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Multilateral Transfer Of Technological Knowledge In MNEs

A study based on IC design MNEs, 2001-2008

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Yen-Chen Ho

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DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Yen-Chen Ho

ABSTRACT

This thesis examines the theoretical background of multilateral knowledge transfer and synthesizes two lines of thinking on the exploitation of multinationality and the contributory role of subsidiaries. Scholars have devoted decades unpacking the mechanisms and dynamics of the creation, transfer and integration of subsidiary knowledge. As the phenomenon is decentralized and multilateral in nature, it often poses a dilemma for MNE managers due to the promising yet conflicting positions of knowledge-creating subsidiaries in local external networks and the corporate internal network. Existing studies generally acknowledge the challenges but tend to accentuate the creative potentials and downplay the costs of maintaining the delicate cross-level interdependencies involved. This thesis reviews the histories and public records of 28 world-leading IC design MNEs and delineates the cross-level interdependencies and multilateral knowledge transfer between the headquarters, knowledge-creating subsidiaries and external knowledge sources in host countries. Incorporating company annual reports, news archives and patenting records, this comprehensive investigation of geographical, industrial and temporal dimensions of inter- and intra-firm knowledge flows reveals the diverse knowledge sources and dynamics of the modern semiconductor industry. The findings also provide insights into the relationships between the heterarchical structure, mandated and entrepreneurial subsidiary knowledge creation and intra-firm cognitive gaps. Finally, the thesis theorizes how MNEs may use intra-firm R&D collaborations to establish incidental interdependencies between members of the MNE corporate network and implement internal entrepreneurship.

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1 INTRODUCTION

1.1 Knowledge-intensive MNEs in the 21st century

Because of the profound implications of semiconductor technologies for national economic, scientific and technological development, numerous studies in political economics, regional studies and technology management have documented the development of the semiconductor industry worldwide. Most of these studies aspire to the manufacturing excellence of integrated circuit (IC) products and often adopt a technological view of the industry, providing ideas about developing a domestic semiconductor industry. Examples include Browning, Beyer and Shetler (1995) on the United States (US), Fong (1998) on Japan, Chen and Sewell (1996) on South Korea and Taiwan, Mathews and Cho (2007) on East Asia, Athreye (2004) on the Cambridge area in the United Kingdom (UK), and ter Wal (2013) on Sophia-Antipolis in France. Also, from the industry perspective, Scott (1987) surveys the diffusion of semiconductor assembly facilities in South East Asia, and Langlois and Steinmueller (1999) review the history of the semiconductor industry.

While very few studies considered the design of IC product, only a smaller number of authors hinted the emerging role of design. For instance, Afuah (1999) reveals how Micron Technology, a US semiconductor company used radical design approach as its innovative, competitive strategies against East-Asian competitors. Chang and Tsai (2002) analyze the niche market strategy of Taiwanese IC design industry, which became only next to the US within two decades and gave rise to several world leading IC design companies in the first decade of the 21st century (see 5.2.19). Brown and Linden (2005) provide an account of IC design offshoring, and Fuller (2014) surveys the IC design industry in China and India. However, these studies barely applied the theoretical lens of international business (IB) studies and sparsely considered the theoretical and policy implications of a high-tech industry absent high-tech manufacturing.

The manufacturing of semiconductor devices is indisputably a remarkable achievement of modern science and technology, and an entire business literature based on the semiconductor industry greatly influences business and economics studies since the 1990s. The knowledge-intensive and capital-intensive nature of the semiconductor industry has long caught the interest of academic researchers in the fields of organization science, strategy and innovation. It is, therefore, worrying that existing studies are largely based on scholarly accounts of the industry from the late 20th century, during which technological development, manufacturing excellence and asset-specific investments in manufacturing facilities were the main concern of academia and policy makers. This inherent focus on manufacturing has resulted in a clear emphasis on manufacturing and cutting-edge semiconductor technologies and, while the later development of the industry towards customized and design-intensive IC product has been largely overlooked (Langlois & Steinmueller, 1999).

Therefore, the decline of vertically-integrated semiconductor giants in the West, the consolidation of semiconductor manufacturing capacity in East Asia and the prospect of a well-funded and fast-growing Chinese semiconductor industry have become a worry for observers concerned with the international diffusion of advanced semiconductor technologies (see Chu, 2008). Meanwhile, facing the approaching bottlenecks of semiconductor manufacturing technologies, companies are experimenting with specialized and customized IC designs to further improve product performance; in the past, the relentless development of manufacturing technologies provide fewer incentives to explore this alternative route (The Economist, 2016). Whatever reasons for the paucity of research into IC design business, a near vacuum of renewed research interests on the development of the semiconductor industry in the 21st century may hinder the recognition of some fundamental changes in the industry and new opportunities for research.

This PhD thesis intends to combine the theoretical lens of the IB research with recent empirical observations of the modern semiconductor industry in the early 21st century. In order to provide a fresh viewpoint and conduct the investigation of subsequent developments of the industry, it requires deep and updated understanding of the industry and the original insight of *generalized internalization theory*, which considers the flows of knowledge and information between activities across borders besides the properties of transactions (Buckley & Casson, 1976, 1985, 2009; Egelhoff, 1991; Rugman & Verbeke, 2003; Verbeke & Greidanus, 2009).

Specifically, the emergence of specialized IC design companies has been accompanied by the shift of industrial focus towards the international market and consumers in this age of tablet computers, smartphones and other consumer electronic devices. Existing large sample studies on the semiconductor industry are mostly based on semiconductor manufacturing companies or patenting records from the 1990s (e.g. Ganco, 2013; Kapoor, 2013; Leiblein & Miller, 2003; McCann, Reuer, & Lahiri, 2015). Since then, the IC design business has become the most creative, highly value-adding, internationalized and R&D-intensive sub-industry in the overall semiconductor industry (Brown & Linden, 2009; Macher, Mowery, & Di Minin, 2007). With new applications on the horizon, such as biochips, the Internet of things (IoT), wearable devices and self-driving cars (Nenni & McLellan, 2014), research on this relatively nascent industry will contribute to both business academia and policy makers.

1.2 Cross-level interdependencies and knowledge-intensive MNEs

This thesis benefits from the advances in the IB and organization science literature in the recent decades and specifically investigates the multilateral knowledge transfer of technological knowledge by IC design multinational enterprises (MNEs) in the modern semiconductor industry. The analysis adopts a structural approach to knowledge transfer and intends to observe and characterize the flows of knowledge between the MNE headquarters, subsidiaries and the host country environment. These knowledge flows link IC design MNEs both internally and internationally and further connect to a wide range of public and private organizations worldwide (see Chapter 6).

The central topic of this thesis is to address the challenge faced by IC design MNEs in the management of the cross-level interdependencies between the headquarters, subsidiaries and the host country environment. This interest can be traced to the literature on the internationalization of research and development (R&D), an important branch of IB studies, which has raised the awareness of MNEs' potentials to access talents and knowledge-based assets in foreign locations. MNEs have however experienced various frustrations in such attempts due to the managerial and organizational challenges to balance between interdependencies in external and internal networks. These networks connect various sources of novel ideas and technological knowledge as well as information about emerging market demand.

IC design MNEs are based on the *fabless business model,* which relinquishes internal semiconductor fabrication plants (fab) and emphasizes the flexibility and responsiveness to changing market demand. These MNEs deal with the interdependencies between the headquarters, knowledge-creating subsidiaries and external knowledge sources worldwide. The fabless model implies that IC design MNEs must leverage external networks to a greater degree than vertically-integrated companies (IDM). Close collaboration with customers and reliance on external manufacturing capacities suggest that the IC design industry is more similar to professional service and creative industries. The IC design industry thus provides valuable opportunities to study knowledge-intensive and entrepreneurial MNEs in the early 21st century.

Beginning with the background of knowledge creation in the IC design industry, this research first asks: *what are the sources of technological knowledge flows* and *what are the intensities of technological knowledge flows?* Answers to these questions closely relate to the internationalization of the semiconductor industry and provide the basis for analyzing the details and dynamics of multilateral knowledge transfer. Based on this knowledge of the industry, the research proceeds to investigate cross-level interdependencies and asks: *what* *are the impacts of the heterarchical structure and cross-level interdependencies on subsidiary knowledge seeking and creation* and *what are the impacts of cross-level interdependencies on multilateral transfer of technological knowledge?*

Increased reliance on internal and external knowledge sources poses challenges to IB theories, which has traditionally assumed the headquarters as the main knowledge source. This thesis adopts the economic approach of the Reading School of IB and incorporates insights from various lines of literature, namely knowledge management, organization science, innovation and entrepreneurship. It is believed that the economic rationale of internalization theory, which explains and predicts the form of coordination, can be enhanced by a more thorough account of cross-level interdependencies. The internalization decision hinges on a critical evaluation of the relative efficiency of organizing interdependencies through the market or the MNE hierarchy (Hennart, 1982, 2013). In this regard, insights from other lines of literature may provide a more clear view of market exchange relationships and elucidate the dynamics within MNE organizational hierarchy.

1.3 Structure of the thesis

Following this introduction, Chapter 2 discusses the concept of multilateral knowledge transfer and proposes a series of research questions to be answered subsequently. Multilateral knowledge transfer as an MNE strategy to systematically transfer and integrate knowledge created in subsidiaries for MNE global competitive advantage emerges from two lines of thinking—the exploitation of multinationality in the R&D internationalization literature and the contributory role of subsidiaries in the subsidiary evolution literature. The chapter criticizes that embeddedness is often misused concept in the IB literature and discusses why interdependency is a more suitable concept, which is rooted in both the organization science and the IB literature. Among three levels of analysis—the headquarters, knowledge-creating subsidiaries and host-country environments, multilateral knowledge transfer emerges on the basis of beneficial cross-level interdependencies. Particularly, the headquarters, which manages cross-level interdependencies, can influence knowledge seeking and creation at the subsidiary level and multilateral knowledge transfer.

Chapter 3 reviews the empirical literature and summarizes and discusses important studies that motivate this thesis and inform its empirical research design. Based on economics, strategy or organizational studies—although their perspectives vary—these empirical works can be broadly categorized into those focused on the firm-country level, those on the subsidiary-location level, those on headquarters-subsidiary relationships, and those on technology management. Different perspectives and focuses sometimes reflect different times of studies and changing research interests. Pioneering and timeless pieces, however, do exist ahead of their time. Findings and empirical analyses of these studies, particularly those based on original patent metrics and research design and those based on the semiconductor industry, are inspiring as well as instructive to the empirical design of this thesis.

Chapter 4 from the IB perspective takes a closer look at the emergence and R&D internationalization of the IC design industry. It first provides a brief review of the global semiconductor industry and the commonly-observed business models in the industry. In particular, the features of the IC design business model are explained in details. The chapter subsequently discusses the data collection process and introduces a sample of 28 top IC design MNEs including their patenting records. This analysis benefits from a wealth of patent data based studies on the semiconductor industry in the past two decades and multiple lines of literature, including IB, innovation research, technology management, organization science and strategic management (e.g. Adams, Fontana, & Malerba, 2013; Almeida, 1996; Almeida & Phene, 2004; Carnabuci & Operti, 2013; Frost & Zhou, 2005; Ganco, 2013; Phene & Almeida, 2008; Yayavaram & Ahuja, 2008). The original dataset and renewed research interest of this research, nevertheless, positions it as one of the first large-sample studies to provide a systematic look into the IC design industry in the early 21st century from the IB perspective.

Chapter 5 intends to develop the background knowledge of the IC design industry by reviewing the histories of the 28 leading IC MNEs in a series of mini case studies. These case studies provide a closer look at these companies than patenting records would allow and further discuss various dimensions of the IC design industry. These include, for instance, the decision to relinquish manufacturing and become fabless, the entrepreneurs who chose the fabless business model, business concerns in the IC design process, business risks of the fabless business model, the decision to establish and manage an international R&D network, and the relationship between the IC design industry and other industries, universities and governments. The chapter incorporates a decade of annual reports of the 28 IC design MNEs, industrial reports, patenting records, news archives and previous studies on the semiconductor industry. This context-rich understanding of the industry helps explain the relevance of this thesis to practitioners and the generalizability of its findings in other industrial contexts. Lastly, the chapter also summarizes the locations of domestic and international R&D sites of these 28 IC design MNEs.

Chapter 6 reports the empirical analysis of the knowledge inflows into the IC design industry, examining the geographical, industrial and temporal dimensions of knowledge flows. Relative to the general concept of knowledge transfer, the concept of knowledge flows specifies the directionalities of transfer and the dyads of knowledge transfer (Mom, Van Den Bosch, & Volberda, 2007). The analysis is based on the patenting and citation records of the 28 top IC design MNEs between 2001 and 2008, which comprise a substantial part of the global IC design industry. From these records, nearly half a million pairwise citations were traced to its original assignee in 39 industry categories. This comprehensive investigation of knowledge sources and inflows reveals the highly dynamic and knowledge-intensive nature of the industry in the global semiconductor business ecosystem and beyond. Patenting and citation records suggest a large number of external knowledge sources in various industrial contexts. Furthermore, internal knowledge sources and intra-firm knowledge flows seem to demonstrate different dynamics vertically or horizontally. The observed variation in knowledge transfer efficiency—the year gap between citing and cited patents—suggests that knowledge flows and the value of a specific piece of knowledge can be highly heterogeneous.

Chapter 7 reports the empirical analysis of cross-level interdependencies, the heterarchical structure and multilateral knowledge transfer. Two processes of multilateral knowledge transfer are investigated—firstly, knowledge inflows that deposit transferred knowledge in subsidiaries and affect subsidiary knowledge creation, and, secondly, subsidiary-to-headquarters knowledge outflows that contribute to knowledge integration at the headquarters. The analysis distinguishes between *mandated knowledge creation*, which is claimed in company annual reports, and *entrepreneurial knowledge creation*, which is derived from patenting records. Mandated knowledge creation is found closely related to intra-firm knowledge flows, and entrepreneurial knowledge creation to inflows from advanced external knowledge sources, but only the mandated type is associated with subsidiary-to-headquarters knowledge flows. The chapter also confirms the positive effect of the heterarchical structure on subsidiary knowledge creation but raises concerns about its adverse effect on the intra-firm cognitive gap. Further test result suggests that intra-firm R&D collaboration may be able to bridge this gap.

Chapter 8 summarizes and extends this research, including its answers to the proposed research questions. This chapter also discusses the implications for policy and theory development. The nature of IC design companies and their fabless business models suggest that some the insights of previous studies on the semiconductor industry are less suitable to meet the challenges of the modern semiconductor industry. The emergence of specialized IC design companies reflects a new emphasis on flexibility and more attention to fast-changing market demand—conditions that are inadequately accounted for in prior studies emphasizing manufacturing and vertical boundary issues. Research findings from these 28 IC design MNEs also provide valuable insights on cross-level interdependencies, the heterarchical structure and multilateral knowledge transfer. The heterarchical structure embraces and internalizes diversity within the entrepreneurial MNE, but innovative strategies and integrative mechanisms are required to manage cross-level interdependencies.

Chapter 9 concludes this research by discussing the implication of environmental volatility and internal diversity for entrepreneurial MNEs. On one hand, the entrepreneurial MNE may have an advantage when globalization and technological innovation are causing the growth of environmental volatility. On the other hand, the MNE and a study of it need to recognize, contemplate and, if possible, harness the differences between locations and the inherent diversity of a geographically-dispersed organization. The future development of internalization theory should incorporate the internalization of diversity. The chapter ends with several suggestions for future research.

2 REVIEW OF THEORETICAL LITERATURE

2.1 Flows of knowledge within the MNE

That firms are more efficient than markets in moving complex knowledge across national borders has been long established as a foundation for the theory of MNEs (Almeida, Song, & Grant, 2002). This important pillar is rooted in internalization theory, which considers the exploitation of firm-specific, ownership advantage by establishing hierarchical control on activities in a foreign location (Buckley & Casson, 1976; Dunning, 1980; Hennart, 1982; Rugman, 1981). However, most existing studies have applied internalization theory in a unidirectional headquarters-to-subsidiary fashion and skipped other lateral relations, such as subsidiary-to-headquarters and subsidiary-to-subsidiary. In fact, even studies adopting the view of the MNE as a knowledge community, which facilities internal international knowledge sharing, have largely focused on the headquarters-to-subsidiary knowledge transfer (Fransson, Håkanson, & Liesch, 2011; Kogut & Zander, 1992, 1993).

Since the early 1990s, researchers began to study and theorize how MNE competitive advantage may emerge from locations outside the corporate home base and be exploited internationally (Dunning & Narula, 1995; Frost, 2001; Rugman & Verbeke, 1992, 2001). As the background of this line of study, it was observed that MNEs and their foreign technological activities increasingly aim at tapping into fields of expertise in foreign locations as new sources of technology (Cantwell, 1995; Cantwell & Piscitello, 2002). Moreover, an organizational phenomenon derived from these foreign technological activities is the transfer and integration of subsidiary knowledge-based assets into the MNE group (Frost & Zhou, 2005; Håkanson & Nobel, 2001; Rugman & Verbeke, 2001; Yamin, 1999). Essentially, this process of knowledge integration enables cross-border application of subsidiary-created proprietary knowledge. Inspired by these studies, this research defines *multilateral knowledge transfer* as a knowledge integration process, which extends from conventional top-down knowledge transfer to incorporate subsidiary-to-headquarters, inter-subsidiary and subsidiary local knowledge transfer.

