highest patent number. Patents in several fields of Electronic engineering are significantly higher than those of other fields, particularly for example in Computer technology, Electrical machinery, apparatus, energy, Semiconductors and Communication technology, etc. In addition, high patent numbers also appear in other fields, such as Optics, Measurement and Transportation.

Figure 4-3. Trends of patent number by technology sector



4.4 The technological dependence on RMs

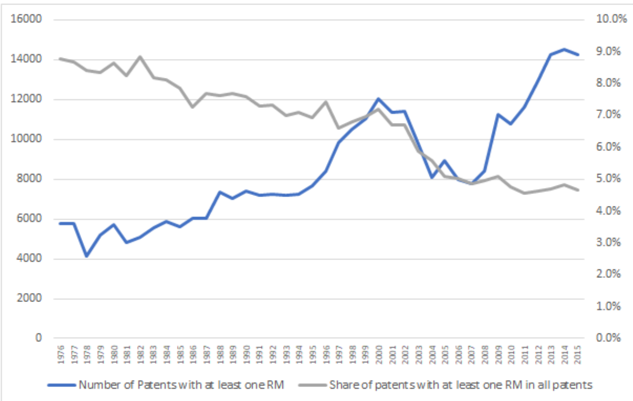
In this section we focus on the technological dependence on RMs. First, the general trends of RM-related patents and their distribution across technology sectors and fields are analysed. Second, we look at the distribution of RM-based technology areas at different levels of aggregations and also describe the RM intensity in 5 technological sectors and 35 fields.

4.4.1 General trends

Through keyword identification, we found that in the 5,214,307 USPTO patent sample, 312,056 patents (5.98%) mention at least one RM keywords. Therefore, more than 1/20 modern technologies are somehow dependent on the 13 RMs we focus on, indicating their high importance in innovation.

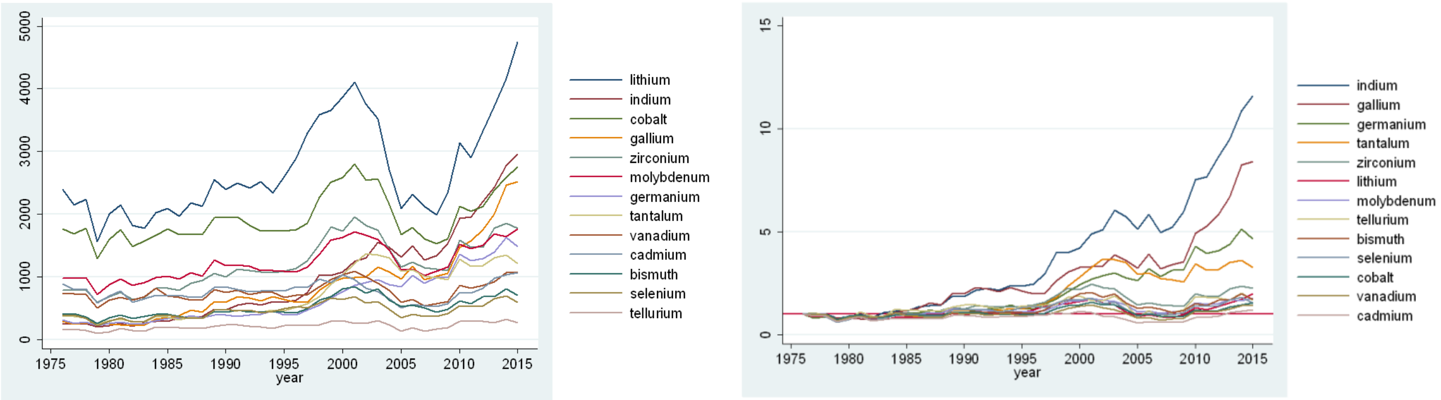
In Figure 4-4, the blue line represents the number of RM-based patents by year, and the grey line represents the proportion of RM-based patents in all patents. Despite a decline between 2000 and 2006, the number of RM-based patents has risen overall over the 40 years: from 6,000 new RM patents per year in 1976 to more than 14,000 in 2015. On the contrary, the proportion of RM patents in all patents gradually decreased, from the initial 9% to less than 5% in 2015. This indicates that RMs are used by more and more patents, but simultaneously the number of all patents has increased more rapidly, making the proportion of RM-based patents gradually decrease.

Figure 4-4. General trend of technological dependence on RMs



Next, we compare the dependence between different RMs over time (Figure 4-5). The left side of the figure illustrates the number of patents based on different metals. The right side shows the relative increase in RM-based patent numbers using 1976 as the benchmark value, reflecting the changing degree of dependence on different metals. In general, the number of patents using lithium has remained the highest, followed by cobalt. Indium experienced the fastest growth, with an increase of more than ten times in the past 40 years, surpassing that of cobalt in 2013, and became the second most intensively used rare metal. In addition, the number of patents based on gallium, germanium, and tantalum has also increased significantly. For other metals, such as cadmium, tellurium and selenium, relevant patent numbers are significantly smaller and did not show any significant growth trend in the studied period.

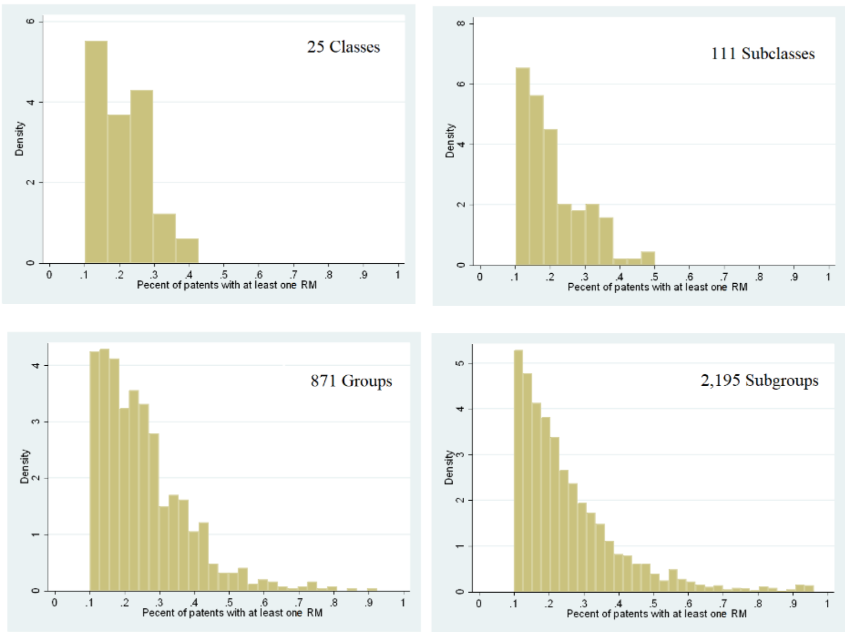
Figure 4-5. General trend of technological dependence by RM, 1976-2015



4.4.2 Technological dependence on RMs in different technology areas

Next, we focus on how technological dependence on RMs varies with technology levels. Figure 4-6 shows the probability density distribution of technology areas with RM dependence at the four IPC classification levels, reporting only RM-based areas where more than 10% of patents rely on at least one RM. In general, at all the four technology levels, more areas show lower dependence degrees on RMs. On the other hand, the finer the technology scale, the higher the dependence. At the level of Classes, all 25 have a dependence degree under 40%, but at the finest – 5 digit IPC classification – Subgroups' level, some show a higher degree of dependence, with more than 90% of patents relying on RMs. These findings indicate that the dependence degree on RMs varies with the scale of analysis. The technology areas highly relying on RMs can be observed in some specialized technological subdivisions.

Figure 4-6. Distribution of RM-based technologies at different technology levels during 1976-2015



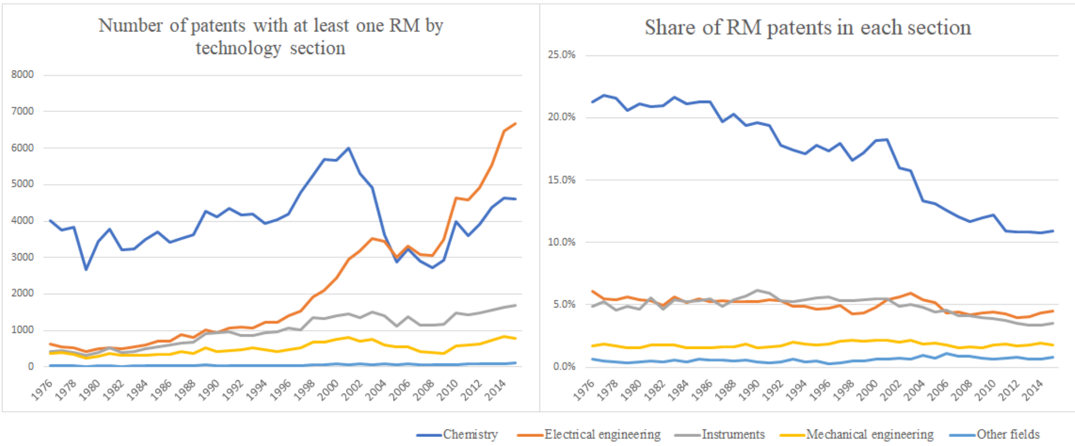
4.4.3 WIPO technology sectors' trends

In this section, we focus on the technological dependence on RMs for each WIPO sector, as shown in Figure 4-7. The dependence is measured in absolute and relative terms, i.e., 1. the total number of RM-based patents (with at least one RM keyword), 2. the share of RM-based patents in the total patent number of the sector. In terms of absolute dependence, the Chemistry sector started at a very high level and had the most RM-based patents for nearly 30 years, even higher than the sum of all other four sectors. It maintained a relatively stable increase until 2000, experiencing a decline in the following decade. For the Electronic engineering sector, we observe a sharp increase since 1995: in 2004 it surpassed Chemistry and became the most RM-based sector. The number of RM-based patents in the sectors of Mechanical engineering and Instruments show modest increases, while the numbers in Other fields are negligible.