This literature review examines the theoretical background of multilateral knowledge transfer and synthesizes two lines of thinking that have heralded the concept—the first is *exploitation of multinationality* (Hedlund, 1986; Papanastassiou & Pearce, 2009), and the second is *contributory role of subsidiaries* (Birkinshaw, Hood, & Jonsson, 1998; Rugman & Verbeke, 2001). Exploitation of multinationality addresses how the MNE headquarters may benefit from extensive geographic reach; the contributory role of subsidiaries is concerned with how advantages developed in MNE subsidiaries may contribute to the business performance of the entire MNE. These two lines of thinking originate in international R&D literature and subsidiary evolution literature, respectively. A synthesis of both establishes the concept of multilateral knowledge transfer as an MNE strategy to systematically transform and integrate knowledge created in subsidiaries for MNE global competitive advantage.

Existing studies following these two lines of thinking tend to emphasize either MNEs exploiting multinationality or subsidiaries developing knowledge-creating competence in advantageous host country environments. The process of multilateral knowledge transfer, however, involves both lines of thinking and all three levels of analysis—the MNE headquarters, subsidiaries, as well as advantageous host country environments. Essentially, the interdependencies between these three different levels are required to illuminate the context of multilateral knowledge transfer fully. This structured literature review intends to promote a cross-level interdependency perspective by synthesizing the R&D internationalization literature and the subsidiary evolution literature and examining the implication of subsidiary embeddedness. Furthermore, based on an integrated conceptual framework of multilateral knowledge transfer, a series of research questions are identified.

2.2 Subsidiary-initiated knowledge transfer

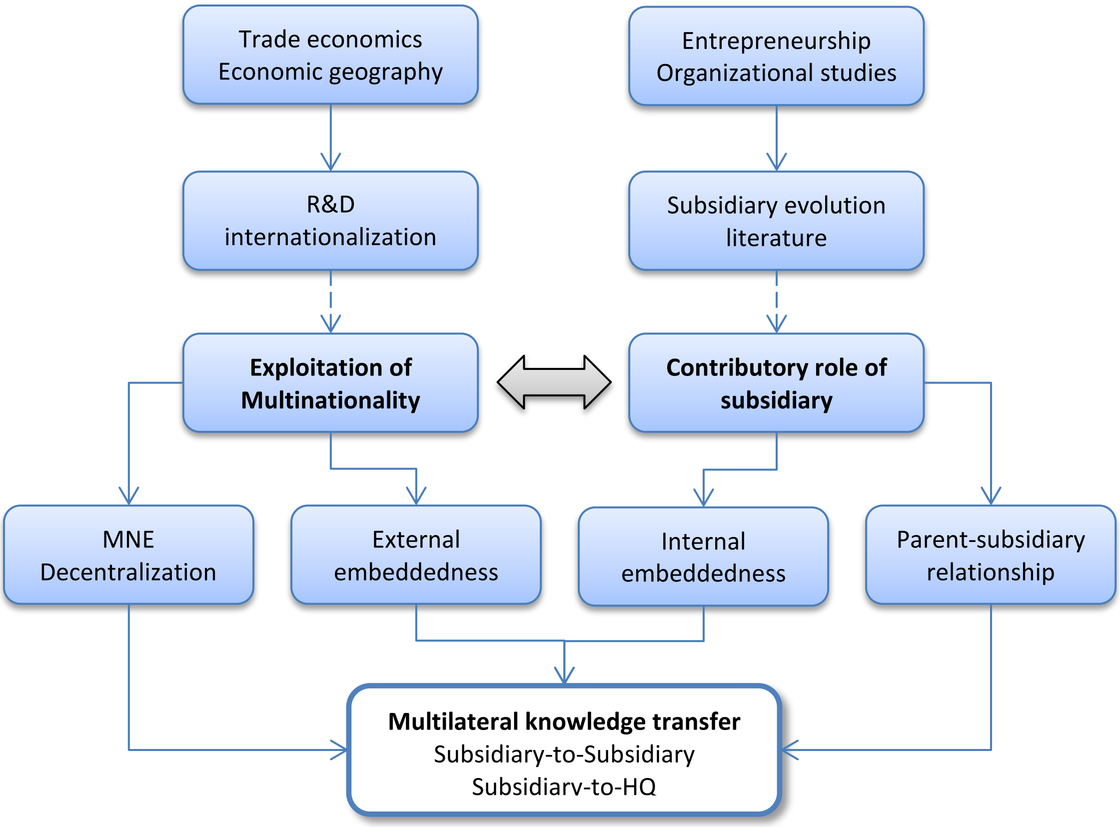
Subsidiary-initiated knowledge transfer begins with subsidiary-level knowledge-creating activities and leads to knowledge transfer to the headquarters and other subunits, contributing to the development of MNE-group competitive advantages (Håkanson & Nobel, 2001; Yamin, 1999). As opposed to the conventional headquarters-subsidiary knowledge transfer (Yang, Mudambi, & Meyer, 2008), the goal of Subsidiary-initiated knowledge transfer is to integrate knowledge created by subsidiaries into the knowledge repertoire of the MNE group (Frost & Zhou, 2005; McCann & Mudambi, 2005). From the viewpoint of the MNE group, this transfer of knowledge further facilitates the recombination of knowledge-based assets acquired at the boundary of the MNE with those retained in the headquarters (Kogut & Zander, 1992, 1993; Rugman & Verbeke, 1992). Knowledge-based assets sought and created by subsidiaries utilizing foreign country-specific advantages are thus globally shared, recombined and leveraged by the headquarters as new firm-specific advantages. Through multilateral knowledge transfer, MNEs may formulate a growth strategy by transforming knowledge created in subsidiaries into the competitive advantages of the entire MNE, from localized subsidiary-specific advantage to internationally mobilized firm-specific advantage, forming the new basis of MNE international leverage (Mudambi & Navarra, 2004; Rugman & Verbeke, 1992, 2001).

Research into multilateral knowledge transfer examines the role of subsidiaries in developing the technological competence of MNEs and the determinants of new technology transfer from subsidiaries to the headquarters (Håkanson & Nobel, 2001; Yamin, 1999). However, the R&D internationalization literature already asked similar questions in the 1970s, concerning R&D decentralization and the implication of subsidiary-level R&D to the MNE group (Florida, 1997; Kuemmerle, 1999; Pearce, 1999a; Pearce & Papanastassiou, 1999; Ronstadt, 1978). Notably, the conventional model of the MNE usually features a centralized R&D function in the MNE home base both in theory and practice (Buckley & Casson, 1976;

Dunning, 1980; Vernon, 1966). The new phenomenon of decentralized knowledge creation, which is subject to centralized monitoring and evaluation by the headquarters, suggest that subsidiaries may also support the development of MNE-group-level technological trajectory (Papanastassiou & Pearce, 2009).

Underlying this departure from the conventional model of the MNE are two lines of thinking in the IB literature. First, cross-country diversity can be a source of competitive advantages which MNEs should actively exploit (Hedlund, 1986; Papanastassiou & Pearce, 2009); second, subsidiaries can become active contributors to the competitive advantage of MNE group (Birkinshaw & Hood, 1998; Rugman & Verbeke, 2001). The two lines of thinking are based on separate logics involving different levels of analysis—the proactive exploitation of multinationality at the MNE group level, and evolution towards a contributory role at the subsidiary level. The relationships between the concepts and lines of literature are illustrated in Figure 2.1.

Figure 2.1 Two lines of thinking



2.2.1 Exploitation of multinationality

Knowledge bases of different countries differ greatly from one another due to specific industrial clusters (McCann & Mudambi, 2005; Sanna-Randaccio & Veugelers, 2007) and heterogeneous technological trajectories resulting from divergent national systems of innovation (Cantwell, 1995; Cantwell & Janne, 1999). These cross-country differences lead to various opportunities for knowledge seeking and learning and may be potentially incorporated into the creative process of the MNE, enhancing the scope of its knowledge repertoire (Pearce, 1999b). In the field of international economics, researchers investigating these positive externalities of foreign direct investment (FDI) argue that certain countries and locations are particularly advantageous for MNE subsidiaries, because of the potential knowledge spillovers from local organizations (Blomström & Kokko, 1998; Kuemmerle, 1999; Sanna-Randaccio & Veugelers, 2007).

Through knowledge absorption, transfer and creation, the extended international reach of MNEs give them unique advantages in leveraging knowledge sought and created in foreign locations. Firstly, MNEs may benefit from location-bound knowledge diffusions in multiple countries, which are unattainable by companies confined to a single country base (Almeida, 1996; Frost, 2001; Kuemmerle, 1997). Secondly, MNEs may access multiple knowledge bases and 'arbitrage' between locations—knowledge assets sought from one country can be deployed in other countries where specific knowledge assets have a relative advantage. The diversity of country environments provides the base assumption to the arbitrage benefit of knowledge assets (Hennart, 2011; Rugman & Verbeke, 2003). Thirdly, MNEs pursuing knowledge-based growth may internalize elements of local creative competencies in subsidiaries and create new goods and services for MNE international competitiveness (Papanastassiou & Pearce, 2009).

The theorization of how the host country environment can become a potential source of competencies and technological opportunities instead of constraints for MNEs marks a departure from conventional approaches to international business (Zanfei, 2000). Instead of merely exploiting competitive advantages derived from home country bases, MNEs may actively create new advantages from a global spread—which makes multinationality itself a unique advantage of the MNE relative to domestics firms (Hedlund, 1986; Papanastassiou & Pearce, 2009). This view of proactive *exploitation of multinationality* leads to subsequent research on how diverse host country environments may affect the roles and mandates of subsidiaries. Over time, subsidiaries in different country environments may develop different competencies and evolve toward specialized roles (Birkinshaw, 1996; Frost, Birkinshaw, & Ensign, 2002; Nobel & Birkinshaw, 1998). Therefore, from the viewpoint of headquarters and MNE organizational structure, the longer-term implication of exploiting the diversity across country environments is to embrace and manage increasingly heterogeneous country subsidiaries.

2.2.2 Contributory role of subsidiaries

Traditionally, both internalization theory (Buckley & Casson, 1976) and internationalization process theory (Johanson & Vahlne, 1977) have theorized a sequential process from the creation of firm-specific, ownership advantages at the headquarters to their diffusion and exploitation worldwide, which is the assumption of conventional MNE models since Hymer (Almeida & Phene, 2004; Papanastassiou & Pearce, 2009). Subsidiaries were considered mainly as the agents to apply and exploit advantages supplied by the headquarters, and subsidiary knowledge seeking and creation were mostly supportive or peripheral as listening posts, such as investments made by Japanese MNEs in the 1980s to assist in the absorption of foreign technologies (Gassmann & Gaso, 2004).

Rugman and Verbeke (1992) challenge this partial view and suggest that advantages may arise anywhere in the MNE, while others observe the growth in scale and accumulation of unique resources in subsidiaries over time (Birkinshaw & Hood, 1998). Related conceptualizations include strategic asset-seeking FDI (Dunning & Narula, 1995), home-base-augmenting FDI (Kuemmerle, 1997), world product mandate subsidiaries (Birkinshaw & Morrison, 1995; Rugman & Bennett, 1982), centers of excellence (Birkinshaw et al., 1998; Frost et al., 2002), creative subsidiaries (Pearce, 1999), and competence-creating subsidiaries (Cantwell & Mudambi, 2005), among others. Essentially, these conceptualizations refer to an increasingly creative and contributory role at the subsidiary level, where the resources and capabilities of the MNE group interact with those rooted in the host country environment, and where the MNE develops new competitive advantages through global knowledge creation. This line of thinking suggests the second view—*contributory role of subsidiaries* (Birkinshaw et al., 1998).

Hosting this encounter at the intersection of MNEs and their host country environments puts subsidiaries in a particularly advantageous position to access knowledge-based assets from both the internal network of MNE units and the external network of host country knowledge sources (Almeida & Phene, 2004; Andersson & Forsgren, 2000). Simultaneous presence and embedded linkages in both internal and external networks give subsidiaries unique exposure to knowledge-based assets and opportunities from both networks (Asakawa, 1996; McEvily & Zaheer, 1999). Moreover, as each subsidiary builds up its unique pattern of embedded network linkages, the MNE also contains greater intra-firm diversity and more opportunities to exploit multinationality (Cantwell & Mudambi, 2005).

2.3 Subsidiary embeddedness

This unique position in dual knowledge networks relates to subsidiary embeddedness in these networks. Embeddedness is a concept from economic sociology (Granovetter, 1985; Uzzi, 1996, 1997) and has been incorporated into the IB literature by Frost (1998) and Andersson and Forsgren (1996). Frost (1998) argues that subsidiary embeddedness affect the strategic orientation and likelihood of subsidiaries to draw upon external knowledge sources in the host country environment. Embeddedness may legitimize subsidiaries in the host country institutional environment (Baum & Oliver, 1992) and allow them to develop experience with inter-organizational collaborations and participation in external networks of learning (Powell, Koput, & Smith-Doerr, 1996). The foreign ownership of MNE subsidiaries bestows them with a lack of legitimacy marked by outsidership and liability of foreignness, prohibiting reciprocal knowledge exchange.

From a slightly different perspective, Andersson and Forsgren (1996) investigate subsidiary business relationships and emphasize the potential subsidiary control issues, which result from subsidiary embeddedness in local external networks as opposed to the internal corporate network. Strong business relationships and interdependencies between subsidiaries and local counterparts construe subsidiary embeddedness but weaken the control of the headquarters over subsidiaries. Several other authors also share this concern (e.g. Asakawa, 1996). When externally embedded subsidiaries assimilate with their counterparts in external networks, there can be risks of gradual deviation from the corporate network (Ghoshal & Bartlett, 1990). Such deviation from the internal network towards external embeddedness can hinder the resource commitment and knowledge transfer from the MNE group, leaving subsidiaries solely with external resources and further isolation.

2.3.1 Dual-embeddedness and multiple-embeddedness

The scenario in which linkages are comprehensively maintained in both external and internal networks gives rise to the concept of *subsidiary dual-embeddedness*. The recommendation that subsidiaries should maintain dual-embeddedness in internal and external networks can be found in several pioneering works, which partially incorporate the concept of social networks in IB studies. Frost (1998) suggests subsidiaries should balance between internal and external sources of innovation. Andersson and Forsgren (1996) investigate the trade-off between corporate embeddedness and external embeddedness. Pearce (1999b) discusses the capability of creative subsidiaries to understand and implement their positions in both MNEs and local technological communities. The discussion on subsidiary dual-embeddedness also relates to the potential dual-legitimacy of subsidiaries in both the MNE and host country institutional environments (Kostova & Zaheer, 1999). Dual-embeddedness implies that subsidiaries maintain positive relationships and effective communication channels simultaneously with the headquarters and local organizations in host country environment.

However, there is one caveat in the dual-embeddedness argument—the corporate internal network of the MNE and external social network are inequivalent. For instance, pressures from the headquarters will very likely outweigh those from the local external counterparts. On one hand, the headquarters tends to exert stronger pressures when subsidiaries lean outward excessively and damage the internal consistency of the MNE (Andersson & Forsgren, 1996; Andersson, Forsgren, & Holm, 2007; Asakawa, 1996; Yamin, 1999). On the other hand, the managerial capacity and experience with managing relationships at the subsidiary level can be limited (Ambos, Ambos, & Schlegelmilch, 2006; Powell et al., 1996). The headquarters-subsidiary relationship is often in jeopardy as subsidiaries build up external linkages and further embed in their host country environment. In other words, the dual-embeddedness argument does not solve the tradeoff balancing issue but reveals its inevitability.

Xu and Shenkar (2002) suggest that the difficulties in headquarters-subsidiary coordination may result from the specific strategy adopted by MNEs. The *multi-domestic* strategy allows subsidiaries to attend locally and exercise significant autonomy, while the *global* strategy pursues global integration, centralization and scale economies and inherently lacks the tolerance for diversity. Therefore, unless MNEs adopt a less centralized international strategy and allow subsidiaries to build competencies locally and embed externally, the attempts to create knowledge and new advantages at the subsidiary level are likely to fail. In other words, subsidiary-level competence building and knowledge creation require suitable conditions at the subsidiary level, but the success of such attempts requires additional suitable conditions at the MNE level.

In fact, this discussion on various factors at the MNE level, such as the control of the headquarters and the international strategy of the MNE, reflects the first view—exploitation of multinationality. The optimistic view to embrace diversity and leverage external competencies encourages MNEs to create advantages from dealing with diversity proactively. The pre-requisite of subsidiary dual-embeddedness and subsidiary knowledge creation is that MNEs are indeed willing to embrace diversity and exploit multinationality.

2.3.2 Rethinking subsidiary embeddedness

The discussion on embeddedness, including the expansion of the embeddedness typology from external-, internal-, dual- to multiple-embeddedness, seems excessive, nevertheless. Notably, given the usefulness of the concept in IB research, the exact theoretical underpinning of embeddedness has remained ambiguous in the IB literature. There are at least three different realizations and lines of discussion that can be identified in the current IB literature. From the perspective of international R&D management, the first line considers the connectedness between subsidiary R&D facilities and external R&D institutes (Asakawa, 1996; Cockburn & Henderson, 1998). Connectedness, particularly personal and business relationships developed through a history of interactions (Dellestrand & Kappen, 2012; Foss, Lyngsie, & Zahra, 2013; Tushman & Scanlan, 1981), facilitates inflows of information about business and technological ideas from external sources, such as research institutions, customers and suppliers. The second line, which is influenced by institutional theory, associates subsidiary embeddedness with its legitimacy in host country environment and access to external knowledge sources (Frost, 1998; Håkanson & Nobel, 2001). Legitimacy in the host country institutional environment affects access to external resources and knowledge and a lack of legitimacy results in liability of foreignness (Zaheer, 1995). The third line of discussion emphasizes the tendency of knowledge flows to be contained within geographical areas (Almeida & Phene, 2004; Rosenkopf & Almeida, 2003). This line of studies, along with a series of empirical studies based on patent data analysis, suggests the sociological impact of physical proximity that grants preferential access to external resources, builds social relationships and enables personnel mobility within specialized regions (Almeida & Kogut, 1997, 1999).

While the exact mechanism and theoretical underpinning of embeddedness is obscure in the IB literature, all three lines of discussion essentially relate to the impact of subsidiary embeddedness on access to external knowledge sources and flows of information about new business and technology opportunities. Similarly, subsidiary embeddedness in corporate internal network also affects the search and transfer of intra-firm knowledge (Hansen, 1999; Hansen, Mors, & Løvås, 2005). Since multilateral knowledge transfer encompasses the knowledge creation and transfer by subsidiaries simultaneously situated in both local external and corporate internal networks, the concept of embeddedness is a useful starting point. Ultimately, however, theorizing multilateral knowledge transfer should incorporate not only the concept of embeddedness, but should more sufficiently address the corresponding managerial and organizational challenges. It requires a more comprehensive framework that establishes and incorporates the interdependencies between all three levels—headquarters, the knowledge-creating subsidiary and host country environment.

2.4 A cross-level interdependency perspective

Depending on the interdependencies between subsidiaries, the MNE headquarters and the host country environment, the evolution of subsidiaries towards a contributory role has been studied from cognitive and behavioral perspectives (Birkinshaw, 1996; Collinson & Wang, 2012; Frost et al., 2002; Taggart, 1997). The success of subsidiary initiatives—entrepreneurial and autonomous behaviors occurring at the subsidiary level, when subsidiaries proactively seek new opportunities and build competencies—requires a certain degree of autonomy and resources allocation granted by the headquarters (Birkinshaw, 1997; Birkinshaw & Hood, 1998; Florida, 1997; Pearce, 1999b). Autonomy and adequate independence are also necessary when subsidiaries build external linkages and access knowledge sources in host country environment (Andersson, Forsgren, & Holm, 2002; Asakawa, 1996). The authorization from the headquarters for these entrepreneurial and autonomous behaviors may only arise from highly trusting, constructive and interdependent headquarters-subsidiary relationships.

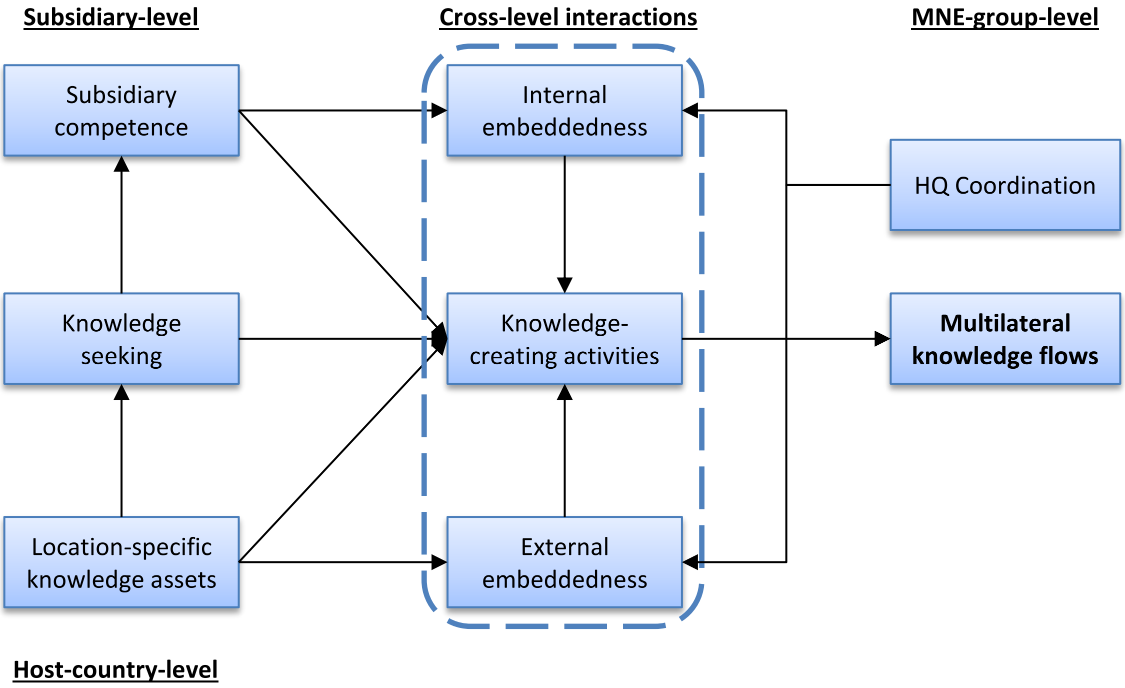
However, potentially hazardous interactions between subsidiaries and the MNE headquarters have been documented, including heightened tensions (Ambos, Andersson, & Birkinshaw, 2010; Asakawa, 1996, 2001; Håkanson & Nobel, 2001), intra-firm power imbalances (Mudambi & Navarra, 2004), bargaining for resource allocation (Andersson et al., 2007), militant subsidiaries (Taggart, 1997), and complete isolation (Monteiro, Arvidsson, & Birkinshaw, 2008), among others. Therefore, a constructive interdependency between subsidiaries and the headquarters must exist while subsidiaries build competencies and interdependency with knowledge sources in the host country environment. Otherwise, deviated interests and tensions can grow between the headquarters and subsidiaries when competencies, initiatives and external embeddedness are developed in absence of support or explicit recognition from the headquarters (Ambos et al., 2010; Andersson et al., 2007; Asakawa, 1996; Papanastassiou & Pearce, 2009).

Developing and administrating the cross-level interdependencies between the headquarters, subsidiaries and the host country environment inevitably pose great challenges to both the headquarters and subsidiary management. In fact, such challenges were reflected in previous studies in multilateral knowledge transfer. Despite the cross-level nature of the phenomenon, researchers usually focus on one or two levels, while somehow assuming or neglecting the interdependencies with other levels of analysis. In fact, this negligence is also reflected in the confusions caused by the term *reverse knowledge transfer*. The term is considered by researchers in the R&D internationalization literature as inter-firm knowledge spillovers and yet by others in the subsidiary evolution literature as intra-firm knowledge transfer. Their concerns of external knowledge seeking and internal knowledge transfer altogether oblige the encompassing concept of multilateral knowledge transfer and the consideration of cross-level interdependency. The question is then, what interdependencies should be incorporated into a conceptual framework that is sufficiently comprehensive and explicit about the testable conditions?

Specifically, the framework should address knowledge seeking and creation at the subsidiary level, which is conditional on the interdependencies between subsidiaries and host country environment and between subsidiaries and the headquarters. Subsequently, the framework should consider knowledge integration at the MNE level, which is based on the interdependencies between the headquarters and subsidiaries and between the specific MNE and all its host countries globally. Multilateral knowledge transfer as an MNE strategy to systematically create, transfer and integrate subsidiary knowledge for new global competitive advantages of the MNE group requires, therefore, a comprehensive consideration of the interdependencies between all three levels of analysis—the MNE headquarters, subsidiaries and host country environment.

From this cross-level interdependency perspective, a conceptual framework of multilateral knowledge transfer is presented in Figure 2.2. Subsequent discussions begin with subsidiaries seeking country-specific knowledge-based assets as depicted in the lower left end of the diagram.

Figure 2.2 The conceptual framework



2.4.1 *Subsidiary-host interdependency*

As previously discussed, exploitation of multinationality—embracing diversity and deriving new advantages from various host country environments—is an MNE-level decision considered by the headquarters. Distinctive knowledge bases and technological specializations in a country environment generate knowledge-based assets, and MNEs may retrieve them by investing in subsidiaries which seek knowledge locally (Papanastassiou & Pearce, 2009). The knowledge base of a host country environment may consist of the R&D resources of local competitors, the knowledge pool of local research institutions and firms in related industries (Freeman, 1995; Sanna-Randaccio & Veugelers, 2007). The availability of these external knowledge sources has two impacts on subsidiary knowledge creation. Firstly, it enhances the creativity of subsidiaries by providing a wealth of local knowledge-based assets to be sought and acquired by the subsidiary (Kuemmerle, 1999). Secondly, it increases the tendency of subsidiaries to embed in external knowledge networks (Andersson et al., 2002). For instance, researchers in subsidiaries may participate in the external network of local researchers and scientists in the host country (Asakawa, 1996).

The first and foremost task of this thesis to study subsidiary knowledge seeking requires identifying the exact host country knowledge sources from which MNEs and their subsidiaries seek knowledge and build competencies. This information is particularly needed because existing large sample studies on the semiconductor industry are mostly based on semiconductor manufacturing companies, US-headquartered MNEs and patenting records from the 1990s (e.g. Ganco, 2013; McCann et al., 2015; Phene & Almeida, 2008; Yayavaram & Ahuja, 2008). These studies are likely limited by time background, sample coverage and the lack of information about specific external knowledge sources. As the first step to analysis the subsidiary-host interdependency in the framework, the investigation and identification of relevant knowledge sources, with which interdependencies are observed, become a priority. The first research question will therefore empirically identify the presence and importance of these sources. Specificlyy, what are the knowledge sources utilized by the IC design MNEs and their subsidiaries in their overall knowledge seeking and creation? The first research question is proposed:

Research question 1: *what are the sources of technological knowledge flows? The question intends to identify and analyze external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

2.4.2 Subsidiary-host-headquarters interdependency

While the international R&D literature emphasizes external knowledge sources (Asakawa, 1996; Cockburn & Henderson, 1998), the subsidiary evolution literature addresses the interactions of subsidiaries with both external sources and the headquarters (Almeida & Phene, 2004; Andersson & Forsgren, 2000). Proximity to both internal and external knowledge sources can endow the knowledge-creating subsidiary with extraordinary creativity (Almeida & Phene, 2004; Frost et al., 2002; Håkanson & Nobel, 2001; Pearce, 1999b). However, external knowledge networks offer the subsidiary new ideas and human capital to the extent the subsidiary is externally embedded in the local environment (Almeida

& Kogut, 1999; Andersson et al., 2002; Cockburn & Henderson, 1998; Håkanson & Nobel, 2001; Mowery & Sampat, 2005). Internal embeddedness, on the other hand, creates a strong bond between the knowledge-creating subsidiary and other units in the MNE corporate network (Papanastassiou & Pearce, 2009). This internal interdependency also ensures the resource commitment from the headquarters on subsidiary knowledge creation and transfer (Dellestrand & Kappen, 2012).

It is challenging yet potentially rewarding that the knowledge-creating subsidiary utilizes external and internal networks and maintains the divergent interests of members in the two networks. When the subsidiary intends to access localized knowledge flows, external embeddedness facilitates the exchange of information with knowledge sources in the host country. The interdependency with external sources, therefore, assists the competence bundling and knowledge recombination at the subsidiary level, which will add novelty and diversity to the MNE knowledge repertoire. On the other hand, internal interdependency facilitates the communication and cooperation between the subsidiary and the headquarters as well as other subsidiaries. However, as previously discussed, the local external network and the corporate internal network are fundamentally different. An intricacy is that the knowledge-creating subsidiary may naturally develop some social relations and a basic level of interdependencies with external knowledge sources in the host country environment, and nevertheless, internal relations are largely subject to the supervision and coordination by the headquarters. In other words, at least in the case of large and geographically-dispersed organization, social network theory may not usefully explain the level of interdependencies between members of the corporate internal network, which is derived from the organization structure and global strategy of specific MNEs.

This unique position of the knowledge-creating subsidiary demands constructive interdependencies and rewards the subsidiary with enhanced flows of knowledge and creativity. While the first research question intends to identify the exact sources of knowledge-based assets, the subsequent question intends to evaluate the intensities of knowledge flows with these external and internal knowledge sources. This information may indicate the levels of cross-level interdependencies in external and internal networks, and the state of cross-level interdependencies likely reflects specific organization structure and global strategy. Moreover, due to limited research on the IC design industry, bounded rational decision-makers in various levels are likely faced with the difficulties to optimize resource allocation and balance between different networks. The analysis and empirical observations from these leading IC design MNEs may provide useful instructions for them. This information also provides the basis for subsequent empirical analysis of cross-level interdependencies in this thesis. The second research question, therefore, investigates the intensities of technological knowledge inflows into the IC design MNEs and their subsidiaries:

Research question 2: *what are the intensities of technological knowledge flows? The question intends to analyze and compare the intensities of knowledge flows from external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

2.4.3 Headquarters-host-subsidiary interdependency

MNEs may benefit from location-bound knowledge diffusions in foreign countries through subsidiaries (Almeida, 1996; Frost, 2001). However, these potentially contributory subsidiaries must depend on the willingness of the headquarters to embrace diversity and exploit multinationality (Papanastassiou & Pearce, 2009). From the viewpoint of the MNE headquarters, exploiting multinationality implies a change in its approach to diverse host country environments, adopting a decentralized, multi-domestic strategy and structuring subsidiaries in a *heterarchy* (Hedlund, 1986). The essence of heterarchy is its greater tolerance of diversity among subsidiaries and the MNE as a whole. Through subsidiary knowledge seeking, diverse external knowledge sources and knowledge-based assets are incorporated into subsidiary knowledge creation and later reincarnated as MNE internal diversity. The heterarchical structure allows the knowledge-creating subsidiary to assume a differentiated and specialized role in the MNE and positions the headquarters as a coordinator of flows of information and knowledge. Such arrangement distributes more decision-making power to the subsidiary level and grants the autonomy to build competencies and external relationships. Meanwhile, the headquarters would be poised to assist in multilateral knowledge transfer—the creation, transfer and integration of subsidiary knowledge.

Although decentralization and the heterarchical structure are necessary for subsidiary knowledge seeking and creation, the transition into heterarchy can be challenging. Decades of studies in the R&D internationalization literature continue to reveal the same phenomenon of MNE home-boundedness—the tendency of large MNEs to concentrate knowledge-creating activities in the home base and the reluctance to seek external knowledge-based assets (Di Minin & Bianchi, 2011; Patel & Pavitt, 1991; Ronstadt, 1978; Wolf, Dunemann, & Egelhoff, 2012). In such case, the headquarters often neglects external knowledge sources (Tan & Meyer, 2011), underrates knowledge created in subsidiaries and refrains from internal knowledge transfer (Di Minin & Bianchi, 2011). Strong reliance on the home country knowledge base renders exploitation of multinationality far-fetched and the contributory role of subsidiaries irrelevant in MNE knowledge creation.

The willingness of the headquarters to embrace diversity and exploit multinationality is the core premise of having contributory subsidiaries. This thesis argues that the adoption of the *heterarchical structure* may reflect such willingness to embrace and internalize diversity within the firm. The heterarchical structure designates subsidiaries for differentiation and specialization most suitable and advantageous in specific host country environments. Subsidiaries are also given the capacity to establish interdependencies and learn from knowledge sources in various host country environments. At the MNE level, adopting a heterarchy has implications beyond the changes at the subsidiary level. From a higher level of decision-making and a global perspective, the headquarters of a heterarchical MNE not only influences cross-interdependencies but also curbs a tendency towards internal interdependencies.

While existing studies on the semiconductor industry are often concerned with the firm vertical boundary issue and the spillovers of semiconductor technologies, the extensive globalization of the modern semiconductor industry is often neglected. IC design MNEs, which tend to have higher levels of R&D internalization (Macher et al., 2007; Nenni & McLellan, 2014), provide a useful sample to observe the development of the modern semiconductor industry and verify the effectiveness of the heterarchical structure. This thesis argues that the levels of cross-level interdependencies hinge on the coordination by the headquarters towards the heterarchical structure. The third research question, therefore, focuses particularly on the heterarchical structure, which preconditions cross-level interdependencies:

Research question 3: *what are the impacts of the heterarchical structure and cross-level interdependencies on subsidiary knowledge seeking and creation? The question intends to analyze their impacts on the creation of subsidiary knowledge.*

2.4.4 Cross-level interdependencies and multilateral knowledge transfer

Lastly, this thesis suggests that establishing cross-level interdependencies is a precondition for multilateral knowledge transfer, and the actual importance and organizational challenges are often downplayed in existing studies on subsidiary knowledge creation. It is critical to recognize that the MNE internal network is created and orchestrated by the headquarters, instead of a naturally occurring social network in which economic agents have the freedom to choose partners and exchange information (Burt, 1992; Kirman, 2005). In general, the corporate network of MNE subunits is either a conventional hierarchy that exerts strong internal isomorphic pressures (Xu & Shenkar, 2002) or a heterarchy that encourages the differentiation of interdependent subsidiaries (Papanastassiou & Pearce, 2009). The ‘network’ position of the headquarters in the corporate internal network is construed by the MNE’s ownership structure, which establishes the headquarters’ ‘network’ connectivity and centrality.