As can be seen from the right side of Figure 4-7, the share of RM-based patents in

Chemistry is significantly higher than in other sectors, but it shrinks gradually over time from 20% in 1976 to 10% in 2015. In comparison, the shares of other technology sectors have remained relatively constant over time. For Electrical engineering and Instrument technologies, it stays at about 5% with slight drops after 2008. The share of Mechanical engineering is lower at about 2%, and that of Other field technologies are the lowest. From this description, we see that the drop of RM-based patent share in all patents shown in Figure 4-4 can be largely attributed to the decline in Chemistry. For the other sectors, the total and RM-based patent numbers increase at the same rate, making the relative dependence on RMs generally unchanged over time.

Figure 4-7. Trends in RM-dependence by WIPO technology sectors, 1976-2015



4.4.4 WIPO technology field level

Next, we zoom in to the WIPO field level. As above, we calculate the technological dependence of 35 technology fields in terms of RM-based patent numbers during 1976-2015 in Figure 4-8 and the share of RM-patents in each field in Figure 4-9. In both figures, the left side reports the patent number/share with at least one RMs, whilst on the right the patent number/share is further divided by each of the 13 RMs. In addition to 35 technology fields, we also single out green energy technologies[10] from USPTO: their dependence on RM is shown at the bottom of Figures 4-8 and 4-9.

Not surprisingly, the Chemistry sector has the highest share of RM-based patent, which are widely distributed across technology fields within this sector. First, Organic fine chemistry shows the highest dependence both in absolute and relative terms: nearly 30 percent of patents use at least one RMs. Similarly, the field Macromolecular chemistry, polymers also shows a

10 We identify green energy technologies using the corresponding table from IPC Green Inventory Project of WIPO (https://www.wipo.int/classifications/ipc/green-inventory/home)

strong dependence on RMs, with a share of 25%. Moreover, two fields related to materials, Material, metallurgy and Basic material chemistry also show strong reliance on RMs. These fields include technologies related to "manufacturing of all types of metals, ceramics, glass materials" (Schmoch, 2008, p.14); since we have excluded the metallurgy technologies (C22-C30) in our sample, this result indicates that besides metallurgy technologies, there are more diversified technologies about inventing, producing new materials which use RMs as components looking for improvements of material properties as, for example, technologies in *C02 Alloys* and *C03C Chemical Composition of Glasses, Glazes, or Vitreous Enamels*. In addition, the dependence on RMs for the fields Surface technology, coating, Pharmaceuticals as well as Chemical engineering is also relatively high. For Micro-structural and nanotechnologies, the RM-based patent number is very low because of the small total patent number in this field, but the share of patent with at least one RMs is as high as 17%. It is important to note that technologies in the Chemistry sector are usually general purpose technologies (GPTs), which are closely related to other technologies – e.g. new materials with specific physical or chemical properties using RMs are an important basis for other technologies and industries. On the contrary, some fields in this sector, like food chemistry and biotechnology have a relatively low dependence on RMs.

Other technology sectors are also related to RMs at different degrees, although with generally lower shares. The field of Semiconductors has the highest number of RM-based patents. Its share is also the highest in all technology fields except those in Chemistry. This field includes "methods for the production of integrated circuits or photovoltaic elements" which is one of the core technologies in the hardware infrastructure for ICT. The second by importance is Electrical machinery, apparatus, energy which covers "the non-electronic part of electrical engineering, for instance, the generation, conversion and distribution of electric power, electric machines but also basic electric elements such as resistors, magnets, capacitors, lamps or cables" (Schmoch, 2008, p.7). Other electrical engineering technologies such as IT methods for management; Telecommunications; Computer technology, mainly about software technologies, depend much less on RMs. For Instruments, the only field with high RM dependence (10%) is Optics, based particularly on indium and tellurium; all other fields have a relatively low dependence, as shares are all below 5%.

For green energy technologies, it can be observed that several fields show very high dependence on the RMs. The highest rate appears in Fuel cells, where 40% patents use at least one RMs as input, particularly lithium and cobalt. In addition, patents in Nuclear energy, Solar energy fields also have a high degree of dependence (nearly 15%) on rare metals, consistently with the literature of green and renewable energy technologies (e.g., Valero et al., 2018; Leader et al., 2019).

We also observe that dependence on specific metals varies greatly across technology sectors and fields, reflecting the matching between unique metal properties and specialised technological demands. For example, gallium and germanium are mostly used in Semiconductors, molybdenum is used intensively only in the Chemical sector, and zirconium has wide application particularly in Nuclear energy technologies. Other metals have multiple technology applications. For example, lithium is not only used as an input for batteries in Electrical machinery, apparatus, and energy but is also intensively used in material and pharmaceutical technologies.

Figure 4-8. Distribution of RM-based patents by WIPO technology field, 1976-2015

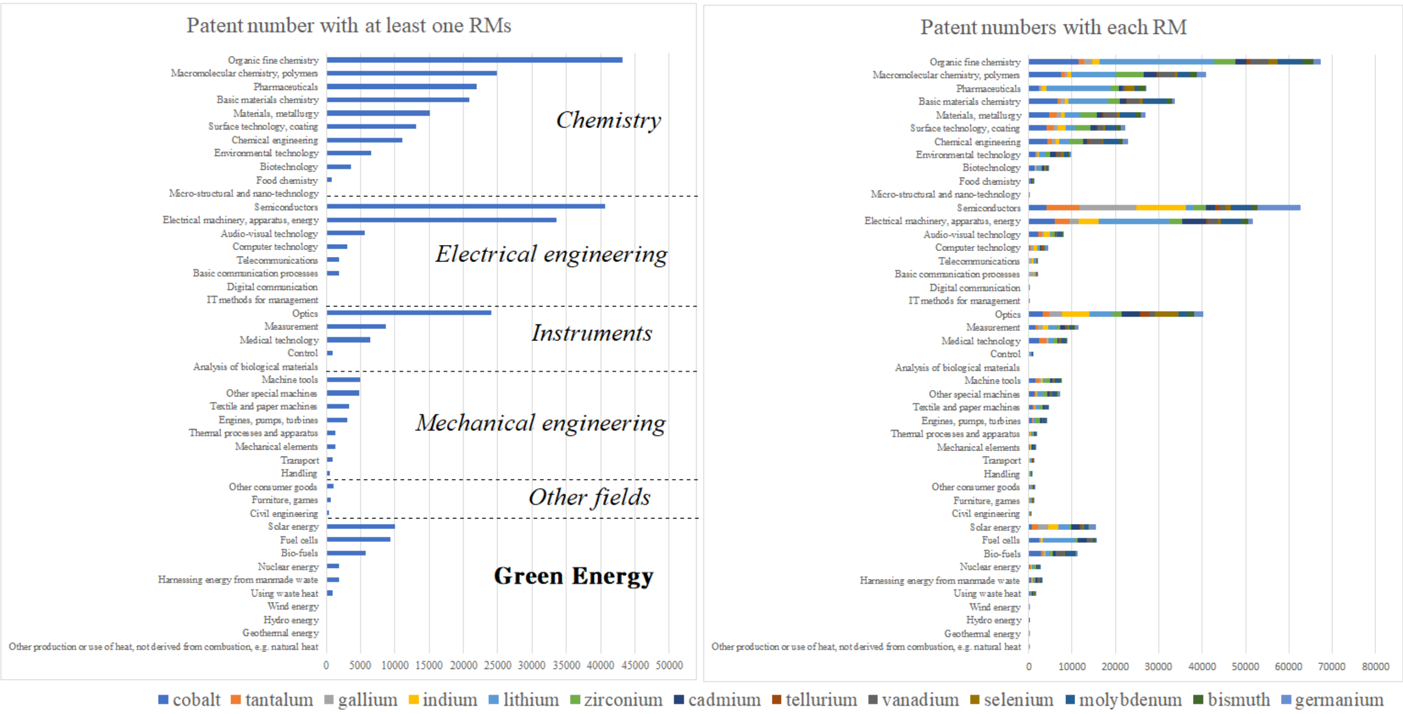
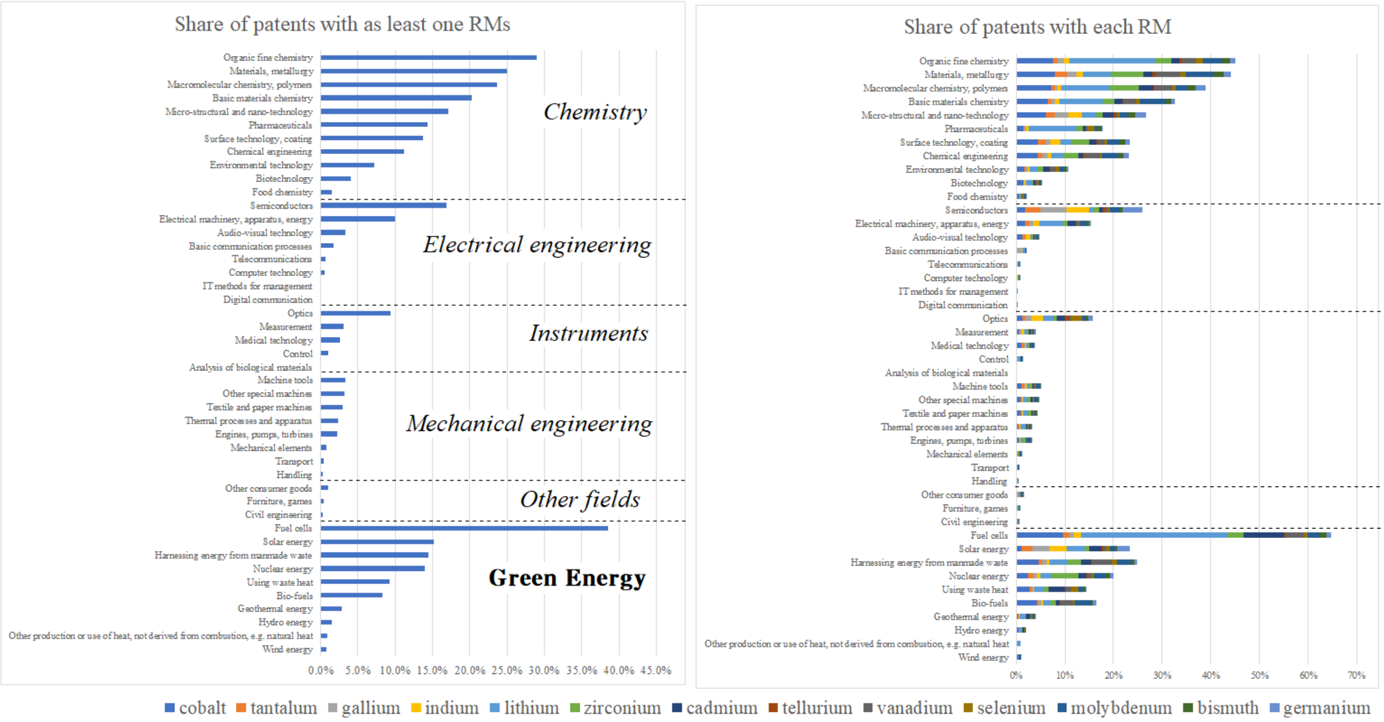