The headquarters’ approach to cross-level interdependencies is, therefore, pivotal to multilateral knowledge transfer, because the flows of information and knowledge in the corporate network are subject to the headquarters’ coordination of a network of differentiated and specialized subsidiaries. Papanastassiou and Pearce (2009) suggest that the headquarters should gain its influence by understanding and evaluating various ongoing knowledge-creating activities at the subsidiary level. Without relevant knowledge and sufficient understanding, the headquarters might inadvertently intervene in subsidiary innovation processes, especially when subsidiaries and these processes are changing (Ciabuschi, Forsgren, & Martín, 2011). It is an organizational challenge for the headquarters of heterarchical MNEs to coordinate the transfer and integration of knowledge created by subsidiaries, which have developed their own structures and competencies in relation to the requirements of particular host country environment (Kretschmer & Puranam, 2008; Lawrence & Lorsch, 1967).

IB scholars have investigated several strategies to improve the information processing capacity of heterarchical MNEs (Egelhoff, 1991). For instance, Di Minin and Bianchi (2011) suggest that IP management practices should also be decentralized and coordinated with subsidiary knowledge-creating activities that otherwise tend not to be noticed and appropriated by the headquarters. Papanastassiou and Pearce (2009) suggest that the central lab in headquarters should facilitate the interdependency between subsidiary labs by encouraging knowledge sharing and developing a non-defensive culture between them. In particular, Frost and Zhou (2005) find that R&D co-practice increases the absorptive capacity and social capital between participants and facilitates subsidiary-to-headquarters knowledge integration.

The common goals of these strategies are to develop communication channels and lateral relationships between subsidiaries and the headquarters (Galbraith, 1974). Otherwise, subsidiary knowledge created in different host countries and derived from idiosyncratic subsidiary-host interdependencies can become inconspicuous and underappreciated by the headquarters and other subunits (Björkman, Barner-Rasmussen, & Li, 2004; Monteiro et al., 2008). Essentially, multilateral knowledge transfer requires effective information processing by the headquarters to discern and integrate diverse and distributed knowledge-based assets from a global perspective

This thesis will focus on intra-firm R&D collaboration as the strategic and integrative mechanism to inform the headquarters and develop cross-level interdependencies for multilateral knowledge transfer. In particular, the cross-level interdependency perspective suggests that different types of intra-firm collaborations may reflect interdependencies of various nature. Collaborations led and initiated by the headquarters may differ from those by subsidiaries. The former reflects the headquarters-host-subsidiary interdependency established by the headquarters, and the latter indicates the subsidiary-host-headquarters interdependency initiated by subsidiaries. The empirical analysis in this thesis will provide insights about the effects of these different cross-level interdependencies on the multilateral knowledge transfer. The fourth research question intends to conduct the investigation with IC design MNEs:

Research question 4: *what are the impacts of cross-level interdependencies on the multilateral transfer of technological knowledge? The question intends to analyze their impacts on the transfer and integration of subsidiary knowledge.*

2.5 Theoretical implications of the cross-level interdependency perspective

Instead of the excessive and often misused concept of embeddedness, this thesis proposes a research on the cross-level interdependencies between the headquarters, subsidiaries and the host country environment. Widely studied in the organization science literature, the concept of interdependency is often intertwined with information flows in the discussion of organizational design and functioning (Galbraith, 1974; Van de Ven, Delbecq, & Koenig Jr, 1976). Economic geographers have also described the interdependency between collocating firms, which explains the knowledge sharing within industrial districts (Tallman, Jenkins, Henry, & Pinch, 2004). Admittedly, embeddedness too has important implications on information flows, but it often has other social and behavioral implications, such as narrower information search, social identity, homophily and cohesion, that counters the diversity and creativity valued by most IB researchers (Rao, Davis, & Ward, 2000; Uzzi, 1997; Uzzi & Spiro, 2005)

According to organizational scientists, a major challenge to organizational design is the choice and adoption of integrative mechanisms to communicate information and coordinate the actions of interdependent subunits (Adler, 1995; Galbraith, 1974). In principle, different integrative mechanisms can give the organization varying level of information processing capacity. While organizations may strategically mix and combine different mechanisms, the overall capacity needs to meet the information processing requirement given the uncertainties and interdependencies associated with the organization (Van de Ven et al., 1976).

In the IB literature, the interdependencies and information flows between international activities are crucial in internalization decision-making. In fact, both concepts are found in the conceptualization of internalization theory. The Reading school of internalization theory suggests that the MNE internalizes information flows within the firm and coordinates activities across borders (Buckley & Casson, 1976, 2009; Casson, 2000). Meanwhile, Hennart (1982, 2013) explains that the MNE arises from comparing the relative efficiency of organizing interdependencies through market transactions or within the firm organization. The importance of information is also found in the work of Hymer(Hymer, 1960)[131], who suggests that the MNE faces disadvantages because geographical and cultural distances inhibit effective communication and reduce the quality of decisions (Kindleberger, 1984). From the perspective of information processing, MNEs, like other business organizations, process information to interpret the host country environment, to coordinate diverse activities and to accomplish business tasks (Daft & Lengel 1986). In that sense, the existence and the organizational design of a particular MNE are rooted in the headquarters' judgment about the coordination of interdependencies and information flows across borders.

However, the management of interdependencies and the maintenance of fit between information processing capacity and requirement are inherently more challenging in geographically-dispersed and differentially-specialized organizations, such as those MNEs based on the heterarchical structure (Egelhoff, 1991; Srikanth & Puranam, 2014). When MNEs intend to empower and coordinate the creation, transfer and integration of subsidiary knowledge, there is an inevitable increase in information processing requirement. In a model of cross-level interdependencies and multilateral knowledge transfer, MNEs must continuously monitor new knowledge and actively intermediate between knowledge bases (Casson, 1997).

The concept of interdependency is considered in this thesis as *cross-level* instead of *inter-unit*, because the headquarters, subsidiaries and the host country environment are intrinsically different concepts. Each of them has own functions, mechanisms, structure and collection of elements, some of which may overlap but not all. Interdependencies across these levels provide the basis for the flows of information and knowledge; on the opposite, independence and irrelevance prevent the flows if so intended. Although the geographically-dispersed nature of MNEs complicates the application of organization science in the IB field, the heterarchical structure may be the field’s answer for how to manage cross-level interdependencies.

Information processing and interdependencies remain important topics in the organization science literature (see e.g. Dunbar & Starbuck, 2006; Puranam, Raveendran, & Knudsen, 2012). While this thesis and its research questions focus on the empirical investigation of IC design MNEs, it also intends to revive the discussion on information processing in the IB literature (Buckley & Casson, 1976, 1985, 2009, Casson, 2000, 1997; Egelhoff, 1991; Egelhoff, Wolf, & Adzic, 2013; Rugman & Verbeke, 2003; Verbeke & Greidanus, 2009). Further discussion on the impact of the cross-level interdependencies between the headquarters, subsidiaries and on host country environment and the implications on information processing is provided in Chapter 8.

2.6 Conclusion

Multilateral knowledge transfer is an interesting but understudied element of the theory of the MNE. This literature review argues that multilateral knowledge transfer emerges from two lines of thinking in the IB literature—*exploitation of multinationality* and *contributory role of subsidiaries.* This literature review provides a synthesis of two lines of thinking, addresses both internal and external knowledge sources, and finally explains the implication of subsidiary embeddedness. In brief, the MNE’s intention to embrace diversity and exploit multinationality is the prerequisite for multilateral knowledge transfer, which creates the organization and social conditions for subsidiaries to evolve towards a contributory role in the MNE group. Studies on subsidiary embeddedness offer a renewed yet unresolved concern with cross-level interdependencies and the role of the headquarters. Without exploitation of multinationality as a premise, cross-level interdependencies may fail and conflict when subsidiaries build up competencies and establish external linkages, ultimately hindering the multilateral transfer of knowledge. By examining the theoretical foundation of multilateral knowledge transfer, this review proposes four research questions which address the implications of the cross-level interdependency perspective and intends to conduct an empirical investigation with MNEs in the IC design industry. These questions are:

Research question 1: *what are the sources of technological knowledge flows? The question intends to identify and analyze external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

Research question 2: *what are the intensities of technological knowledge flows? The question intends to analyze and compare the intensities of knowledge flows from external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

Research question 3: *what are the impacts of the heterarchical structure and cross-level interdependencies on subsidiary knowledge seeking and creation? The question intends to analyze their impacts on the creation of subsidiary knowledge.*

Research question 4: *what are the impacts of cross-level interdependencies on the multilateral transfer of technological knowledge? The question intends to analyze their impacts on the transfer and integration of subsidiary knowledge.*

Each of these four questions encapsulates a different dimension of the integrated conceptual framework (see Figure 2.2) and gradually develops a cross-level interdependency perspective on multilateral knowledge transfer. Following internalization theory, which theorized the conventional, headquarters-to-subsidiaries flows of knowledge 40 years ago, this research highlights the multi-level and multi-disciplinary nature of the IB field and indicates new directions for theoretical and empirical development, advocating for the potentials of multinationality.

3 REVIEW OF EMPIRICAL STUDIES

3.1 Introduction

In the IB literature, the question of where to source knowledge outside the home country of MNE begins with the discussion in the 1970s concerning the internationalization of R&D. Most theoretical works which created the field (i.e. Buckley & Casson, 1976; Hennart, 1982; Rugman, 1981) have had dedicated sections for knowledge-creating activities of MNEs, which indicates the importance of R&D for theories of MNE as well as MNE business practices. Buckley and Casson (1976: 52) discuss in detail various stages of R&D activities and apply the concept of communication cost to location decision for each stage of R&D. Hennart (1982: 94–97) draws upon the work of the SPRU research group at the University of Sussex in the 1970s and describes the innovation process as the synthesis of various types of specialized knowledge, such as foreign MNEs' product and process knowledge marrying local producers' knowledge of material supply and market demand. Rugman (1981) reviews various studies in the 1970s, especially the pioneering investigation by Ronstadt (1978), and emphasizes the fact that most large MNEs operate highly centralized R&D facilities.

Notably, although knowledge creation, transfer and integration are found in the terminology of organizational and strategic theory discussion, most research designs and empirical observations actually focus on *knowledge flows*, or, more specifically, the inter- or intra-firm flows of knowledge. For instance, multilateral knowledge transfer within MNEs can be considered as intra-firm knowledge sharing and exchange, and the concept of knowledge flow further specifies the directionalities of transfer and clarifies the source and recipient of knowledge (Gupta & Govindarajan, 1991, 2000; Mom et al., 2007). Delineating different knowledge flows, therefore, presents a more realistic, structural and systematic view of MNE knowledge management. On one hand, knowledge inflows carry and deposit knowledge in knowledge-creating subsidiaries, which continue to recombine internal knowledge-based assets of the MNE with external knowledge-based assets acquired from host country sources

(Almeida & Phene, 2004; Schulz, 2003). On the other hand, knowledge outflows from knowledge-creating subsidiaries enable the sharing and leveraging of subsidiary knowledge within the entire MNE (Pearce, 1999b; Rugman & Verbeke, 1992, 2001).

As this thesis intends to study the efforts of IC design MNEs in global knowledge creation, transfer and integration, this chapter reviews previous empirical studies on knowledge-creating flows, which have developed and employed similar methodology and subsequently informed this research. Moreover, the semiconductor industry has been widely used as the sampling ground for localized knowledge flows, inter- and intra-firm knowledge flows as well as knowledge creation. In particular, the pioneering work by Saxenian (1996) has inspired a large number of studies looking into the networks of companies in Silicon Valley, their knowledge-sharing and collaborative nature. Meanwhile, the relatively high patent intensity and strong patenting records of companies in the semiconductor industry allow other researchers to conduct quantitative investigations. They have developed various patent data based measurements, or *patent metrics*, for constructs at geographical, organizational and personal levels. In particular, because the internationalization of the industry began as early as the 1960s and most leading companies initiated international R&D and manufacturing in the past few decades, the industry thus provides ideal samples for IB research (Phene & Almeida, 2008).

In this review, studies that directly motivate this thesis and inform its empirical research designs are summarized. The authors of these highly cited studies consider issues about sources of knowledge, knowledge flows and the potential impacts on knowledge creation. Whether economic, strategic or organizational—although the perspective may vary—these studies can be broadly categorized as firm-level, subsidiary-level and headquarter-subsidiary-level. Different emphases largely reflect the time background of studies and the changing research interest among researchers. This review is structured around these different emphases and is limited to those directly relevant to the empirical studies in subsequent chapters. The following sections first review earlier patent data studies on knowledge flows and subsidiary-level survey data studies, before proceeding to more recent patent data studies, which draw up the insights of these earlier works. The chapter ends with a discussion on the implications of these works for the empirical design of the analytic chapters of this thesis.

3.2 The validity of patent data research

The past two decades have seen an enormous wealth of patent data studies conducted with different foci, from economics and policy implications of IP to strategy, innovation, international business as well as organization studies. As this repertoire continues to grow, various researchers have also critically examined the reliability of patent information and validity of patent metrics. These efforts began decades ago and had been continuing to provide critical insights for current and future patent data studies ever since. This section reviews several of such studies on citation record, inventor information and others.

3.2.1 Citation records and knowledge flow

Jaffe and his coauthors developed some the most widely used patent metrics, of which many variations could be found. Based on the assumption that citations are informative of the linkage between patented innovations, Hall, Jaffe, and Trajtenberg (2001) suggest that backward citations (citations made) may constitute a paper trail for spillovers and knowledge flows between patents. Forward citations (citations received) on the other hand may suggest the importance of the cited patent (Jaffe, Trajtenberg, & Henderson, 1993). Moreover, self-citations refer to citations to previous inventions patented by the same assignee rather than patents by unrelated assignees. Self-citations likely represent internalized transfer of knowledge, whereas citations to patents by external inventors indicate knowledge diffusion or spillovers.

Jaffe et al. (1993: 583) address a number of validity issues concerning the use of patent citation count as the proxy measure of knowledge flows. Firstly, unlike academic references, which may contain gratuitous citations, patent citations are based on the knowledge of inventors and the expertise of patent examiners. In fact, gratuitous citations in patents may reduce the granted scope of monopoly and damage the financial returns for patent inventors. Secondly, examiners may indeed add citations unknown to patent inventors and introduces noise into patent citation count as a proxy measure for spillovers. This examiner practice can bias test results away from significant findings. Thirdly, because spillovers are by definition unintended economic externalities, intended citations to partner or alliance companies are not spillovers. Fourthly, at least regarding spillovers studies, the implication of self-citation is not clear. Finally, an enormous amount of spillovers is not documented and recorded by patent citations.

Jaffe and his coauthors have also used qualitative evidence to address the validity issue of patent metrics. To triangulate and have more balanced view, Jaffe, Trajtenberg, and Fogarty (2000a, 2000b) survey inventors of both the citing and cited patents who tend to have a different perspective on patent citations. Based on interviews with patent attorneys, R&D directors, and inventors for a project on the commercialization of federal lab technology, inventors are found most knowledgeable about R&D spillovers mechanisms and therefore most suitable subjects for a questionnaire survey. These interviews also suggest that patent citations are a noisy but potentially valuable indicator of the importance of the technology as well as the extent of knowledge spillovers.

Jaffe et al. (2000a) report the result of a survey on 1,306 patent inventors, including citing patents granted in 1993 and cited patents between 1985 and 1993. Inventors of citing patents are asked about two patents, which they cite, and a third, which is similar but not cited. In the meanwhile, the cited inventors, picked from either of the two citations, are asked about their communication with the citing inventors and their judgment of the likelihood—through actually reading the citing patents—that the citing inventors have utilized the knowledge in the cited patents. According to 166 usable responses from citing inventors and 214 from cited inventors (72 are matched pairs), affirmative reporting is shown to be statistically greater among the cited patents than the control. One-half does not seem to suggest perceived communication or even a perceptible technological relationship between the inventions. However, this does not exclude the possibility of other forms of communication that bypass inter-personal communications.

To clarify the implication of examiner citations—citations added by patent examiners as potential source of noise for patent metrics, Alcácer and Gittelman (2006) analyze US patents granted between January 2001 and August 2003 and find that examiner citations largely track applicant citations in geographical pattern, one of the main topics in knowledge flow studies. Their findings to some extent confirm the reliability of patent metrics based on citation information but raise another validity issue. Applicant citations were added by some patent attorneys who were previously patent examiners.

Moreover, based on a randomly-selected sample of 1,456 patents and 16,095 citations, Alcácer and Gittelman (2006) have several notable findings. Firstly, inventors may strategically suppress self-citation to previous inventions from a previous job and leave it to examiners to find those citations in order to avoid signaling inter-firm knowledge transfer and the danger of IP litigation. Secondly, citations to older patents are more likely to be associated with patent applicants than with examiners. This implies that average citations lag would become larger if examiner citations were excluded. Thirdly, patent applicants tend to include citations covering greater technological scope than would examiners, who specialize in specific technological fields. Hence, when both applicant and examiner citations are included, analyses may indicate more same-class citations and technology search in greater depth.

Alcácer, Gittelman, and Sampat (2009) analyze the backward citations of 429,984 US patents granted between 2001 and 2003, and find that examiners account for 63% of citations in an average patent and 40% of patents only contain examiner citations. A higher percentage of examiner citations on a patent is associated with examiner experience level [+], the computers and communications industry [+], the electrical and electronic industry [+], assignee experience [+] and foreignness of assignee [+], especially those from Asian countries. Moreover, as variance decomposition analysis on examiner citation percentage reveals, among the 36% explained variation, assignee effects explain 91%, while examiner effects only explain 9% and technology categories 8%. When the sample is restricted to experienced assignees with at least 1000 patents, the distribution shifts to 87% assignee effects, 13% examiner effects and 18% technology categories, among the 28% explained variation. Their finding suggests that assignee effect accounts for almost all the explained variation in the share of examiner citations (Alcácer et al., 2009: 423).

3.2.2 Inventor information

Bergek and Bruzelius (2010) review the validity of using co-patenting—patents by co-inventors from multiple countries—as an indicator of international R&D collaboration. By the taxonomy of Archibugi and Michie (1995), co-patenting records include both international technological collaboration between firms and international generation of technology by subunits of common ownership, such as MNE subsidiaries, although organization structure and managerial challenge also vary between MNEs. Previous studies assume the authenticity of inventor residence information and some degree of organizational separation between the inventors in an international collaboration. Bergek and Bruzelius (2010), however, argue that a small percentage of inventors may yet work and live in different countries, relocate amid patent application processing or rotate temporarily during R&D collaboration.

They conduct interviews with the Swedish inventors of 53 patents (44 are international) assigned to ABB, a renowned Switzerland-headquartered MNE in electrical equipment with rather frequent cross-country patenting. Of these patents, 83% indeed involve international cooperation between inventors in different countries, including 68% confirmed as international cooperation within the firm, although the exact form of cooperation and how close inventors are working together are less clear. Only 15% of these patents are the result of collaboration between independent organizations. A small percentage resulted from activities less relevant to R&D, such as patent application writing or industrial services. In brief, cross-country patents remain a reasonably good indicator of international activity but only in the case of intra-firm international collaboration.

Their research also provides important insights on the country of origin of innovations. Among four frequently used approaches to attribute a patent to its country of origin—first inventor, majority counting, fractional counting and multiple counting, first inventor approach and majority counting seem most in line with the self-reporting from interviewed inventors. The distribution of inventors' country of residence is also consistent with the locations of ABB's main subunits. In particular, the residence information of first inventors is often prioritized when attributing patented inventions (Cantwell & Piscitello, 2002), which is also the approach currently adopted by the USPTO in generating patent statistics.

3.2.3 Value of patents

Griliches (1990) reviews a number of earlier patent data studies, which address the rate of technical and scientific progress and the changes over time, across industries and across national borders. Despite the technical challenges to group patents by industry and product and the intrinsic variation in patent value, economists have analyzed the technological development of industries, inter-industry technology flows, technology spillovers and other related topics. Regarding the reliability of patent metrics, he suggests that differences in patentability, patent propensity and intensity may vary by industry and firm size. Moreover, researchers can mitigate the variation in patent quality by aggregating a sufficiently large number of patents, assuming the random distribution of economic significance of individual patents. Although the association between patenting and profitability is less clear, patent data are simply unparalleled in terms of quantity, accessibility, flexibility and potential industrial, organizational and technical details (Griliches, 1990).

Hall, et al. (2001) review some of the validity issues of patent data. Firstly, some inventions are not patented because they fail to meet the patentability criteria of the USPTO—*novelty, non-triviality* and *commercial application*. Secondly, some inventors may have strategically decided not to patent their inventions but rely on secrecy or other means of appropriability. Thirdly, due to patent process times, truncation problems—missing data—increase approaching the end of a time series. Hence, it is advisable to keep a 3-year safety-lag and to include year fix-effects in empirical models. Fourthly, among almost 3 million patents granted between January 1963 and December 1999 and over 16 million citations made to these patents between 1975 and 1999, 50% of citations are at least 10 years older than the citing patent, 25% are at least 20 years older, and 5% are at least 50 years older. Notably, self-citations show much shorter backward citation lags, and the average self-citation rate is between 11% and 13.6%.

They also discuss the metric properties of generality and originality measures proposed earlier (Trajtenberg, Henderson, & Jaffe, 1997: 26). These Herfindahl-style variables are calculated as:

$$\text{Originality}_i = 1 - \sum_{j=1}^{J} \left(\frac{N_{ij}}{N_i}\right)^2 \qquad \text{(Equation 1)}$$

where $Originality_i$ is the originality measure of patent i, N_i is the total number of backward citations made by the patent, and N_{ij} is the number of backward citations made to each class j. In addition, the calculation of $Generality_i$ is based on a similar equation with forward citation counts. Because of the integer nature of observed citation counts and the positive correlations between both measures and N_i, both measures may be biased downward when the N_i is small. In particular, the right truncation problem of forward citations exacerbates the bias in the measurement of patent generality. Therefore, with several distributional assumptions, Hall et al. (2001) propose an adjustment based on N_i for both originality and generality measures:

$$\text{Adjusted Originality}_i = \left(\frac{N_i}{N_i - 1}\right)\left(1 - \sum_{j=1}^{J}\left(\frac{N_{ij}}{N_i}\right)^2\right) \qquad \text{(Equation 2)}$$

Besides metrics generated from citation records, IP litigation is a direct indicator of patent value, which sort out the property rights of patent assignees in courts. Hall and Ziedonis (2007) compile a sample of 547 patent litigation events, which involve 136 semiconductor companies between 1973 and 2001. They find that a firm's probability of being involved in litigation in a year is associated with firm size: number of employee [+], R&D expenditure per employee [+], patent yield: ratio of firm patent stock to R&D expenditure, including a separate dummy variable for IC design company [+]. The significant finding on R&D expenditure per employee, which measures the importance of knowledge-based assets to firms, also reflects the point raised by Alcácer and Gittelman (2006). They suggest that companies may patent more aggressively when employee mobility is a channel for knowledge leakage. Moreover, Hall and Ziedonis (2007) point out that IC design companies are more likely to be involved in litigation due to the fact that knowledge assets are central to their business model.

Researchers have also used qualitative evidence to verify the value of patents. Reitzig (2003) consults a panel of technical and marketing representatives, which evaluates the value of 127 individual patents from a semiconductor company. Test result suggests that the value of a patent is determined by its importance for current [+] and future research [+], difficulty to invent around [+], and whether it provides the basis for other patents of the firm [+]. Bessen (2008) identifies valuable patents by checking whether a specific patent is renewed through the payment of renewal fee. Based on a sample of 56,816 US utility patents, he finds that patent values are significantly associated with entity change—change in assignee size and ownership [+], litigation record [+], reissued record [+], backward self-citation count [+], claims [+], forward citation count [+], squared forward citation count [-], generality [+] and originality [-].

Lastly, Odasso, Scellato and Ughetto (2015) provide a comprehensive review of previous studies and measurements of patent value, ranging from patent renewals, market value estimations, surveys of inventors and assignees and bibliographic indicators. Their empirical analysis is based on patent auction records but suffers from a small sample and selection effects. After controlling for inverse Mill’s ratio, the closing price of the 390 patents in 223 patent lots successfully sold is found associated with number of claims [+], average numbers of backward citation [-] and forward citation [+]. They suggest that the negative effect of higher backward citation count is due to lower radicalness of patents, which affects the likelihood of litigation and licensing from third parties. However, their other findings show that both average numbers of backward citation and forward citation are positively associated with the patent seller’s offer price, which may imply a disparity in patent evaluation between transaction parties.

Finally, Di Minin and Bianchi (2011) study R&D internationalization and intra-firm knowledge based a mixed-methods approach. They analyze US patenting records of four leaders in the wireless telecom industry—Ericsson, Motorola, Nokia and Qualcomm—and show that their most critical, standard-setting R&D projects tend to stay in the headquarters, despite the general trend of R&D internationalization during the 1990s. Their interviews with top managers in research, standardization and IP management reveal the appropriability concern of these firms, which encourages R&D centralization and close coordination between R&D and centralized IP management. Their conclusion confirms the importance of patenting in technology-intensive industries. Moreover, as their interviewees point out, efficiency gains from R&D decentralization are often offset by the costs of technology transfer, research personnel training, coordination between geographically-separated research teams, unintended knowledge dissipation and other organizational complexities.

3.2.4 Heterogeneous patenting behavior

Almeida, Song, and Grant (2002) use patent citation data to investigate cross-border knowledge building of firms and different subunits. They argue that patent and patent citations are valid measurements for knowledge building particularly for the semiconductor industry, because (1) every major player worldwide in the semiconductor industry patents extensively for their inventions created worldwide, and (2) the use of citations is applied uniformly across firms regardless of nationality.

The heterogeneity issue affects the validity of patent metrics. Therefore, some researchers suggest patent-based measures are only applicable to technology intensive and patent-intensive industries (Neffke & Henning, 2012). While the claim is subject to verification, the industry contexts of these industries do seem to promote patenting more often than others do. For example, according to ESA and USPTO (2012), the computer and peripheral equipment industry and the communications equipment industry have the highest patent intensities at 277.5 and 264.8 respectively, calculated by the number of patents per 1000 employees in the 5 years between 2004 and 2008. The patent intensities of several other industries—semiconductor and other electronic components (111.6), other computer and electronic products (108.5), navigational, measuring, electro-medical, and control instruments (96.1), and basic chemicals (80.2)—are in the group that is closely behind and remains far beyond the average of manufacturing industry of 25.5.

The survey study by Cohen, Nelson and Walsh (2000) reveals, respondents in the medical equipment industry and the drug industry suggest that patenting can effectively protect more than 50% of their product innovations, although process innovations seem more difficult to protect. Moreover, Hall and Ziedonis (2007) show that IC design companies are more likely to be involved in patent litigation than other semiconductor companies do. In brief, these industry- and firm-level heterogeneities have been less addressed in earlier multiple industry studies, especially when researchers compile and analyze large samples indiscriminately.

3.3 Patent data and inter-firm knowledge flows

At a time when most firm-level IB studies were conducted with financial data, survey and interviews, the use of patent data emerged from economists tracking and analyzing knowledge flows with patenting records. Accounting based R&D expenditure and intensity indicate the commitment of corporate resources on R&D, and patent data based measurements essentially reflect the outcome of knowledge-creating activities (Ketchen, Ireland, & Baker, 2013). Although both are widely used as archival indicators of firm-specific knowledge-creating activities, patenting records have the advantages of extended longevity, regular and open availability, and consistent and nuanced detail (Pavitt & Patel, 1988). Patenting records, which chronicle knowledge creation at the piecemeal level, can also be aggregated by individuals, firms, countries and other levels of analysis (Griliches, 1990). In addition, patent data also have better coverage of inventions generated by small enterprises without R&D divisions, from production line engineering as well as other less organized technological activities (Patel & Pavitt, 1991). This section briefly reviews some these studies, which have deep impacts on subsequent application of patent data in IB studies.

3.3.1 Locally bounded knowledge flows

Jaffe, Trajtenberg, and Henderson (1993) compare the geography of forward citations with that of cited patents to investigate the extent to which knowledge spillovers are geographically bounded. In response to Krugman's view on knowledge flows, Jaffe et al. (1993: 578) point out that knowledge flows do sometimes leave a paper trail in the form of patent citations made to technological antecedents. Subject to a number of limitations to be discussed later, the residence information reported in patent documents allows researchers to follow these trails. They compile a dataset based on the patenting records of universities and top corporations in 1975 and 1980, respectively. The 1975 patent cohort contains about 950 patents and about 4,750 citations by the end of 1989; the 1980 patent cohort contains about 1,450 patents and about 5,200 citations by the same time. Their analysis shows that university patents receive more forward-citations but fewer self-citations, and that 1980 patents are cited earlier and more often. In all cases, close to 60% of citation-pairs have the same patent classes, and around 70% of citation-pairs (excluding self-citation) are from the same countries. In addition, their research design for testing localized knowledge flows is based on the matched sample method, which rules out other unknown sources of agglomeration effects, such as the nature of technology and the timing of citation.

Similarly, Jaffe and Trajtenberg (1998) study the localization of knowledge flows through geography, institutional setting and technology space and, particularly, the fading of localization over time. They compile a dataset consisting of three parts: 1.5 million corporate patents granted between 1963 and 1993 with primary inventors in the US (65%), the UK (5%), France (4%), Germany (10%) or Japan (17%), 1.2 million citing patents granted between 1977 and 1994, and 5 million pair-wise citations between citing and cited patents. Their analysis of patent-pairs across different times and countries suggests (1) citations are more likely and sooner to occur between patents of same assignees, (2) citations are around a hundred times more likely between patents in the same classes, (3) citations are 30-80% more likely and sooner to occur between inventors residing in the same countries, (4) citations show clear country-specific tendencies and time trends, and (5) in addition to outward diffusion over time, knowledge also gradually becomes obsolete.

3.3.2 Knowledge flows in the semiconductor industry

Following the work by patent economists, Almeida and his coauthors conducted a series of empirical studies on the semiconductor industry, which are highly relevant to this thesis. Almeida and Kogut (1997) use both patent and geographic data for their study on the innovative ability of small firms in the semiconductor industry, specifically the exploration of technological diversity and integration within local knowledge networks. They first conduct a broad search in semiconductor patent classes for patents applied in 1985 and forward cited by more than 10 other patents. An expert panel of two electrical engineers was invited to screen these patents by titles, abstracts and the patent documents if necessary. This search in semiconductor patent classes, as specified by the USPTO, failed to identify any patent assigned to small start-ups and can only be conducted for large semiconductor companies. Hence, secondly, they instead identify all patents assigned to 176 semiconductor start-ups formed between 1977 and 1989, according to Dataquest database. 57 of them show patenting records with 3 or more patents. From these patents, the 20 most cited patents filed in 1985 are identified and included in the sample of innovations by semiconductor start-ups. Close examination of these patents reveals that they are not in the semiconductor patent classes defined by the USPTO. Apparently, major startups' innovations belong to different technological fields from those dominated by larger firms.

Moreover, by plotting the location of semiconductor plants (fabs) throughout the US, Almeida and Kogut (1997) identify 18 main regions of semiconductor activity, among which the Silicon Valley area and the New York-New Jersey-Pennsylvania area (NY-NJ-PA) are the most important regions in terms of both numbers of plants and employment. The rest include the Boston 128 corridor; Austin, Texas; Los Angeles, California and Arizona. They also analyze the localized knowledge flows in 12 of these 18 regions, which account for more than 95% of highly cited semiconductor design patents. They exclude self-citation and adopt the matched sample approach, which is based on a control sample of uncited patents in the same patent classes and on the nearest application date.

Firstly, with the local matches between the focal patent and the uncited control patent as the baseline, the percentage of the focal patent and forward citations in one region was found significantly higher, especially in the case of small start-ups. However, that knowledge flows were more localized among small start-ups (33.71% of 264 forward citations) than other firms (19.72% of 147 forward citations) might have resulted from the fact that 55% of the 176 start-ups in the sample were located in Silicon Valley between 1977 and 1989. When restricted to Silicon Valley, both small start-ups (53.80% of 158 forward citations) and other firms (52.9% of 34 forward citations) show higher localization. Secondly, knowledge seeking by start-ups was investigated by the analysis of backward citations to other firms and other start-ups. The result suggests that backward citations to start-ups are much more localized (70.73% of 41 backward citations) than those made to other firms (26.91% of 223 backward citations). Almeida and Kogut (1997) explain, these start-ups are connected with each other and with large semiconductor companies, but large companies are further connected to their counterparts in other regions, even in Japan. Lastly, patenting records of large companies and start-ups suggest that larger companies seem to concentrate their technological activities in more established fields, according to the range of patent classes. For instance, established firms like Intel, Motorola, Toshiba and Siemens dominate the technological fields relating to the microprocessor and dynamic random access memory (DRAM) technologies, while smaller firms are more active in the areas of Application Specific Integrated Circuits (ASICs), Gallium Arsenide and analog ICs (see Chapter 5).

The matched sample and expert panel approaches used by Almeida and Kogut (1997) are quite rigorous but subject to critical limitations. Firstly, they could only analyze a very small number of patents, as limited by the capacity of the expert panel. If more large company patents were covered, the conclusion concerning technological concentration in a limited range of technological fields might be reversed. It is likely that large companies are more likely to diversify with relatively abundant resources and wider access to knowledge sources. Secondly, the criterion of 10 forward citations set for the 20 important patents is simply arbitrary. In fact, it should also be judged by the expert panel. Thirdly, since most of the start-ups only have trivial patenting records, their patents and properties of derived patent metrics may not be comparable to those of large firms. Despite similar average forward citation counts, the forward citations of these two sets of sampled patents may have different implications.

3.3.3 Early patent data studies in IB

A critical difference between studies on MNE knowledge creation and studies on innovation, in general, is the specific focus of the former on the internalization and administration of knowledge flows, which links various external and internal knowledge sources and enables the global creation, transfer and integration of knowledge. Sharing the interests of patent economists in the development of national economies and large corporations, researchers in the field of innovation policy and IB began to use patent data in the late 1980s. Patel and Pavitt (1991) analyze the international concentration of technological activities of the 686 world's largest manufacturing companies and their patenting records between 1981 and 1986. Despite considerable variation across firms, Patel and Pavitt (1991) generate aggregate statistics by computing the percentage of patents invented outside the MNE home country. Aggregated by MNE nationality, the percentages of international patenting are mostly under 15%, although the percentages for the Netherlands and Switzerland seem exceptionally high. Instead, MNEs headquartered in United States, Japan and Western Germany—the three countries with most considerable technological activities—tend to source knowledge only domestically. In most cases, the internationalization of technological activities has stayed far behind that of manufacturing activities. While the managerial and policy implications of this home-boundedness remain disputed, it is clear that most MNEs are not 'stateless corporations'.