Figure 4-9. Share of RM-based patents by technology field, 1976-2015



To sum up, the above analysis shows that many types of cutting-edge technologies show a strong dependence on rare earth metals. First, the number of RM-based patents has increased over time, and more and more patents employ RM as critical inputs. At the same time, RM-based innovation shows significant structural changes. With the decline in the share of RM patents of Chemistry, the technology sector with the most RM-based patens has gradually shifted to Electronic engineering, which is consistent with the overall trend of the world's patent structure change under the ICT revolution. In addition, the technological importance of the 13 metals is also different. Among all technologies, the number of patents based on lithium and cobalt has remained the highest, though indium, gallium, and germanium have become increasingly important. Looking at different technology scales, we found that the dependence on metals is significantly higher at the level of specific technological fields. Rare metals have diversified applications in a number of GPTs. For example, in the fields of Materials science, Macromolecular chemistry, and Nanotechnology nearly 20% of patents depend on RMs. For Pharmaceuticals, Semiconductors, Electronic machinery as well as Optics, this rate exceeds 10%. In addition, the proportion of green energy technologies using RMs is significantly higher than other technologies. At the same time, each technical field depends on different types of metals, reflecting the matching of specialized technical requirements and specific properties of RMs.

4.5 The impact of RM availability on technology dynamics

In this section we use econometrics models to further explore whether changes in the metal supply, in terms of production, influence the innovative output of RM-based technologies, thus testing our main research hypothesis.

4.5.1 Sample

As shown above, the dependence on certain RMs can be better understood at finer technology scales and specialised technology areas. Therefore, the econometric model uses the finest subgroup classification to assess the impact of RM supply. The model sample is set in the format of technology-metal pairs, allowing us to explain the technology dynamics by the joint effects from both dimensions. We focus on RM-based technologies, which are defined as the subgroup $Technology_i$ whose share of patents using a certain REM_j is higher than 10% during the research period. $Tech_i - REM_j$ pairs exceeding this threshold enter the sample, for each $Tech_i$, there may be one or several pairs, depending on how many RMs it uses intensively. In order to ensure that technology subgroups in our sample are comparable, we exclude those extremely small subgroups whose total number of patents is less than 100 during the four decades. The final sample includes 2,187 Tech-RM pairs in which 1,259 technology subgroups applied 453,014 patents (accounting for 8.68% of all USPTO patents) during 1976-2015 (see, for detail, Tables A 4-2, A 4-3 and A4-4 in the Appendix).

4.5.2 Model specification

We use this sample to test the relationship between RM production and technology dynamics. The model is set by referring to the induced innovation hypothesis studies discussed in Section 2 (Popp, 2002; Böhringer et al., 2017). We regress the share of each RM-based technology over the total USPTO patent number in each year on the corresponding RM production as well as other control variables. The independent variable is lagged by one year to control for endogeneity.

$$\frac{Patent\ Number_{i,j,t}}{Total\ Patent\ Number_t} = \beta_1\ RM\ production_{j,t-1} + \sum_{k=2}^{5} \beta_k\, Z_{i,j,t-1} + RM\ FE + Year\ FE + Tech\ FE + \varepsilon_{i,j,t}$$

where i indexes 1,259 technology subgroups, j the 13 rare metals and t=1976,...2015 the observation year. $Patent\ Number_{i,j,t}$ represents the number of patents for technology subgroup i in year t; the share over the $Total\ Patent\ Number_t$ measures the relative output of this subgroup by controlling the time trend. In the regression, this dependent variable is normalized by z-score. Using this share as the dependent variable, we consider the impact of macroeconomic and exogenous changes, such as changes in patent laws or government policy, leading to changes in both the total patent application and the RM-based patents. The model uses the application date rather than the grant date of patents as measure of innovation in order to document the date of innovation as early as possible (Johnson & Popp, 2003; Daniels & Johnson, 2019). $RM\ production_{j,t-1}$ measures the production of RM j in year t, in terms of ratios relative to the initial level in 1975.

In addition to the influence of RM production, we control for several other factors that are likely to affect the innovation output of RM-based technologies, denoted by $Z_{i,j,t-1}$. First, we control for $Knowledge\ stock_{i,t-1}$ which is the knowledge accumulated until the previous year in technology subgroup i: this variable represents the path-dependency feature of technology development, and it is calculated as follows:

$$Knowledge\ stock_{i,t} = \sum_{s=0}^{p} e^{-\gamma_1 s} \cdot (1 - e^{-\gamma_2 (s+1)}) \cdot PA_{i,t-s}$$

Referring to (Popp, 2001), this formula measures the pre-existing state of knowledge at each time t for technology subgroup i. Since innovation decays in value with time, $\gamma_1$is the depreciation rate of past technologies and γ_2 is the diffusion rate of existing patents with the assumption that it takes time for technology information to diffuse among innovators. Following (Kim et al., 2017), we use the mean values as estimated by Popp (2001) with γ1 = 0.44 and γ2 = 2.97.

Second, technological change is not only influenced by the technologies in the same area but also by spillovers from related technological areas (Grupp, 1996). It has been found that relatedness helps to achieve knowledge recombination and leads to more innovation output (e.g. Boschma & Frenken, 2012). Assuming that technologies in the same group have larger relatedness with each other, we measure this impact by the variable $Technology\ in\ same\ \ Group_{i,t-1}$ which denote the number of patents in the same technology group but not in subgroup i. Third, the development of RM-based technologies may also be influenced by other technology subgroups which depend on the same RMs. To control this cross-technology effect we also include the variable $RM\ Demand\_other\ subgroups\ _{i,j,t-1}$ which measures the number of patents using the same RM j in other technology subgroups except i. A higher $RM\ Demand\_other\ subgroups\ _{i,j,t-1}$ implies that technology subgroup i may face more competition for the same metal. We also control for the degree of dependence of technologies on the corresponding RMs by the variable $RM\ dependence\ intensity_{i,j,t-1}$. The correlation matrix for the independent variables is reported in Table A 4-5 in the Appendix.

We include several fixed effects in the model to control for constant unobservable factors.

The propensity to patent innovation varies across technology areas. In some, such as chemistry and electronic engineering, is higher than in others, where secrecy is more important to protect the innovation. Therefore, technology subgroup fixed effects are included. Second, year fixed effects are added to control for macrolevel economic and technological trends (Grilliches, 1989). Moreover, RM fixed effect are included to eliminate the RM-specific characteristics.

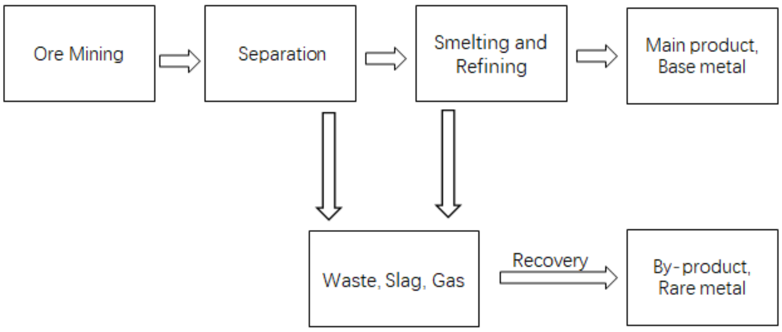
4.5.3 Endogeneity and identification strategy

It is important to note that the model above could be impacted by potential endogeneity problems, which may bias the estimated results. First, reverse causality is the major concern in this study, because technology dynamics reversely influence the production of rare metals. When a key technological breakthrough using a rare metal occurs, the expected and actual demand for the metal will increase, leading to an increase in prices, thereby stimulating metal producers to increase production capacity, resulting in the effect in the above model being overestimated.

At the same time, omitted variables bias potentially exists. Some factors may influence RM production and technology dynamics at the same time. For example, some basic discoveries in natural or engineering science may enhance the understanding of the properties of certain RMs. This may simultaneously improve the metal production efficiency and inspire the innovators about new ways of RM application. Moreover, government policies pay special attention to the shortage of some certain RMs and try to stabilize their supply (European Commission, 2012); at the same time, policies may support certain industries or technologies which are impacted by the potential RM shortages.

To solve these endogeneity concerns, in this paper we adopt an instrumental variable estimation model and use the metal companionability to identify exogenous shocks to the rare metal production. Unlike major metals, RMs are typically found in relatively low concentrations in the mineral, and they are only, or largely, constituents in deposits of more abundant base metals (copper, iron, aluminium, etc.). As a result, RMs seldom form viable deposits of their own, and instead are mined and produced as companion metal or by-products and recovered from the different forms of waste, scraps, slags or gas of the base metals in the processing, smelting, refining stages (e.g. Eggert, 2010; Nassar et al., 2015; Harper et al., 2015), as shown in Figure 4-10. For example, both cadmium and indium are the "by-product of zinc-concentrate processing" and "the most lithium [is] recovered from subsurface liquid brines"(p.51, Eggert, 2010), in which the main product is the potassium compounds. Therefore, RM supply is strongly influenced by the demand for the base metals. A major demand reduction for a base metal causes significant supply constraints for its companion rare metals (Graedel, 2015; Sprecher et al., 2017).

Figure 4-10. Co-production process of base metals (main product) and RMs (by-product)



Information Sources: (Nassar et al., 2015; Harper et al., 2015)

We argue that the influence of the base metal production on rare metal production is exogenous for two reasons. First, this influence is unidirectional, the production of RM does not reversely influence base metal production because base metals account for the major revenue of mining and their production is mainly driven by macroeconomic factors such as, for instance, urbanization speed in China and India. On the other hand, even if the prices for by-product metal increases, small market scale means the commercial incentive is limited, therefore, mining and producing decisions are mainly determined by the exogenous shocks on the base metal and RMs are difficult to have supply expansion in short time (Moss et al., 2013; Sprecher et al., 2017). A production increase for base metals results in supply increases and price drops for the by-product and co-product metals (e.g. Campbell, 1985; Hagelüken, 2011; Moss et al., 2013; Afflerbach et al., 2014). Second, the production of base metals does not impact the dependent variable, i.e. patent numbers in RM-based technologies, because base metals are more widely used as basic materials and in much larger amounts in a variety of industrial sectors, such as construction materials and metal containers, and have very different properties and functions than RMs. This assumption is further verified in the robustness test.

The type of base metal and the degree of metal companionability vary greatly among RMs, are shown in the Table 4-2. For almost all RMs in our sample, more than 50% of the production is from a single base metal. Some RMs are entirely co-produced with one base metal, for example cadmium from zinc, zirconium from titanium, and gallium from aluminium. Others have more than one base metal as source, like cobalt and tantalum.

Table 4-2. Metal companionability between base and rare metals[11]

Rare metals	Base metals and companionability degree[12]
Bismuth (Bi)	Lead (Pd) (54%)
Cadmium (Cd)	Zinc (Zn) (100%)
Cobalt（Co）	Nickel (Ni) (50%); Copper (Cu) (35%)
Gallium (Ga)	Aluminium (Al) (100%)
Germanium (Ge)	Zinc (Zn) (60%)
Indium (In)	Zinc (Zn) (80%)
Lithium (Li)	Potassium (K) (52%)
Molybdenum (Mo)	Copper (Cu) (46%)
Selenium (Se)	Copper (Cu) (90%)
Tantalum (Ta)	Tin (Sn) (15%); Niobium (Nb) (13%)
Tellurium (Te)	Copper (Cu) (90%)
Vanadium (V)	Iron (Fe) (62%)
Zirconium (Zr)	Titanium (Ti) (100%)

Therefore, we use the production of the base metal (if one RM have multiple base metals, we use the primary one with the highest companionability degree) as an instrumental variable to predict the exogenous shocks to the rare metal production, the production amount of base metals is obtained from the USGS data base and standardised relative to the production amount in 1975.

4.5.4 Regression results

Tables 4-3 and 4-4 show the OLS regression results and the second stage results of the IV estimation[13], respectively. We explore the robustness of the estimates by changing the setting of both control variables and fixed effects in 8 different models. In all models, the variable of interest, $REM\ production_{j,t-1}$ is always positive at the 1% significance level, indicating that the supply of a RM indeed improves the innovation output of the technology subgroups which are based on it. Model 8 includes all control variables as well as fixed effects. The results show that one unit increase in the production of a certain RM on average leads to a rise of the share of patents by 0.204 standard deviation. In comparison, with the same model setting, this coefficient in the OLS estimation is 0.0263 (model 4), thus higher than the IV

[11] Information Sources: Nassar et al., 2015; Harper et al., 2015.

[12] Companionability degree measures what percentage of a RM is produced from co-production process with a base metal.

[13] For the full sample model, first stage estimation results are shown in Table A 4-6 in the Appendix. The IV $Primary\ Base\ metal\ production_{j,t}$ is significantly and positively correlated with the variable of interest $RM\ production_{j,t-1}$, indicating that one unit increase in the production of primary base metal corresponds to a 3.83 unit increase in the by-product RM production, controlling for other variables and fixed effects. The results of Cragg-Donald Wald F statistic show that the IV passes the weak identification test. We now obtain the levels of RM production exogenously predicted by the instrument and examine their causal effects on innovation dynamics.

estimator. In addition, comparing other results between OLS and IV regressions, the coefficients of $RM\ production_{j,t-1}$ are all smaller in the IV models. This confirms that endogeneity issues overestimate the effect of RM production as expected. These findings support our research hypothesis: increasing supply of RMs does provide incentives to innovation in the relevant technologies and encourage new patents. On the contrary, a decreasing supply or supply disruption constrains new invention growth in such technologies.

Looking at the control variables, the effect of $Knowledge\ stock_{i,t-1}$ on patents is significant and positive in Models 3, 4, 7 and 8, indicating that past knowledge accumulation leads to more innovation output. In line with other studies (e.g. Kim et al., 2017), innovation in RM-based areas is also path-dependent and build on the existing knowledge stock of its own technology subgroup. Similarly, the coefficient of $Technology\ in\ same\ \ Group\ _{i,t-1}$ is also positive and significant in all models, indicating the positive correlation between RM-based technologies with innovation activities in other technology subgroups of the same group. This may be due to the positive spillover effect from related technologies or to technologies in the same group being influenced simultaneously by similar market demands and policies. Moreover, $RM\ Demand\_other\ subgroups\ \ _{i,j,t-1}$ is insignificant in model 3 and 7 but significantly positive in model 4 and 8. This indicates that the increasing demand for a certain RM in other subgroups is positively correlated with the innovation output in the observed RM-based technology subgroup. The literature argues that there is competition for RMs in the production between different industrial sectors: for example, solar energy competes with electronics for gallium and indium materials (Leader et al., 2019). However, our result shows that this competition does not seem to occur in upstream R&D activities: this may be because unlike production, which is exclusive, research on the use of the same RM in different technological subgroups are complementary and mutually reinforcing.