Cantwell (1995) conducts a longitudinal patent data analysis based on US patents assigned to 287 companies of various nationalities between the 1920s and 1990s. He identifies the location of inventive activities and country-origin of each patent by the residence of individual inventors. It was found that the country origins of a significant number of patents are indeed associated with the location of R&D facilities that generated these patents. This location information is further aggregated by countries to measure the degree of R&D internationalization. Among these largest US and European enterprises, the percentage of foreign R&D in total corporate technological activities reaches 7.91% in 1920-1939 and 8.08% in 1940-1968 before rising to 14.52% in 1969-1990. Although a small number of companies and those headquartered in several European countries have made significant progress in R&D internationalization, the majority have shown only mild increase over three-quarters of a century. On summarizing his observation, Cantwell (1995) concludes that the home country has remained the single most important knowledge source for the technological development of most companies. As Hymer (1960) and Vernon (1966) have rightly assumed, home country operations stand at the pinnacle of MNE hierarchy as the base for geographically concentrated and technologically sophisticated production (Cantwell, 1995).

To investigate the geographical and sectoral distribution of MNE technological activities in Europe and their potential to access, transfer and use knowledge in cross-border networks, Cantwell and Janne (1999) analyze the 1969-1995 patenting records of largest European companies in 14 European countries and regions. Patenting records are compiled according to corporate family information in 1984, classified by country origin, categorized in 18 technological fields, and then grouped by the home and host countries of corporate assignees. Group RTA index—defined as a group's (firms of the same nationality) share of all US patenting in a technological field, relative to its share of all US patenting in all fields—is calculated to provide a technological profile of each group. An explorative cluster analysis of profiles clusters these national groups by similarities in technological specialization and thereby provides an overview of the similarities between the technological activities in home and host countries. For instance, in the chemicals and pharmaceuticals industrial group, German MNEs have differentiated technological activities in home and host countries. Similar findings were reached among Swedish and Swiss MNEs in the metal products and mechanical engineering industrial group and Dutch MNEs, Philips in particular, in the electrical equipment and computing industrial group. In addition, a series of multiple regressions analyses is also conducted to verify whether the RTA of the subsidiary group is affected by the RTA of the home country group and the RTA of other firms in the host country.

Cantwell and Piscitello (2002) use the same database to analyze the 1969-1995 patenting records of the 784 largest industrial companies in the world in 1982. It is shown that, from the perspective of MNEs, the most popular European host countries in 1991-1995 for R&D activities include Germany (28.87%), the United Kingdom (21.15%), France (15.60%) and Italy (6.46%). As they examine around one hundred domestic regions in Germany, the United Kingdom and Italy, they found that both MNEs and local firms had concentrated R&D activities in specific regions in Southeast UK. The same pattern was found in Lombardia, Italy but not in Germany.

Cantwell and Piscitello (2002) also specify a negative-binomial regression model to verify a series of variables as the determinants for the number of patents granted to MNEs in specific regions over the period of 1969-1995. They include in their model agglomeration effects: industry-specific spillovers [proxied by (1) industrial patents granted to local firms in the region], local knowledge externalities: external sources of knowledge [proxied by (2a) government R&D expenditures, (2b) government R&D personnel, (2c) R&D personnel in the in higher education, (2d) full-time students, (2e) full-time students in higher education], localized inter-firm technological presence [proxied by (3a) mean share of each firm’s patenting divided by standard deviation of share of each firm’s patenting, (3b) localized industry-specific spillovers and (3c) their interaction term as localized inter-company cluster-based spillovers], general purpose spillovers [proxied by (4a) mean share of patenting in each technological field divided by standard deviation of share of patenting in each technological field, regional technological specialization measured by (4b) RTA index in 56 technological fields], and (5) local market size proxied by the GDP per capita and industry dummies. These studies provide examples of how patent data can be used in the firm- and country-level research.

3.4 Survey data and subsidiary-level studies

While patent data became popular in studies on inter-firm knowledge flows and MNE knowledge creation, which consider MNEs as a whole, survey data were more frequently used in subsidiary-level studies. These studies investigate the changing role of subsidiaries and look into the inner knowledge dynamics of MNEs. In this stream, researchers use questionnaires to measures various organizational aspects of MNEs and the properties of MNE corporate networks. The use of patent data in subsidiary-level research only became possible with the research design convened by pioneering survey data research and with the novel patent metrics developed in organizational and strategic literature. This section reviews several key studies based on survey data before continuing to further discussion on patent metrics.

In his study of 55 foreign R&D units of seven US-based MNEs, Ronstadt (1978) reveals that 37 of these R&D units, more than half, mainly transfer knowledge from the headquarters in order to support foreign manufacturing units. A minority of 9 units, mostly acquired, develop new products and processes for the local market and own managerial and technological capabilities, which are recognized by headquarters managers. Managers in these units are capable of identifying investment opportunities new and distinctive to MNEs. Headquarters' recognition of subsidiary-level capabilities permits the relocation of knowledge-creating activities abroad and projects of considerable size and scope that utilize local knowledge sources. Finally, another 9 units purport to develop new product and processes or explore new technological fields for MNEs. Although the large majority (93%) of these R&D units were located in advanced economies in the Western Europe and Canada, his research design becomes the basis of subsequent studies on subsidiary evolution and knowledge creation.

Papanastassiou and Pearce (1994) summarize the findings of the Pearce and Singh survey, in which 211 MNEs of various nationalities reveal varying statuses and attitudes toward R&D internationalization. In particular, 81.5% of Japanese MNEs and 69.9% of US MNEs reported their increased emphasis on globally-integrated R&D networks. Pearce (1999b) conducts another survey study on 812 subsidiaries in the UK manufacturing sector. Among 184 responses, 35.9% reportedly focus on developing, producing and marketing new products adding to their corporate groups in the United Kingdom, European or wider markets. Regression analysis on 174 responses from the same dataset further suggests that such a focus is associated with the tendency to employ subsidiaries' own R&D labs as a source of technology (Pearce, 1999a).

Pearce and Papanastassiou (1999) analyze a sample of 48 foreign R&D labs in the United Kingdom in various industries. Excluding missing responses, 81.6% of these R&D labs are greenfield investment, and 76.5% account for less than 10% of the overall R&D expenditure of the parent MNEs, which are headquartered in the US, Japan and Europe. More labs are focused on applied research, which commercializes basic research from the MNE, and on development, which creates products for particular markets. Their finding suggests that market competition, industrial technology capability and scientific personnel in the host country (UK) were the main intentions behind the establishment and expansion of these labs. Noticeably, 73.9% of responding labs point out that their increasing role within the MNE motivates the labs' future growth. Moreover, these labs report that their role with the firm can be negatively affected by the external financial situation (53.2%), the internal financial situation (74.5%), headquarters' decision to reallocate R&D work (70.2%) and rationalization in response to market conditions (59.6%).

Based on responses from 374 subsidiaries of 75 MNEs headquartered in the US, Europe, and Japan, Gupta and Govindarajan (2000) verify the determinants of knowledge flows between a focal subsidiary, the headquarters and peer subsidiaries. The value of subsidiary knowledge stock and transmission channels were found positively associated with knowledge outflows from a focal subsidiary to peer subsidiaries and the MNE headquarters. Transmission channels were found positively associated with knowledge inflows from peer subsidiaries and from the headquarters. Motivational disposition and absorptive capacity were found negatively associated. In brief, although the actual measurement for each construct varies by each case and becomes questionable sometimes, the value of subsidiary knowledge stock and transmission channels are the most common determinants of multilateral knowledge transfer within the MNEs.

Birkinshaw (1996) conducts a series of interviews with managers in 40 Canadian subsidiaries of US MNEs. His mixed-methods approach shows that mandated subsidiaries tend to be more specialized and have more proven capabilities. He emphasizes that the subsidiary need to prove its capabilities to the headquarters before moving to more substantive responsibilities. Birkinshaw, Hood, and Jonsson (1998) survey 673 manufacturing subsidiaries in Canada, Scotland and Sweden. With 180 usable responses, partial least squares regression analysis shows that the contributory role of a subsidiary (the percentage of subsidiary revenue gained from international responsibilities and world mandates) is associated with subsidiary initiative, leadership, and autonomy and headquarters-subsidiary communication. Moreover, subsidiary initiative is associated with a subsidiary’s specialized resources—defined by its overall capabilities in R&D, manufacturing, marketing, managing international activities, innovation and entrepreneurship relative to other subsidiaries of the corporation. In particular, Birkinshaw et al. (1998) refine the earlier findings of Ronstadt (1978) and Birkinshaw (1996), suggesting that the headquarters’ recognition of subsidiary capability is indirectly associated with the contributory role of the subsidiary and the effect is mediated by subsidiary initiative, measured by the pursuit of market opportunities internal or external to the MNE corporate system.

Frost, Birkinshaw, and Ensign (2002) survey 780 foreign-owned manufacturing companies in Canada. Among 99 usable responses, those with recognized research competence and development competence are found younger and less involved in product flows, including both internal and external sales. They also report receiving more investment from parent firms and more influence from external organizations on competence development. The influence from external organizations is measured by the respondent’s assessment of the impacts of customers, suppliers, competitors and external research institutes on the development of subsidiary competencies.

Kuemmerle (1999) studies 156 R&D labs owned by 32 MNEs of 5 different nationalities by examining firm archives and conducting questionnaire surveys and interviews with senior managers. These R&D labs, partially or wholly owned, operate in 19 host countries and in the pharmaceutical and electronics industries. His survey results suggest that the majority (81) of these labs are solely focused on projects that support foreign manufacturing facilities or product localization, but around a third (56) intend to absorb knowledge from competitors and universities in host countries. He terms the former home-base-exploiting and the latter home-based-augmenting, while the home base refers to the main R&D site in the headquarters (Kuemmerle, 1997). Logit regression analysis shows that differences between target country and home country in national R&D intensity [+], industry-specific exports [+], GNP [-], number of Nobel laureates [+] and percentage of population with tertiary education [+] are associated with the likelihood that an R&D lab has home-base-augmenting activities.

Cantwell and Mudambi (2005) survey 601 MNE subsidiaries in the UK engineering and related industries. With 225 usable responses and supplemental data from company annual reports and the UK government, they argue that competence-creating mandates (product development, international strategy development) are associated with (1) location variables: RSA-1 (Development Area under the Regional Selective Assistance Program), RSA-2 (Intermediate Area under the Regional Selective Assistance Program), subsidiary sales and variance of subsidiary return on capital, (2) subsidiary variables: subsidiary strategic independence (supplier decisions, hiring decisions, marketing decisions, and top management team), export share, export duration, geographic scope, process decisions and training decisions, (3) MNE group variables: acquisition entry, diversification, parent nationality dummies (US, JP). They also control for external focus (export share, export duration, and geographic scope), abnormal return on capital, duration of subsidiary operation, and industry dummies. Significant results are found for RSA-1 [-] and subsidiary strategic independence [+].

Moreover, based on the assumption that subsidiary competence-creating mandate and subsidiary R&D level were determined sequentially, Cantwell and Mudambi (2005) test two-stage models with instrumental variables and Heckman selection. LR tests (significant improvement in model fit over one-stage models) and significant coefficient estimates for inverse Mills ratio (hazard rate) confirm the correction for model endogeneity. Significant results were found for subsidiary sales [+], variance of subsidiary return on capital [-], acquisition entry [-], diversification [-] and subsidiary competence-creating mandate [+]. In particular, they also find that competence-creating subsidiaries have higher R&D intensity and that their patents are more likely to be cited in patents of other members of the MNE group. This may imply that the purpose of R&D activities is more aligned with the MNE group than local parties in host countries.

3.5 Patent metrics and knowledge flow studies

Jaffe and his coauthors convened some most widely used patent metrics of which many variations could be found. Based on the assumption that citations are informative of the linkage between patented innovations, Hall, Jaffe, and Trajtenberg (2001) suggest that backward citations (citations made) may constitute a paper trail for spillovers and knowledge flows between patents. Forward citations (citations received) on the other hand may suggest the importance of the cited patent (Jaffe et al., 1993). Moreover, self-citations refer to citations to previous inventions patented by the same assignee rather than patents by unrelated assignees. Self-citations likely represent internalized transfer of knowledge, whereas citations to patents by external inventors indicate knowledge diffusion or spillovers.

Hall et al. (2001) also point out several general trends in patent citation counts since late 1960s: (1) the average number of citations received per patent (forward citations) in their first 5 years has been rising over time, (2) the average number of citations made per patent (backward citation) has been rising over time, and (3) the observed citation-lags of older cohorts have flatter distributions. Possible explanations for the mechanisms underneath these trends include growing patenting, an increasing rate of innovation, and a growing stock of patents, or simply artificial changes in patent examination practices.

Accordingly, two approaches are suggested to correct for these trends. One is the fixed-effects approach, which rescales citation counts by dividing them by group means of yearly group, technological field group and year-field group. The downside of the approach is that it removes from the data variance components of potential interests as well as those attributed to truncation and artificial aspects of the citations generation process. Under additional assumptions, the alternative quasi-structure approach which is based on econometric modeling imposes a structure on the data generation process and allows identification of different sources of variation, including cited year-effects, citing-year-effects, field-effects and citation-lag-effects (see Hall et al., 2001: 31).

3.5.1 Subsidiary-level studies with patent metrics

While survey data research is often limited by sample size, single respondent, low response rate and reliability of measurement, the features of patent data allow researchers to overcome some of these problems. The consistency, abundance and public availability of patenting records allow users of patent data to analyze intra- and inter-firm, cross-border and longitudinal knowledge flows and knowledge creation.

Besides his work on inter-firm knowledge flows, Almeida (1996) also investigates the local learning and contribution of MNE subsidiaries in the US semiconductor industry. He first identifies 22 foreign semiconductor companies from the UK, Canada, France, Germany, Italy, Japan, Korea and Taiwan, which have patented in semiconductor-related technological fields. A random selection of a maximum of three design and three fabrication patents filed between 1980 and 1990 for MNE subsidiaries comprises a sample of 114 patents. Then, a domestic set of 114 patents is generated with patents assigned to US semiconductor companies in the same patent classes and subclasses, same geographic regions and similar firm size. Then, the backward citations of these domestic patents can be contrasted with those of subsidiary patents in terms of their location distributions. Finally, based on the backward citation list of the 114 subsidiary patents, a matched control group is generated with same patent classes and nearest application time in order to verify whether subsidiary patents contain more local backward citations than with the control group. Their finding suggests that innovations by MNE subsidiaries rely more on local knowledge (local citations account for 13.8% of 622 backward citations with the control group at 9%). This percentage is also significantly higher than domestic firms (10.5% of 674 backward citations). Almeida (1996) therefore suggests, learning-oriented FDI may be necessary if production and knowledge flows are confined within spatial boundaries. In addition, also based on the matched sample approach, the forward citations of these subsidiary patents are also significantly more localized (local citations account for 14.6% of 301 backward citations compared with the control group at 7.3%).

Almeida, Song, and Grant (2002) use patent citation data to investigate cross-border knowledge building of firms and different units of a firm. They first employ an MNE sample of 146 subsidiary patents from 21 MNEs, which have patented in the US as well as their home countries (Japan, Taiwan, Korea, Singapore, Italy, France, Germany, the Netherlands, and the UK). Secondly, they employ an alliance sample of 146 domestic unit patents (in the same patent classes) of US companies, which have had strategic alliances with the 21 MNEs but no subsidiary in their home country. Thirdly, they construct a market sample of 146 control group patents with the same classes and application year as the patents in the two other samples. The control group patents belong to US companies, which had no formal links to MNEs nor subsidiaries in their home countries. With self-citations excluded, they find that citation links from host to home country are most frequent in the MNE sample, less frequent in the alliance sample and minimal in the market sample. They also apply negative binomial regression, which is more suitable to analyze event occurrences in violation of the equidispersion assumption of the Poisson model. Coefficient estimates suggest similar results. Their model controls for the number of forward citations in the first five years and the number of patents filed by parent MNEs in the first five years since the filing of the focal patents. The result suggests that MNEs are more likely to make backward-citations to home country patents than alliances.

Developing from on his dissertation, Frost (2001) seeks to explain the geographic origin of the technical ideas embodied in the innovations of US subsidiaries of non-US MNEs. Laboriously excluding patents associated with acquired subsidiaries and self-citations, he analyzes the backward citations (home country, host country and host state) of 10,589 patents issued between 1980 and 1990 and invented by inventors located in the US, the host country of these MNEs. He tests three different logit models with binary dependent variables indicating the origin of cited patent: MNE home country and host country (or state), each could be the knowledge sources of MNEs.

Independent variables for the separate models [home/host] include (1) adaptation of HQ technology: whether a subsidiary patent cites any headquarters patent [+/-], (2) technology leadership of subsidiary: subsidiary's share in firm-wide patenting by technical field and application year [-/+], (3) home country is advantageous in the technological field: home country RTA in the technological field is greater than 1 during the application year [+/], (4) host country is advantageous in the technological field: host country RTA in the technological field is greater than 1 during the application year [/+], (5) Host state is advantageous in the technological field: host country RTA in the technological field is greater than 1 during the application year [/+], (6) innovation scale of subsidiary: logged number of subsidiary patent count by application year [-/+], (7) subsidiary age: logged number of days between subsidiary’s first-time patent application and the application date of the focal patent [-/+], (8) parent presence in host country: logged number of host country patents by other subsidiaries of the same MNE in the same year [-/+], (9) geographic control based on matched sample approach: an uncited patent of the same technological field and application year, and (10) fixed-effects for home countries, years and five broad technological areas (chemicals, drugs and medical technology, electronic arts, mechanical arts, and other).