Table 4-3. OLS regression results

	OLS estimation			
	(1)	(2)	(3)	(4)
$RM\ production_{j,t-1}$	0.0355***	0.0431***	0.0181***	0.0263***
	(0.00127)	(0.00127)	(0.00106)	(0.00134)
$Knowledge\ stock_{i,t-1}$			0.0101***	0.00441***
			(5.23e-05)	(7.10e-05)
$Technology\ in\ same\ \ Group_{i,t-1}$			6.34e-05***	0.000148***
			(4.95e-06)	(7.83e-06)
$RM\ Demand\_other\ subgroups\ \ _{i,j,t-1}$			2.10e-06	4.99e-05***

			(6.14e-06)	(1.29e-05)
$RM\ dependence\ intensity_{i,j,t-1}$			-0.0387*	0.00121
			(0.0231)	(0.0323)
Constant	-0.0841***	-0.102***	-0.395***	-0.295***
	(0.00453)	(0.00404)	(0.00788)	(0.0132)
Year Fixed effect	Yes	Yes	Yes	Yes
RM Fixed effect	No	Yes	No	Yes
Technology Fixed effect	No	Yes	No	Yes
R-squared	0.023	0.394	0.338	0.434
Technology subgroup number	1,259	1,259	1,259	1,259
Technology-RM pairs	2,187	2,187	2,187	2,187
Observations	84,645	84,645	84,645	84,645

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Table 4-4. 2nd stage IV estimation results

	IV estimation			
	(5)	(6)	(7)	(8)
$RM\ production_{j,t-1}$	0.0111***	0.0176***	0.0115***	0.0204***
	(0.000355)	(0.00437)	(0.00239)	(0.00283)
$Knowledge\ stock_{i,t-1}$			0.0102***	0.00444***
			(5.26e-05)	(7.16e-05)
$Technology\ in\ same\ \ Group_{i,t-1}$			6.83e-05***	0.000154***
			(5.19e-06)	(8.22e-06)
$RM\ Demand\_other\ subgroups\ _{i,j,t-1}$			4.33e-06	6.80e-05***
			(6.19e-06)	(1.50e-05)
$RM\ dependence\ intensity_{i,j,t-1}$			-0.0437*	0.00129
			(0.0231)	(0.0323)
Constant				
Year Fixed effect	Yes	Yes	Yes	Yes
RM Fixed effect	No	Yes	No	Yes
Technology Fixed effect	No	Yes	No	Yes
R-squared	-	-	-	-
Technology subgroup number	1,259	1,259	1,259	1,259
Technology-RM pairs	2,187	2,187	2,187	2,187
Observations	84,645	84,645	84,645	84,645

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

4.6 Robustness checks

There are further concerns for the estimation methods used above. We test the robustness of our results by checking the validity of the IV and by using different thresholds and grouping for RM-based technologies.

(1) Further validations of the instrumental variable.

First, the validity of the IV is based on the assumption that the base metal production is related to the rare metal production, but uncorrelated to innovation in RM-based technologies. However, there is the possibility that the base metals are also used in those technologies, which may invalidate the IV and bias the estimation results. To eliminate this potential problem, by using the same text mining method, we identify keywords of base metals in the patent summary text and exclude 28,642 patents which mentioned both rare and base metals. By doing so, we rule out the probability that base and rare metals are not only related on the supply (production) side but also on the technological demand side. The regression result is shown in column 1 of Table 4-5. After excluding those patents, the estimated effect is reduced to 0.0153, which is slightly smaller than the result in the main model because of the exclusion of some patents, but it remains significantly positive.

Second, the IV in the main model is the production of the primary base metal of RMs without considering differences in the companionability across RMs and corresponding base metals. RM with a high companionability may be more impacted by changes in the base metal production. To consider this heterogeneity, we use the $Base\ metal\ production_{j,t-1} \times Companionability\ degree_j$ as the new IV and re-estimate the model. The results are shown in column 2 of Table 4-5. We observe that the coefficient and significance of the variable of interest did not change much. The above two robustness tests further validate our IV estimation methods.

Table 4-5. Robustness test on IV

	(1) Excluding patents with base metal keywords	(2) Changing IV
$RM\ production_{j,t-1}$	0.0153***	0.0188***
	(0.00284)	(0.00495)
$Knowledge\ stock_{i,t-1}$	0.00482***	0.00444***
	(7.18e-05)	(7.32e-05)
$Technology\ in\ same\ Group_{i,t-1}$	0.000159***	0.000156***
	(8.25e-06)	(9.17e-06)
$RM\ Demand\_other\ subgroups_{i,j,t-1}$	9.47e-05***	7.29e-05***
	(1.50e-05)	(1.94e-05)
$RM\ dependence\ intensity_{i,j,t-1}$	-0.0776**	0.00132
	(0.0324)	(0.0323)
RM Fixed effect	Yes	Yes
Year Fixed effect	Yes	Yes
Technology Fixed effect	Yes	Yes
Technology subgroups number	1,259	1,259

Technology-RM pairs	2,187	2,187
Observations	84,645	84,645

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

(2) Changing regression sample.

The results may also vary with the technology grouping and definition of RM-based technologies. We further check the robustness by changing technology grouping and threshold of RM-based technologies.

First, in the models above, we define as RM-based technologies those subgroups with at least 10% of RM-based patents. We change this threshold to 15%, 20% and 25%. The results are shown in Table 4-6. $RM\ production_{j,t-1}$ is positively significant using all three alternative thresholds and the coefficients are larger than in the 10% threshold sample. This result confirms that the findings above are robust to different definition of RM-based technology.

Second, the regression above is based on the finest technology scale, subgroups, 5-digit IPC classification. We further test whether the impact of RM production is robust under different technology scales. Using the same data structure, a new Tech-RM pair sample is built at the technology group level, 4-digit IPC classification. Because of the aggregation level change, the number of observations significantly decreases to 264 tech-metal pairs (always share of patents using a certain RM in each group above 10%) with 172 technology groups. Column 2 shows its IV estimation result. The results are generally similar to that of the main subgroup model with larger coefficient of RM production. The robustness checks indicate the findings above still hold with different thresholds and definition of RM-based technologies.

Table 4-6. Robustness test by changing regression samples (IV estimation)

	(1) Changing thresholds for RM-based technologies				(2) Changing technology scale to group level
	10%	15%	20%	25%	
$RM\ production_{j,t-1}$	0.0204***	0.0425***	0.0415***	0.0364***	0.0392***
	(0.00283)	(0.00422)	(0.00537)	(0.00880)	(0.00748)
$Knowledge\ stock_{i,t-1}$	0.00444***	0.00368***	-0.000314**	0.000407**	0.00682***
	(7.16e-05)	(9.87e-05)	(0.000150)	(0.000200)	(0.000367)
$Technology\ in\ same\ Group_{i,t-1}$	0.000154***	3.84e-05***	-9.16e-07	-2.63e-05	2.60e-05***
	(8.22e-06)	(1.30e-05)	(2.14e-05)	(3.32e-05)	(2.09e-06)
$RM\ Demand\_other\ subgroups\ _{i,j,t-1}$	6.80e-05***	8.13e-05***	0.000129***	0.000191***	-1.91e-05
	(1.50e-05)	(1.89e-05)	(2.27e-05)	(3.22e-05)	(2.52e-05)
$RM\ dependence\ intensity_{i,j,t-1}$	0.00129	-2.70e-05	-0.000426	2.29e-05	0.00803
	(0.0323)	(0.0425)	(0.0588)	(0.0929)	(0.0869)

RM Fixed effect	Yes	Yes	Yes	Yes	Yes
Year Fixed effect	Yes	Yes	Yes	Yes	Yes
Technology Fixed effect	Yes	Yes	Yes	Yes	Yes
Technology subgroup number	1,259	794	496	307	164
Technology-RM pairs	2,187	1,194	674	387	254
Observations	84,645	45,218	25,546	14,825	9,249

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

4.7 Conclusion

Frontier technologies are experiencing tremendous shifts, changing the types, modes, and efficiency in the utilisation of natural resource. On the one hand, economists believe technological innovation makes it possible to replace rare and expensive resources with relatively abundant and cheap resources, which helps overcoming natural resource constraints and achieving sustainable development (Rosenberg, 1976). For example, for energy resources, new technologies enable us to shift from wood to coal, to petroleum to hydropower, and then to solar, nuclear, and other unconventional energy sources. On the other hand, technological progress also makes the materials in use become more diversified and advanced with special properties, in order to achieve the specific functionalities. As a result, some important non-renewable resources have become necessities in technological development and economic growth (Groth & Schou, 2002). In this way, natural resources, in return, influence the trajectory of frontier technology dynamics.

Rare metals are regarded as "technology materials" with great significance to high-tech manufactures and cutting-edge technological innovation, especially under the paradigm shifts of clean and green energy as well as the ICT and AI revolutions. The functionality provided by RMs cannot be easily replaced with substitutes (Graedel et al., 2015; Leader, 2019). Using 13 widely concerned RMs, we have explored the impact of critical natural resource availability on the endogenous innovation dynamics and contributed to further understanding of their co-evolution relationship.

We have here provided the first systematic exploration of the dependency of frontier technologies on RMs. We find that modern technologies are deeply dependent on RM materials during the four decades 1976-2015, and 5.98% of patents granted by the USPTO use RMs as inputs. We also find that this dependence varies with technology areas, scale of analysis as well as types of rare earth metals. Moreover, technology application of RMs has experienced scale and structural changes over time. The number of RM-based patents has more than doubled over time – more and more patents employ RM as critical inputs. At the same time, Electronic engineering surpassed Chemistry and became the technology sector with most RM-based patens. Among all metals, whilst lithium and cobalt have shown the highest number over the period, indium and gallium have experienced the biggest increase in technology applications, and at the same time their production growth has been the most significant. Our econometric exercise, which accounts for endogeneity, support our hypothesis that RMs supply has a significant causal impact on the innovation output of RM-based technologies.

Our findings have some policy relevance and implications for future research. The case of RMs may further encourage scholars and policymakers to devote attention to the entire system and value chain within which innovation happens. Given the high dependency of innovation on those critical resources, it can be predicted that a continuously increasing supply of RM is needed to ensure the sustainability of innovation. However, RM supplies are recognized to be subject to great societal and environmental risk and uncertainty (US National Research Council, 2008; Humphries, 2010; Hayes & McCullough, 2018). Future policies should, on the one hand, put more effort on ensuring the supply stability of rare metals, especially those with significantly high technological dependence. On the other hand, we can predict the potential shocks on innovation in advance under different RM supply scenarios. Moreover, many rare metals, such as cobalt and tantalum are regarded as "conflict minerals". Their exploitation and trade contribute to many human right violations in less developed countries, such as Democracy Republic of Congo (Hofmann et al., 2018). Exploring the relationship between their supply with technological dynamics enable us to better understand the "dark side of innovation" (Diemer et al., 2021).

Future research should focus on several aspects: First, because of the data availability, this paper only focuses on 13 important RMs. Some other RMs are also of significant technological importance, especially the widely concerned Rare Earth Elements (REE) (Hayes & McCullough, 2018). Different critical materials have distinct technological properties and applications and may experience different supply dynamics. They should be included in the future studies. Second, in this paper, RM availability and technological dynamics are all measured at the global scale. However, their actual availability varies with geography, thus being influenced by multifaceted factors such as geological mineral distribution, local socio-economic and political conditions, national polices, trade agreements as well as global geopolitics events. All these makes their supply far more complicated. For example, in 2010 under the embargo of China, Japan had little access to new REE materials (Mancheri, 2015); because of Dodd Frank Act, the companies listed in the US stock market had additional limits in obtaining some critical RMs such as cobalt and tantalum from the Republic of Congo (Dalla & Perego, 2018). Future research should focus on finer geographic scales (Diemer et al., 2021) and explore whether and how difference in rare metals' availability shape the development and growth trajectories of firms, regions and countries.

Appendix

Table A 4-1. Table of correspondence between WIPO classification and IPC subclass

Sector	Field	IPC technology classes
Chemistry	Basic materials chemistry	A01N;A01P;C05B;C05C;C05D;C05F;C05G;C06B;C06C;C06D;C06F;C09B;C09C;C09D;C09F;C09G;C09H;C09J;C09K;C10B;C10C;C10F;C10G;C10H;C10J;C10K;C10L;C10M;C10N;C11B;C11C;C11D;C99Z
Chemistry	Biotechnology	C07G;C07K;C12M;C12N;C12P;C12Q;C12R;C12S
Chemistry	Chemical engineering	B01B;B01D;B01F;B01J;B01L;B02C;B03B;B03C;B03D;B04B;B04C;B05B;B06B;B07B;B07C;B08B;C14C;D06B;D06C;D06L;F25J;F26B;H05H;
Chemistry	Environmental technology	A62C;B01D;B09B;B09C;B65F;C02F;E01F;F01N;F23G;F23J;G01T;
Chemistry	Food chemistry	A01H;A21D;A23B;A23C;A23D;A23F;A23G;A23J;A23K;A23L;C12C;C12F;C12G;C12H;C12J;C13B;C13D;C13F;C13J;C13K
Chemistry	Macromolecular chemistry, polymers	C08B;C08C;C08F;C08G;C08H;C08K;C08L;
Chemistry	Materials, metallurgy	B22C;B22D;B22F;C01B;C01C;C01D;C01F;C01G;C03C;C04B;C21B;C21C;C21D;C22B;C22C;C22F
Chemistry	Micro-structural and nano-technology	B81B;B81C;B82B;B82Y
Chemistry	Organic fine chemistry	A61K;A61Q;C07B;C07C;C07D;C07F;C07H;C07J;C40B;
Chemistry	Pharmaceuticals	A61K;A61P
Chemistry	Surface technology, coating	B05C;B05D;B32B;C23C;C23D;C23F;C23G;C25B;C25C;C25D;C25F;C30B
Electrical engineering	Audio-visual technology	G09F;G09G;G11B;H04N;H04R;H04S;H05K;
Electrical engineering	Basic communication processes	H03B;H03C;H03D;H03F;H03G;H03H;H03J;H03K;H03L;H03M
Electrical engineering	Computer technology	G06C;G06D;G06E;G06F;G06G;G06J;G06K;G06M;G06N;G06T;G10L;G11C;G16B;G16C;G16Z;
Electrical engineering	Digital communication	H04L;H04N;H04W;
Electrical engineering	Electrical machinery, apparatus, energy	F21H;F21K;F21L;F21S;F21V;F21W;F21Y;H01B;H01C;H01F;H01G;H01H;H01J;H01K;H01M;H01R;H01T;H02B;H02G;H02H;H02J;H02K;H02M;H02N;H02P;H02S;H05B;H05C;H05F;H99Z
Electrical engineering	IT methods for management	G06Q;
Electrical engineering	Semiconductors	H01L;
Electrical engineering	Telecommunications	G08C;H01P;H01Q;H04B;H04H;H04J;H04K;H04M;H04N;H04Q
Instruments	Analysis of biological materials	G01N;
Instruments	Control	G05B;G05D;G05F;G07B;G07C;G07D;G07F;G07G;G08B;G08G;G09B;G09C;G09D;
Instruments	Measurement	G01B;G01C;G01D;G01F;G01G;G01H;G01J;G01K;G01L;G01M;G01N;G01P;G01Q;G01R;G01S;G01V;G01W;G04B;G04C;G04D;G04F;G04G;G04R;G12B;G99Z;
Instruments	Medical technology	A61B;A61C;A61D;A61F;A61G;A61H;A61J;A61L;A61M;A61N;G16H;H05G
Instruments	Optics	G02B;G02C;G02F;G03B;G03C;G03D;G03F;G03G;G03H;H01S
Mechanical engineering	Engines, pumps, turbines	F01B;F01C;F01D;F01K;F01L;F01M;F01P;F02B;F02C;F02D;F02F;F02G;F02K;F02M;F02N;F02P;F03B;F03C;F03D;F03G;F03H;F04B;F04C;F04D;F04F;F23R;F99Z;G21B;G21C;G21D;G21F;G21G;G21H;G21J;G21K;
Mechanical engineering	Handling	B25J;B65B;B65C;B65D;B65G;B65H;B66B;B66C;B66D;B66F;B67B;B67C;B67D;
Mechanical engineering	Machine tools	A62D;B21B;B21C;B21D;B21F;B21G;B21H;B21J;B21K;B21L;B23B;B23C;B23D;B23F;B23G;B23H;B23K;B23P;B23Q;B24B;B24C;B24D;B25B;B25C;B25D;B25F;B25G;B25H;B26B;B26D;B26F;B27B;B27C;B27D;B27F;B27G;B27H;B27J;B27K;B27L;B27M;B27N;B30B;
Mechanical engineering	Mechanical elements	F15B;F15C;F15D;F16B;F16C;F16D;F16F;F16G;F16H;F16J;F16K;F16L;F16M;F16N;F16P;F16S;F16T;F17B;F17C;F17D;G05G;
Mechanical engineering	Other special machines	A01B;A01C;A01D;A01F;A01G;A01J;A01K;A01L;A01M;A21B;A21C;A22B;A22C;A23N;A23P;B02B;B28B;B28C;B28D;B29B;B29C;B29D;B29K;B29L;B33Y;B99Z;C03B;C08J;C12L;C13B;C13C;C13G;C13H;F41A;F41B;F41C;F41F;F41G;F41H;F41J;F42B;F42C;F42D;
Mechanical engineering	Textile and paper machines	A41H;A43D;A46D;B31B;B31C;B31D;B31F;B41B;B41C;B41D;B41F;B41G;B41J;B41K;B41L;B41M;B41N;C14B;D01B;D01C;D01D;D01F;D01G;D01H;D02G;D02H;D02J;D03C;D03D;D03J;D04B;D04C;D04G;D04H;D05B;D05C;D06G;D06H;D06J;D06M;D06P;D06Q;D21B;D21C;D21D;D21F;D21G;D21H;D21J;D99Z
Mechanical engineering	Thermal processes and apparatus	F22B;F22D;F22G;F23B;F23C;F23D;F23H;F23K;F23L;F23M;F23N;F23Q;F24B;F24C;F24D;F24F;F24H;F24J;F24S;F24T;F24V;F25B;F25C;F27B;F27D;F28B;F28C;F28D;F28F;F28G
Mechanical engineering	Transport	B60B;B60C;B60D;B60F;B60G;B60H;B60J;B60K;B60L;B60M;B60N;B60P;B60Q;B60R;B60S;B60T;B60V;B60W;B61B;B61C;B61D;B61F;B61G;B61H;B61J;B61K;B61L;B62B;B62C;B62D;B62H;B62J;B62K;B62L;B62M;B63B;B63C;B63G;B63H;B63J;B64B;B64C;B64D;B64F;B64G;
Other fields	Civil engineering	E01B;E01C;E01D;E01F;E01H;E02B;E02C;E02D;E02F;E03B;E03C;E03D;E03F;E04B;E04C;E04D;E04F;E04G;E04H;E05B;E05C;E05D;E05F;E05G;E06B;E06C;E21B;E21C;E21D;E21F;E99Z;
Other fields	Furniture, games	A47B;A47C;A47D;A47F;A47G;A47H;A47J;A47K;A47L;A63B;A63C;A63D;A63F;A63G;A63H;A63J;A63K;
Other fields	Other consumer goods	A24B;A24C;A24D;A24F;A41B;A41C;A41D;A41F;A41G;A42B;A42C;A43B;A43C;A44B;A44C;A45B;A45C;A45D;A45F;A46B;A62B;A99Z;B42B;B42C;B42D;B42F;B43K;B43L;B43M;B44B;B44C;B44D;B44F;B68B;B68C;B68F;B68G;D04D;D06F;D06N;D07B;F25D;G10B;G10C;G10D;G10F;G10G;G10H;G10K;