With a rather large sample size, significant results are found for all variables except for subsidiary age. Patents by mature subsidiaries are found more likely to cite home country than host country patents. As this implies that older subsidiaries are more likely to draw upon home country sources, Frost (2001: 120) suggests that some mature subsidiaries may have maintained the same technological orientations with headquarters instead of evolving toward local stimuli and resources. In terms of limitations, he mentions the model convergence problem of the severely unbalanced data panel, because most subsidiaries do not patent during the entire period. However, the analysis also neglected the difference in patent intensity across industries and firm-level heterogeneities, such as firm size, R&D intensity, degree of internationalization, R&D internationalization, and capabilities among others. In addition, it is unclear whether robust or cluster-robust standard errors were estimated in response to the hierarchical data structure.

Despite room for improvement, this research by Frost (2001) has been pioneering in the combination of patent data and subsidiary-level studies, which creates a new path for MNE knowledge transfer research. Notably, although Frost (2001: 110) has mentioned the earlier studies by Almeida (1996) and Jaffe et al.(1993) as the methodological precursors to his work, the logic behind his research design is more similar to aforementioned survey studies, such as the research by Gupta and Govindarajan (2000) on knowledge inflows into a focal subsidiary. The study also pioneered the use of patent matrices to measure subsidiary characteristics. In addition, the matched sample approach is less common in studies on organizations. In these studies, research design has shifted to using subsidiaries as the main level of analysis in empirical analyses, while the matched sample approach is meant to control the heterogeneity of patents.

In addition, Frost (2001: 110) also mentioned the study by Mowery, Oxley, and Silverman (1996), who analyze inter-firm organizational learning among alliance partners. As one of the breakthrough patent data studies in strategy, Mowery et al. (1996) have applied patent metrics to study cross-border knowledge flows and inter-firm learning. However, before the further discussion on their analysis, it is necessary to review works that develop relevant patent metrics.

3.5.2 More recent knowledge flow research

Beyond the focus on subsidiary knowledge sourcing in the host country, Frost (2001: 113) also hints that his future work would examine directly patterns of intra-firm patent citations as a way of studying internal transfers of knowledge within multinational firms. Including his subsequent works, the research design and insights of some more recent works have greatly influenced the empirical design of this thesis.

Frost and Zhou (2005) argue that R&D co-practice—intra-firm joint technical activities—increases absorptive capacity and social capital between participating units and thereby improves the likelihood of future knowledge sharing through reverse, subsidiary-to-headquarters knowledge integration. They analyze the US patenting records of 104 MNEs (68 in automotive, 34 in pharmaceuticals), which have received more than 30 patents and whose subsidiaries account for more than 10 patents. These 104 MNEs, covering 14 home and 19 host countries, received 49,091 patents between 1975 and 1995.

They test the dependent variable reverse knowledge integration, which equals one if any headquarters to subsidiary citation was observed in headquarters-subsidiary dyads in a given year. The main explanatory variable, R&D co-practice, is the number of joint-patenting instances between headquarters and subsidiary inventors in the past 5 years. They explain the choice of a 5-year moving window over one-year lag is due to the difficulty in modeling the relationship between joint technical activity and the growth rates of shared knowledge (absorptive capacity) and inter-unit relationships. Control variables include acquisition entry; subsidiary age: year since first filing; subsidiary resources: subsidiary patent count weighted by forward citation count with 10% depreciation rate; headquarters resources; geographic distance and cultural distance; industry dummy; home country dummies and host country dummies. The calculation of subsidiary and headquarters resources with depreciation is based on the following function:

$$\begin{aligned}\text{Subsidiary resources}_i \\ &= \left[\left(\sum q\right)(1-\delta)\right]_{t=T} + \left[\left(\sum q\right)(1-2\delta)\right]_{t=T-1} + \cdots \\ &+ \left[\left(\sum q\right)(1-T\delta)\right]_{t=0}\end{aligned}$$

(Equation 3)

where q is a measure of patent quality derived from patent forward citation counts, δ is the depreciation rate, t is current time period and T is total time length of observation. Binary logistic regression (Logit regression) on 4,588 dyads shows highly significant effects for R&D co-practice [+], acquisition [-], subsidiary age [+], subsidiary resources [+] and headquarters resources [+], although findings from the 1,009 dyads of the automotive industry are less clear.

Frost and Zhou (2005: 684) attribute this mixed finding to sectorial difference due to the fact that pharmaceutical MNEs engage in more headquarters–subsidiary joint technological activities and generate more reverse citations. Moreover, in the pharmaceutical industry, acquired subsidiaries are 50% less likely than greenfield subsidiaries to be utilized by headquarters as a knowledge source. On the other hand, the effect size in the automotive industry is actually much larger: a unit increase in R&D co-practice is associated with 27.1-37.1% increase in the odds-ratio of reverse citation, whereas the percentage is only around 5% in the pharmaceutical industry. A unique contribution of this study is that the authors intentionally analyze headquarter-subsidiary citation and co-patenting, and their observations imply that the role of R&D co-practice may systematically differ between industries.

The seminal work by Rosenkopf and Almeida (2003) also has several direct impacts on the empirical design of this thesis. They analyze dyadic knowledge flows between 74 semiconductor companies between 1990 and 1996. In a sample of 992 patents and 4,560 citations, each citation is treated as one instance of the focal firm drawing upon the knowledge of the cited firm. They find significant effects of (1) technological similarity: Euclidean distance between the patent class profiles of two firms during 1980-1989 [-], (2) geographical similarity which is 1 when both firms are in the same state or same foreign country [+], (3) alliance [+], (4) personnel mobility between firms [+], (5) interaction terms of similarities with alliance and mobility [+]. Control variables include firm age [-], number of employee [+], knowledge stock of focal firm: propensity to cite measured by patents counts during 1990-1995 [+], knowledge stock of cited firm: propensity to be cited measured by patents counts during 1980-1989 [+], and the citability: exposure variable calculated as total forward citation counts between the focal and cited firms [+].

3.5.3 Measurement of technological similarity

Rosenkopf and Almeida (2003) point out that alliances are more than twice as likely and inventor mobility is more than five times as likely when the dyadic technological similarity between firms is higher than average. To compute dyadic technological similarity from firm’s patent class profiles, they first draw 10 patents from its patent stock from 1980 to 1989 or later, compute the percentage distribution across the patent classes covered, and use the percentage series as a vector profile. This distance measure varies between 0 when patent class vectors are identical and 1.4 when the two vectors are perpendicular. Their measurement of technological similarity is closer to the technological proximity in Garcia-Vega (2006: 236), which is used in this thesis to measure the knowledge distance between subunits (see Chapter 7). It however differs from the common citation measurement of Mowery, Oxley, and Silverman (1998), where technological similarity increases with the degree to which two firms cite the same patents.

Mowery et al. (1996) also suggest measuring technological similarity by backward citation records. Based on the citation patterns of alliance partners, Mowery et al. (1998) examine whether alliance partner selection can be predicted by inter-firm technological overlap and whether alliances affect firms' technological portfolios. Two measures were proposed to indicate the acquisition of technology-based capabilities from alliance partners, the extent of inter-firm knowledge transfer and the technological overlap between partners (Mowery et al., 1996, 1998). Firstly, the cross-citation rate is calculated by the following equation:0

$$\text{Cross citation rate}_{(i,j)} = \frac{Backward\ citation\ count_{(i,j)}}{Total\ citations_{(Firm\ i)}} + \frac{Backward\ citation\ count_{(j,i)}}{Total\ citations_{(Firm\ j)}}$$

(Equation 4)

where *Backward citation count*$_{(i,j)}$ is the number of backward citations in patents of firm *i* to patents of firm *j*, and *total citations count*$_{(i)}$ is the total number of backward citations across all patents of firm *i*. The same applies to the second part of the equation. An alternative measure for technological overlapping is based on common patent citation rate calculated by the following equation:

$$\text{Common citation rate}_{(i,j)}$$
$$= \frac{Common\ backward\ citations\ _{(i,j)}}{Total\ citations_{(i)}} + \frac{Common\ backward\ citations_{(j,i)}}{Total\ citations_{(j)}}$$

(Equation 5)

where *Common backward citations* $_{(i,j)}$ is the number of backward citations in patents of firm *i* to patents that are also cited by patents of firm *j*, and *total citations count*$_{(i)}$ is the total number of backward citations across all patents of firm *i*. The same applies to the second part of the equation. The common citation rate measures the degree to which both firms draw upon the same external patent pools, therefore exhibiting their higher degree of technological overlap (Mowery et al., 1998). In a sample of 229 companies in 151 alliance firm-pairs (at least one is a US firm), significant findings are mostly based on common citation rate. Joint venture partners show significantly higher levels of technological overlap than non-partners; technological overlap between joint venture partners increases significantly after alliance formation; moreover, at a moderate significance level, partners of international joint venture show greater technology overlap than joint ventures of only US firms. That last finding is particularly interesting in the sense that that partner selection in international joint ventures is to a greater extent affected by technological overlap.

In order to simplify the analysis of intra-firm knowledge flows, this thesis adopts the more straightforward measurement based on patent class profiles (see Chapter 7). However, the discussion here implies that the use of patent metrics can be contingent on specific research design, and test results can be subject to the specific choice of patent metrics.

3.5.4 Knowledge flows and innovation performance

As Jaffe et al.(1993) notes, the granting of a patent makes a legal statement that the embodied idea in patent is a novel and useful contribution beyond the previous state of knowledge indicated by citations to prior art, and thus citations in principle represent pieces of previously existing knowledge on which the new idea is built. This section reviews a number studies, which explore the factors behind technological innovations of individual companies by empirically analyzing patenting and citation records.

In their seminal study on knowledge search, Rosenkopf and Nerkar (2001) use patenting and citation records to analyze the local search, boundary-spanning and exploration in optical disk industry. They first define (1) self-citations as internal knowledge search (external knowledge search otherwise), and (2) backward citations to optical disk patents as within domain knowledge search (across domain knowledge search otherwise). Along these two dimensions, they categorize each firm-year observation as internal boundary-spanning exploration (spanning the technological boundary), external boundary-spanning exploration (spanning the firm boundary), radical exploration (spanning both boundaries) and local exploration (spanning neither boundary). Four types of exploration are then operationalized with backward citation counts—self-citation, within-domain citation, self- and within-domain citation and neither. Lastly, the impacts of innovations are measured by forward citations (received by focal patents in 1989) within or outside the domain of optical disk technology. Based on a sample of 371 firm-years, their results suggest that adequate boundary spanning, either across firms or across technological fields, can raise the potential impact of patented inventions.

Almeida and Phene (2004) find that subsidiary innovation performance is affected by three factors—technological richness of the semiconductor MNE, technological diversity of the host country and a subsidiary’s knowledge linkages to host country firms. More recently, Phene and Almeida (2008) use patent data to gauge subsidiary capabilities associated with sourcing and combination of knowledge and find these two capabilities significantly affecting the scale and quality of innovation. Their research design and use of patent metrics in subsidiary-level research combine both previous firm-level patent data studies and survey data research.

From the dual network perspective, Almeida and Phene (2004) analyze patenting records of 58 MNE subsidiaries in 26 host countries between 1981 and 1992. These subsidiaries belong to 7 US MNEs in the semiconductor industry, and their sampled patents are in 20 broad technology classes, which cover 95% of the inventions in the industry. With subsidiary innovatory performance—number of successful patent application by subsidiary—as the dependent variable, they include in the empirical model (1) technological richness [+] and technological diversity [+] of the MNE knowledge base, (2) subsidiary knowledge linkage with the MNE—number of other affiliated subsidiaries cited by the focal subsidiary [+], (3) technological richness [+] and technological diversity [+] of the host country knowledge base, (4) subsidiary knowledge linkage with the host—number of host country firms cited by the subsidiary [+]. Control variables include subsidiary knowledge stock—subsidiary patent count in the past 5 years, subsidiary focus on knowledge exploitation—subsidiary self-citation count, subsidiary R&D intensity: R&D intensity weighted by subsidiaries' share in firm-wide patenting, firm total asset, firm debt-to-equity ratio, firm alliances: number of alliances in the past five years, host country GDP, and year dummies. All yearly continuous variables are computed with one year lag.

Based on an unbalanced panel of 374 subsidiary-years, positive significant coefficient estimates are found for MNE technological richness, host country technological diversity, subsidiary knowledge linkage with host country firms, and subsidiary R&D intensity. Specifically, richness and diversity measures are calculated by the following equations:

$$\text{Richness}_i = \frac{M_{i,t-1}}{T_{t-1}} * 100 \qquad \text{(Equation 6)}$$

where $M_{i,t-1}$ refers to the number of semiconductor patents applied by MNE i in year t-1 (or applied by inventors from host country i) in year t-1, and T_{t-1} is the total number of semiconductor patents applied in year t-1.

$$\text{Diversity}_i = 1 - \left[\sum_{k=1} f_{ik,t-1}{}^2\right]^{1/2} \qquad \text{(Equation 7)}$$

where $f_{ik,t-1}$ is the proportion of MNE i's patents (or patents by inventors from host country i) in semiconductor class k in year t-1. The measure is based on the assumption that the distribution of a firm’s (or a country’s) patent output reflects its emphasis on certain technological fields (2004: 854).

Almeida and Phene (2004) also test whether more capable and mandated subsidiaries utilize both MNE and host country knowledge resources more effectively in their innovation. They split the sample by whether subsidiaries had two or more patents in the past 5 years. In the split sample of 189 capable subsidiaries, significant positive effects are found for MNE technological richness, host country technological richness and diversity, subsidiary knowledge linkage with host country firms, and subsidiary R&D intensity. However, in the sample of 185 less capable subsidiaries, only MNE technological richness shows a significant positive effect. The result suggests that capable subsidiaries utilize both external and internal knowledge sources, while the less capable rely more on internal sources.

Phene and Almeida (2008) further explore the impacts of external and internal knowledge sources and subsidiary capabilities for knowledge absorption and utilization. With a sample of 240 subsidiary-year (26 subsidiaries, 6 US MNE and 12 years), they test the effects on subsidiary innovation scale (number of subsidiary patent application in a year) and on subsidiary innovation (total number of citations received by subsidiary patents within 6 years). Included in their models are (1) knowledge assimilated from the MNE headquarters: mean number of self-citations (per subsidiary patent) made to home country inventors [+], (2) knowledge assimilated from other MNE subsidiaries: mean number of self-citations made to other country inventors [+], (3) knowledge assimilated from host country: mean number of citations to host country inventors [+], (4) subsidiary sourcing capability: subsidiary patent count in the past 5 years using a perpetual inventory method with a 20% depreciation rate, and (5) subsidiary combinative capability: diversity of subsidiary knowledge sources [+]. Control variables include the adjustment for the general trend of increasing patenting activity, knowledge assimilated from other sources: the subsidiary itself, other firms in the home country, other firms in other countries, home-host culture distance, firm size: log of firm assets, firm R&D intensity. In order to avoid the danger of model endogeneity, all variables are computed with one-year lag except the adjustment variable. Subsidiary combinative capability is calculated based on the following equation:

$$\text{Combinative Capability}_i = 1 - \sum_{j=1}^{6} {p_j}^2 \qquad \text{(Equation 8)}$$

where p_j is the proportion of citations made by the subsidiary i to each of six mutually-exclusive knowledge sources—the subsidiary itself, the MNE headquarters, other subsidiaries in the MNE, other firms in the host country, other firms in the home country, and other firms in all other countries—in the last 5 years. The combinative capability measure varies between from 0 when all knowledge has been sourced from one single source to 0.83 when knowledge has been sourced equally from the six potential knowledge sources.

Random-effect negative binomial regression analysis shows significant positive effects for knowledge assimilated from host country, subsidiary sourcing capability and subsidiary combinative capability on both scale of subsidiary innovation and quality of subsidiary innovation. Noticeably, the random-effect estimator is usually more efficient but less appropriate for firm-level analyses, which are unlikely to satisfy the strong exogeneity assumption—all explanatory variables are independent of individual effects and error terms. To validate the random-effect model, Phene and Almeida (2008) perform the Hausman specification test, which compares the efficient estimates of fixed-effect and random-effect model and determines that the random-effect model is appropriate.

Based on the US patenting by 211 greenfield subsidiaries of 21 Swedish MNEs over the period of more than a century (1893-2008), Blomkvist, Kappen, and Zander (2010) investigate the longitudinal pattern of MNE subsidiaries entering technological fields new to the entire MNE group. These 211 subsidiaries are located mostly in advanced economies, including Germany (19), Switzerland (16), the UK (13), the Netherlands (13), Denmark (13), Finland (12), US (19), Canada (9), Japan (8), Australia (6), New Zealand (4), Mexico (3), South Africa (3) and others. They examine historical archives and digital databases to identify majority-owned greenfield subsidiaries, which have received at least one US patent, and time period of MNE ownership, name changes and mergers and acquisitions. Despite extensive data collection, it is acknowledged that limited availability of longitudinal data at subsidiary-level prohibits fine-grained measurement of various factors.

To model the phenomenon of interest—accelerated entry into new patent classes, Blomkvist et al. (2010) analyze the number of years between events—subsidiaries' first patenting and first patenting in an entirely new patent class. The main explanatory variable, or main covariate of the repeated events analysis, is then the number of prior entries. A number of control variables are also included, such as the size of the local market measured by GDP; industry dummies (automotive, material processing, pharmaceutical and chemical, and mechanical engineering); modernity dummy for subsidiaries established after 1980; internal network: number of innovative subsidiaries; technological diversity: other subsidiaries' entry into new technological fields; and culture distance. Significant effects are found for prior entries [+], the squared terms of prior entries [-], GDP [+], internal network [-] and technological diversity [+].