Figure A 4-1. Total patent number by technology field

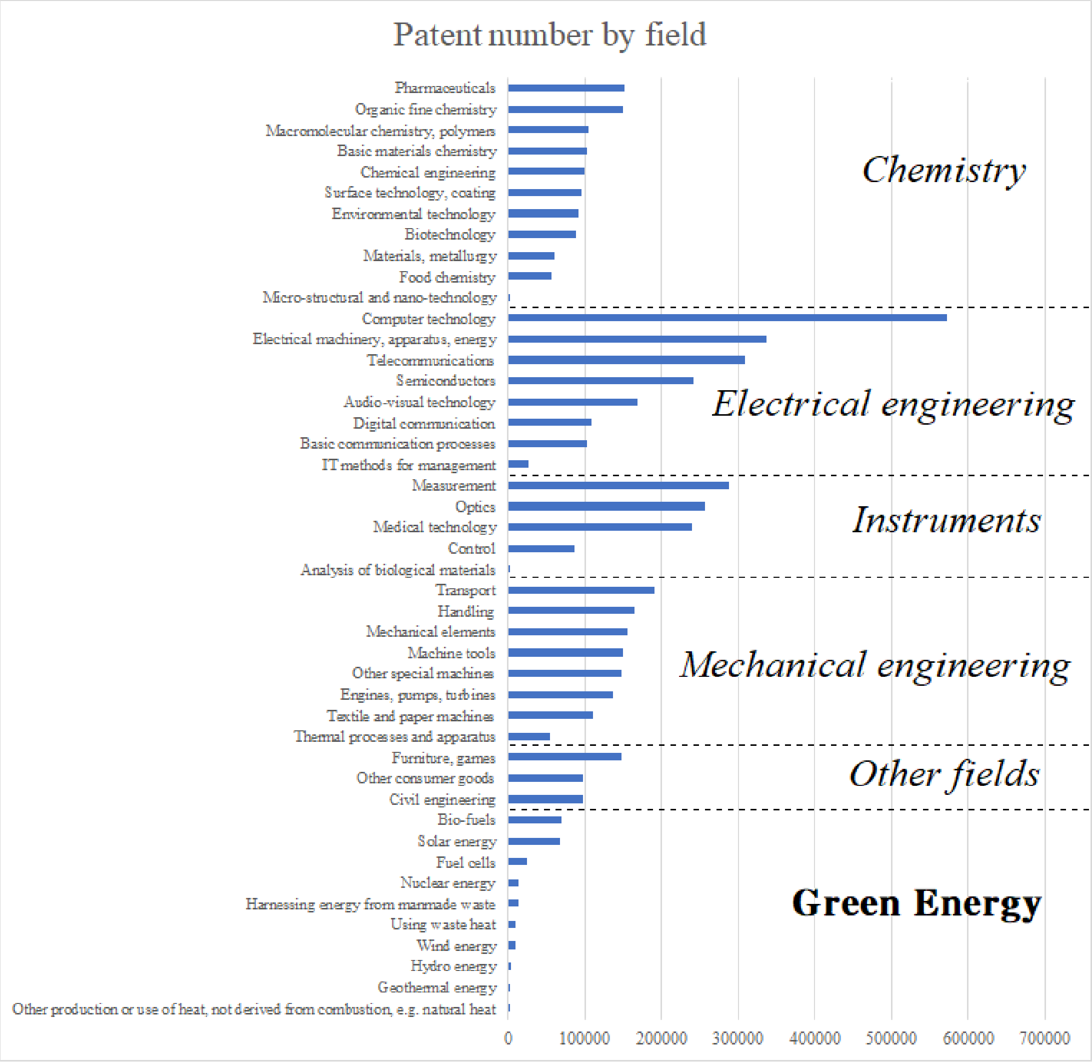


Table A 4-2. Distribution of Tech-RM pairs by technology sector and field

Sector	Field	Number of pairs
Chemistry	Organic fine chemistry	486
Chemistry	Macromolecular chemistry, polymers	232
Chemistry	Basic materials chemistry	209
Chemistry	Materials, metallurgy	171
Chemistry	Pharmaceuticals	128
Chemistry	Chemical engineering	128
Chemistry	Surface technology, coating	25
Chemistry	Environmental technology	25
Chemistry	Biotechnology	5
Chemistry	Food chemistry	1
Electrical engineering	Electrical machinery, apparatus, energy	291
Electrical engineering	Semiconductors	170
Electrical engineering	Audio-visual technology	23
Electrical engineering	Basic communication processes	6
Electrical engineering	Computer technology	2
Instruments	Optics	216
Instruments	Measurement	8
Instruments	Medical technology	7
Instruments	Analysis of biological materials	1
Mechanical engineering	Engines, pumps, turbines	16
Mechanical engineering	Other special machines	13
Mechanical engineering	Machine tools	10
Mechanical engineering	Mechanical elements	5
Mechanical engineering	Thermal processes and apparatus	3
Mechanical engineering	Textile and paper machines	2
Other fields	Furniture, games	3
Other fields	Other consumer goods	1

Table A 4-3. Distribution of Tech-RM pair by metal

Metal	Number of pairs
bismuth	42
cadmium	102
cobalt	390
gallium	103
germanium	67
indium	127
lithium	732
molybdenum	170
selenium	47
tantalum	40
tellurium	27
vanadium	136
zirconium	189

Table A 4-4. Top 20 RM-based technology subgroups

Technology Subgroup	Subgroup title	Technology field	Dependence on different RMs
C10G3508	Reforming naphtha	Basic materials chemistry	vanadium(45%);lithium(41%);bismuth(19%);zirconium(51%); germanium(47%);cadmium(22%);indium(20%);gallium(22%); cobalt(47%);molybdenum(40%);tantalum(15%)
C07C6705	Preparation of carboxylic acid esters	Organic fine chemistry	bismuth(26%);tellurium(22%);tantalum(10%);selenium(18%); zirconium(19%);lithium(32%);molybdenum(18%);cadmium(27%) ;cobalt(24%);vanadium(19%);
B01J2714	Catalysts comprising the elements or compounds of halogens, sulfur, selenium, tellurium, phosphorus or nitrogen; Catalysts comprising carbon compounds	Chemical engineering	lithium(18%);molybdenum(43%);vanadium(51%);cobalt(33%); zirconium(26%);bismuth(25%);germanium(13%)
G03C109	Photosensitive materials (photosensitive materials for multicolour processes for diffusion and transfer processes)	Optics	tellurium(49%);lithium(10%);cadmium(26%);thallium(18%); cobalt(20%);selenium(68%);bismuth(13%)
H01M432	Electrodes of nickel oxide or hydroxide electrodes	Electrical machinery, apparatus, energy	indium(13%);lithium(25%);cadmium(65%);zirconium(11%); cobalt(72%)
C07F1700	Metallocenes	Organic fine chemistry	vanadium(19%);lithium(47%);tantalum(11%);germanium(32%); zirconium(66%)
H01M452	Electrodes of nickel, cobalt or iron	Electrical machinery, apparatus, energy	vanadium(11%);cobalt(69%);lithium(68%);cadmium(26%)
C10G4508	Refining of hydrocarbon oils using hydrogen or hydrogen-generating compounds	Basic materials chemistry	molybdenum(75%);vanadium(28%);cobalt(67%)
H01M4131	Electrodes based on mixed oxides or hydroxides, or on mixtures of oxides or hydroxides	Electrical machinery, apparatus, energy	cadmium(12%);cobalt(47%);lithium(93%);vanadium(14%)
C07C25300	Preparation of carboxylic acid nitriles (of cyanogen or compounds)	Organic fine chemistry	molybdenum(25%);vanadium(22%);lithium(17%);cobalt(25%) ;indium(11%);bismuth(12%);tantalum(10%);tellurium(11%); cadmium(15%);zirconium(18%);
B01J2102	Catalysts comprising the elements, oxides or hydroxides of magnesium, boron, aluminium, carbon, silicon, titanium, zirconium or hafnium	Chemical engineering	cadmium(11%);zirconium(22%);bismuth(16%);vanadium(26%); lithium(19%);cobalt(33%);molybdenum(33%)
H01M4505	Electrodes of mixed oxides or hydroxides containing manganese for inserting or intercalating light metals	Electrical machinery, apparatus, energy	zirconium(10%);lithium(92%);cobalt(45%);cadmium(12%)
C10G4504	Refining of hydrocarbon oils using hydrogen or hydrogen-generating compounds	Basic materials chemistry	molybdenum(65%);vanadium(35%);cobalt(57%)
H01M4485	Electrodes of mixed oxides or hydroxides for inserting or intercalating light metals	Electrical machinery, apparatus, energy	cadmium(16%);vanadium(15%);lithium(91%);cobalt(32%); cobalt(63%);lithium(91%)
C07C5116	Preparation of carboxylic acids or their salts, halides, or anhydrides	Organic fine chemistry	molybdenum(28%);tellurium(11%);zirconium(21%); vanadium(25%);bismuth(17%);tantalum(10%);cobalt(39%)
H01M448	Electrodes of inorganic oxides or hydroxides	Electrical machinery, apparatus, energy	cadmium(17%);vanadium(20%);cobalt(29%);lithium(84%)
C01B3948	Compounds having molecular sieve and base-exchange properties	Materials, metallurgy	cobalt(13%);indium(20%);gallium(36%);lithium(15%);vanadium(21%); germanium(30%);molybdenum(14%)
C07D30760	Heterocyclic compounds containing five-membered rings having one oxygen atom as the only ring hetero atom	Organic fine chemistry	lithium(19%);bismuth(17%);zirconium(12%);molybdenum(25%); cobalt(19%);vanadium(53%)

Table A 4-5. Independent variable correlation matrix

	1	2	3	4	5
1. $RM\ production_{j,t-1}$	1				
2. $Knowledge\ stock_{i,t}$	0.2308	1			
3. $Technology\ in\ same\ subgroup_{i,t}$	0.3904	0.2025	1		
4. $RM\ Demand\_other\ subgroups\ _{i,j,t-1}$	0.507	0.1974	0.3113	1	
5. $RM\ dependence\ intensity_{i,j,t-1}$	-0.0197	-0.0279	0.0935	0.0763	1

Table A 4-6. First stage regression results

$REM\ production_{j,t-1}$	(5)	(6)	(7)	(8)
$Base\ metal\ production_{j,t-1}$	2.584***	2.352***	3.54***	3.83***
	(0.0232)	(0.0268)	(0.0250)	(0.0249)
$Knowledge\ stock_{i,t-1}$			0.00217***	0.00324***
			(0.000152)	(0.000163)
$Technology\ in\ same\ Group_{i,t-1}$			0.000645***	0.0007209***
			(0.0000144)	(1.79e-06)
$REM\ Demand\_other\ subgroups\ _{i,j,t-1}$			0.00166***	0.00484***
			(0.0000204)	(0.0000305)
$REM\ dependence\ intensity_{i,j,t-1}$			-0.838**	0.0196
			(0.050)	(0.0743)
RM Fixed effect	No	Yes	No	Yes
Year Fixed effect	Yes	Yes	Yes	Yes
Technology Fixed effect	No	Yes	No	Yes
Weak identification: Cragg-Donald Wald F statistic	1.2e+04	7782.684	2.0e+04	2.3e+04
Technology subgroups number	1,259	1,259	1,259	1,259
Technology-RM pairs	2,187	2,187	2,187	2,187
Observations	84,645	84,645	84,645	84,645

Note: *, **, *** indicate significance level at 10%, 5% and 1%, respectively

Conclusion

In this thesis, Chapter 1 reviews the existing empirical studies on CMNEs and use the "3 IA" framework to explain their special characteristics. CMNEs not only depend on FSA but also on state-created and network-based advantages in the early stage of internationalization. The latter two types of advantages enable Chinese firms lacking enough FSAs to invest abroad. The necessary condition for Chinese firm to conduct OFDI is not owning strong enough FSA to compete in the global market, but rather possess FSA relatively stronger than other Chinese competitor firms in order to access government support and network linkages. Chapter 2 finds that CMNEs originating from each province show significantly different destination preferences, which is correlated with heterogenous patterns of global connectivity among home regions from which CMNEs originate. A panel model of 31 provinces and 125 country pairs finds that export to foreign countries, international innovation collaboration and "friendship city" relationship effectively facilitate OFDI, and this pattern changes across specific investment motivations. Chapter 3 studies the effect of OFDI on the innovation performance of Chinese firms, with particular emphasis on the influence of IFDI. The OFDI innovation gain is significantly influenced by Chinese firms' prior within- and between-firm interactions with foreign subsidiaries in China and is also moderated by "country-of-origin effect" of IFDI from different foreign countries.

The major contribution of my three chapters on Chinese OFDI is that I try to further explain the important role played by home country advantages in explaining CMNEs, including their internationalization decisions (Chapter 1), investment strategies (Chapter 2) and post investment performance (Chapter 3). More importantly, in all these chapters, I emphasize that CMNEs have heterogenous access to home country advantages, which depends on their specific contexts within the home country. These contexts are multidimensional: organizational (FDI equity participation), industrial (intra- and inter-sector), institutional (firm ownership structure and governmental policies) and spatial (subnational regions of origin).

Chapter 4 uses the case of thirteen critical rare metals to study the relationship between technologically critical natural resource and technological progress. Taking into consideration endogeneity issues, our econometric model finds that increases in the supply of a certain RM significantly improve the innovation output of technologies based on it. In this way, we argue that natural resources supply indeed influences frontier innovation developments. This chapter try to further understand endogenous technological change and the importance of rare metals, which have long been ignored in economics and innovation studies.

As discussed in each chapter above, I acknowledge that this thesis has limitations. Especially, the empirical analysis is subject to the issue of data availability. First, for OFDI studies, there are limitations in the measurement of OFDI. In line with many existing analyses, my main data source of OFDI is the project level OFDI name list from the China's Ministry of Commerce. This dataset includes names of parent firms, investment destinations, investment motivations and origin provinces; however, it does not report the investment amount for each OFDI project. As a result, in Chapter 2, the province-country OFDI flow is measured as the total OFDI project numbers, and in Chapter 3, OFDI is used as a dummy variable between investors and non-investors. For the time coverage, this dataset continues until 2015, so it is difficult to consider some recent factors closely related with OFDI dynamics, such as the Belt and Road Initiative, which was launched in 2014, as well as the Covid-19 global pandemic. Second, in Chapter 2, besides the 3 dimensions of connectivity discussed in the thesis, other forms of connectivity would also be important for OFDI location choice, such as infrastructure linkages through global airlines, immigration, and inward FDI. However, there are no available and complete statistics on these variables at the level of Chinese province and foreign country pairs. For the rare metal study reported in Chapter 4, due to data constraints we were not able not cover all rare metals/minerals which are technologically important, and the current analysis is only at the global level without considering crucial geographical differences.

All the above limitations encourage extensions and further research in different directions. For the Chinese OFDI studies, with more complete data sources becoming progressively available, it will be possible to consider other important home country factors and cover more sectors, firms and longer time periods. Moreover, it is important to consider whether my findings are unique to CMNEs, or they can also be applied to MNEs from other emerging markets, or advanced economies with different economic and institutional conditions. For the research on rare metals, the actual availability varies with geography, thus being influenced by multifaceted factors such as geological mineral distribution, local socio-economic and political conditions, national polices, trade agreements as well as global geopolitics events. All these makes their supply chains far more complicated. Future research will be directed to explore whether and how difference in rare metals' availability shape the development and growth trajectories of firms, regions and countries. Moreover, it is important to study the connections between MNEs, especially CMNEs, and technological development based on RM. In fact, on the one hand the patents of frontier technologies relying on RMs are largely invented, hold, and commercialized by the large MNEs. They are the first to be impacted by potential RM supply shocks. Second, it is also MNEs who organize and coordinate the RM global value chain by linking different activities across different locations, from RM-related innovation to mineral extraction, metal production and manufacturing final goods. This becomes even more prominent when considering that my ultimate research units of analysis are CMNEs, which have been playing a dominant role in global RM value chains. Future research will integrate these two streams of studies to have a multi-scale analysis on RM resources and frontier technology dynamics in MNEs’ global organization, commodity, and innovation networks across different geographies.

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