Regarding the unexpected last two findings, Blomkvist et al. (2010) argue that competition for resources may explain why the number of innovative subsidiaries shows negative effect while access to advanced technology shows positive. MNEs may rationalize their internationally dispersed knowledge structures by allocating fewer but more extensive subsidiary mandates and concentrate new technological initiatives in a small group of ''superstar'' foreign subsidiaries.

Carnabuci and Operti (2013) use patent data to test the concept of recombinative capabilities—a firm innovates by recombining existing technologies (Henderson & Clark, 1990; Kogut & Zander, 1992). They suggest that two types of such capabilities—recombinant creation capability and recombinant reuse capability—are associated with two underlying organization factors—the degree of integration of a firm’s intra-organizational (inventor) network and the diversity of its knowledge base. A high degree of collaborative integration enhances recombinant reuse capability, because integrated intra-organizational networks facilitate intra-firm transfer of sticky and dispersed knowledge in a timely fashion (Hansen, 1999; Szulanski, 1996). On the other hand, although shared knowledge is essential for communication and technological knowledge exchange within the firm, knowledge diversity facilitates innovation outside the firm’s existing repertoire by enabling novel combinations which could have been considered as risky moves by inventors specialized in similar technological area (Carlile, 2004; Cohen & Levinthal, 1990; Levinthal & March, 1993).

To test these hypothesized relationships, Carnabuci and Operti (2013) compile a sample of 127,094 patents assigned to 126 semiconductor companies in the 30 most popular patent classes between 1984 and 2003. Significant effects on recombinant reuse are found for collaborative integration [+], knowledge diversity [-], average cumulative combination [+], self-citation ratio [+], and current ratio [-]. On the other hand, significant effects on recombinant creation are found for collaborative integration [-], knowledge diversity [+], external ties [+], self-citation ratio [-], and current ratio—measure of slack resources [+]. Moreover, the interaction term between collaborative integration and knowledge diversity shows moderate to strong positive effect on both recombinant reuse and creation.

3.6 Discussion and conclusion

The empirical design of this thesis greatly benefits from both earlier patent data studies on inter-firm knowledge flows and more recent studies, which extend the use of patent data in organizational studies and intra-firm knowledge flows (see Chapter 6 and 7). Although more recent studies have more direct influence on the empirical analysis of this thesis, as this review shows, these studies have drawn upon earlier studies while adopting creative research design and patent metrics. The application of patent data in subsidiary-level studies provides a useful solution to data limitation, but it would not have been possible without three decades of patent data studies and survey research.

The use of patent data has been widely appreciated in economics and strategy studies, but what has been emphasized in this review is the importance of sufficient articulation and justification of research design according to specific research questions. In part, previous methodology studies have provided strong empirical evidence suggesting that controlling various heterogeneities in patenting records is necessary to model specification. For instance, the matched sample approach uses control group by specific criteria to control unknown heterogeneity. On the other hand, more recent studies based on sizable samples often include several series of fixed effects, which is also the approach adopted in this thesis. Both modeling strategies have advantages and shortcomings, yet both intend to address the heterogeneities across industries, firms, nationalities, time trend as well as individual inventors and technological fields. In other words, even though patenting records potentially allow for very flexible research designs and considerate sample size, inadequate articulation and justification of the research design leave any findings subject to scrutiny.

Meanwhile, patent metrics are increasingly based on complex formulae, which raise more validity concerns. Often, these more advanced measures adopted in more recent studies can be traced back to more basic measures proposed and verified in earlier studies. However, the metric properties and validity of these derived measures are unclear. In other words, although there is an increasing repertoire of patent metrics at modern researchers' disposal, validation of these derived measures based on patenting and citation records remains limited. The introduction and application of advanced patent metrics, therefore, can be problematic and arbitrary, especially in the case of measuring latent constructs, such as firm capabilities, technological distances, patent value and others. Researchers have also reported the technical challenges of data management and model estimation, while sophisticated patent metrics and research design exacerbate the issue and increase the difficulty in tracing the problem.

This review acknowledges the development of these advanced patent metrics but maintains the view that established, unsophisticated and straightforward measurements are preferred over novel yet less tested metrics of unknown metrical properties. The research design of this thesis, while following the approach established in recent subsidiary-level studies with patent data, maintains the principle of simplicity.

4 THE IC DESIGN INDUSTRY

4.1 Introduction

Research based on the semiconductor industry has been an important source of inspiration for policy and business studies. However, existing studies that explore knowledge flows in the semiconductor industry are mostly based on datasets collected in the 1990s. Since then, various changes have emerged as the industry moves toward higher maturity and further internationalization. The sources of FDIs are no longer concentrated in North America but dispersed globally. Companies in the present day semiconductor industry, especially those adopting the fabless business model, demonstrate a complex pattern of internationalization, which was unseen two decades ago and remains a rarity among most contemporary industries. Other companies in the global semiconductor business ecosystem have also developed highly specialized business models, including intellectual property (IP) core vendors, electronic design automation (EDA) companies, and specialized semiconductor logistics and distribution companies. All these developments leave an enormous gap in the empirical literature of the semiconductor industry.

While previous studies have examined the history and industrial policies involved in the development of the overall semiconductor industry in specific country locations, this chapter from the IB perspective examines the emergence of the IC design industry. The following sections provide a brief review of the global semiconductor industry and introduce the four popular semiconductor business models, which are frequently observed in the modern semiconductor industry. In particular, the features of the innovative IC design business models are explained in detail. Subsequently, the second half of the chapter introduces the research sample of this thesis—28 world-leading IC design MNEs. In the process to achieve global knowledge creation, these IC design MNEs have to varying degrees achieved R&D internationalization and administrated multilateral knowledge transfer between the headquarters, foreign subsidiaries and knowledge sources in various host country environments. More of the stories of these 28 companies will be further detailed in Chapter 5.

4.2 The semiconductor industry

Four decades ago, cutting-edge technologies of vertically-integrated semiconductor companies, or integrated device manufacturers (IDMs), drew the attention of technologists; more recently, the implication of leapfrogging scientific progress and national development led analysts to appreciate the manufacturing excellence of professional semiconductor foundries in newly-industrialized economies (NIEs). Since then, vertical specialization has overhauled the industry, finely slicing the creation of IC products into stages performed by various organizations in a global production network spanning countries and continents (Macher & Mowery, 2004), including specialized logistics companies linking these stages (Bhatnagar & Viswanathan, 2000).

Previous political economy and industrial research provide an extensive list of explanations for this trend towards vertical specialization in the global semiconductor industry. These explanations include government policy (Ernst, 2005a), US immigration policy (Brown et al., 2005), and defense spending (Langlois & Steinmueller, 1999), patent regime (Hall & Ziedonis, 2001), institutional environment (Linden & Somaya, 2003), design tool development (Brown & Linden, 2009), and technological factors (Ernst, 2005b; Macher & Mowery, 2004), among others. Moreover, Langlois and Steinmueller (1999) and Adams, Fontana, and Malerba (2013) suggest that demand-side change, such as the transition toward civil use of IC products, have influenced the trajectory of the semiconductor industry.

4.2.1 The growth of the modern semiconductor industry

The overall growth of the semiconductor industry has been phenomenal since the commercialization of semiconductor technologies in the 1950s, expanding by nearly thirty times between 1980 and 2010, while multiple booms and slumps have occurred in the recent history of the industry (Dicken, 2007). The two recent crises in 2001 and 2008 have both resulted in slumps in the industry. The most severe contraction is seen after the dot-com crisis in the early 2000s, which directly and severely affected the closely related semiconductor and information technology (IT) industries in general (see Figure 4.1). As shown in the figure, the industry took longer to recover a pre-crisis level after the 2001 dot-com crisis.

Figure 4.1 Global sales of the semiconductor industry, 1977–2014

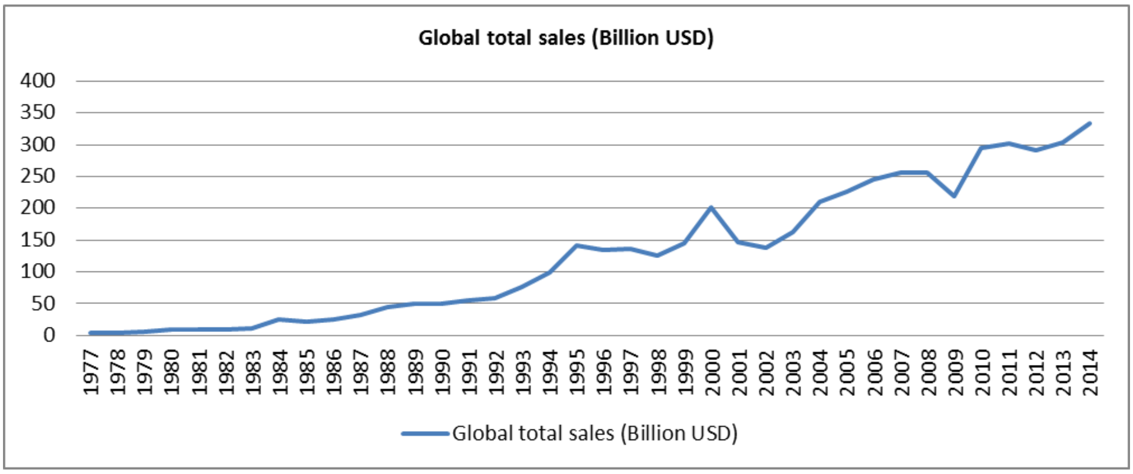
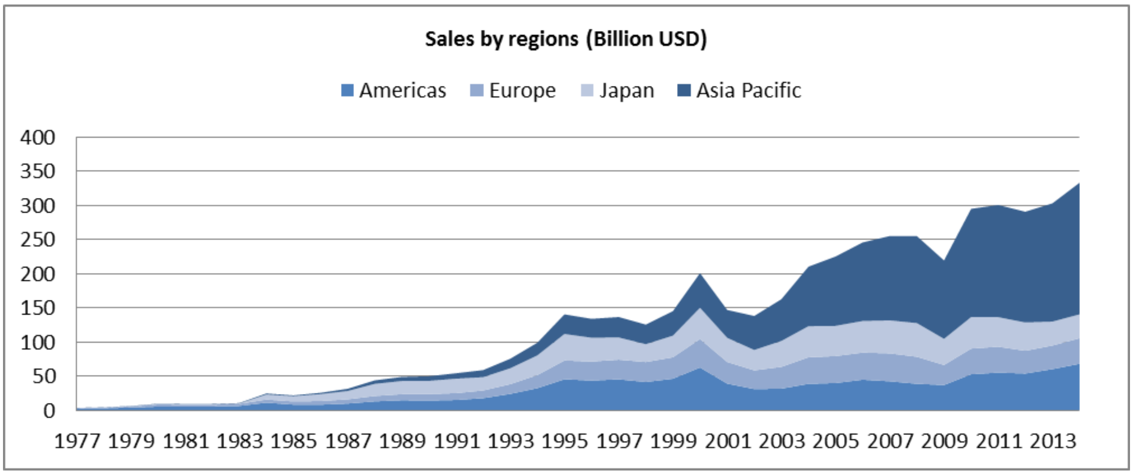


Figure 4.2 Global sales of the semiconductor industry, 1977–2014

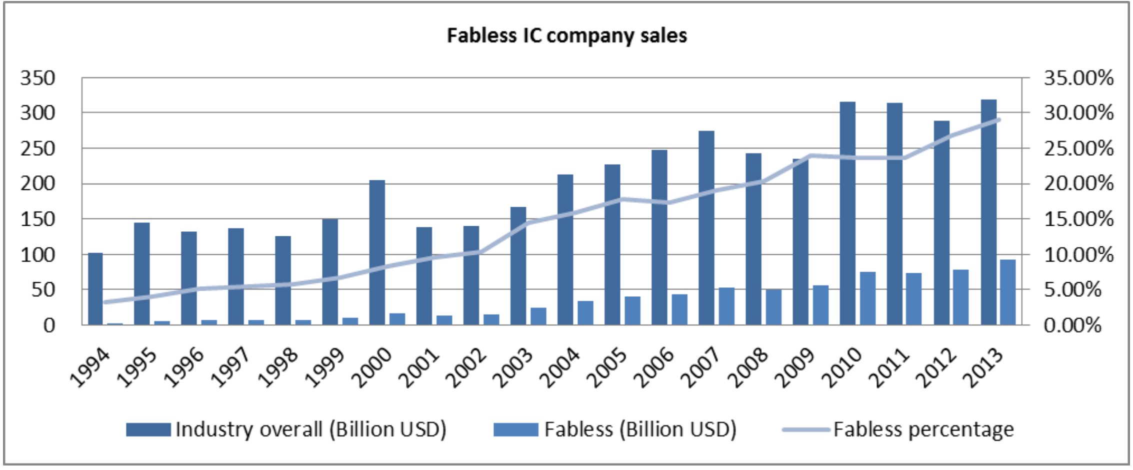


Note: The Semiconductor Industry Association (SIA) publishes the Global Sales Report (GSR), which is prepared by the World Semiconductor Trade Statistics (WSTS) organization. Source: Semiconductor Industry Association (http://www.semiconductors.org/industry_statistics/global_sales_report/)

On the other hand, since the early 2000s, the geographic segment in East Asia except Japan has outgrown and outweighed other regions which have remained stable (see Figure 4.2). Following the electronics industry, a gradual shift of geographical sales to the East Pacific has been observed since the mid-20th century. A number of leading semiconductor companies in the US have maintained a technological lead through technological and managerial innovations (Afuah, 1999). The gradual internationalization of the semiconductor industry largely follows the Vernon type of technological diffusion during the first decade of the 21st century. However, since then, the manufacturing sector in East Asia has created a strong local demand for IC products and many opportunities for IC design companies in the region.

Figure 4.3 shows worldwide sales data of the overall semiconductor industry and the fabless companies between 1994 and 2012. The figure reveals the growth of fabless companies and their increasing share in the entire semiconductor industry, representing a general growth of the fabless business model within the population of semiconductor companies since the 1990s. While significant declines in the worldwide sales of the entire semiconductor industry are observed in years following the dot-com crisis and the recent financial crisis, sales declines seem moderate among the fabless companies in the meantime.

Figure 4.3 Market size of global IC design industry 1994-2012

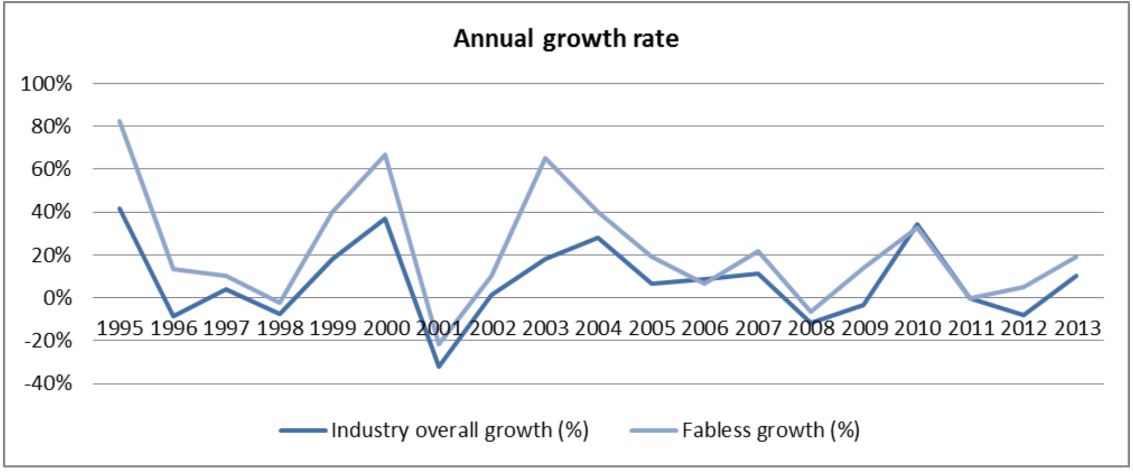


Source: Global Semiconductor Association
https://www.gsaglobal.org/gsa-resources/forecasts/actual-growth/)

As shown in Figure 4.4, during the period between 1994 and 2012, the growth rate of the fabless sector has clearly outpaced the entire semiconductor industry, although the dot-com crisis and the financial crisis have clearly affected both. In contrast with the severe contraction of the overall semiconductor industry in 2001, 2008 and 2009, overall sales of fabless companies have suffered much less and only brief stagnation ensued surrounding the crises before a fast recovery.

Notably, archival data nevertheless reveal intensive corporate restructuring, business model change and industry composition change right after both crises. The worldwide sales data do not show the structural changes within the semiconductor industry. As will be discussed in the following sections, these structural changes include vertical disintegration, entry and exits, mergers and acquisitions, and new sources of demands and new applications of IC products. In retrospect, both crises to some extent reshuffled the composition of the industry, welcoming restructured former IDM companies as well as entrepreneurs and start-ups.

Figure 4.4 Market size of global IC design industry 1994-2013



Source: Global Semiconductor Association
(https://www.gsaglobal.org/gsa-resources/forecasts/actual-growth/)

4.3 Modern semiconductor value chain

The semiconductor value chain, including at least product conceptualization, design, manufacturing, packaging and testing, warehousing and shipping, forms a sequential process involving both internal facilities and external suppliers. Main stages are further grouped by different specialization—design, fabrication and testing and packaging—and each imposes different requirements on capital, expertise, scale and infrastructure and has different degrees of internationalization (Browning et al., 1995). By extents of vertical integration and specialization, four business models are found in the center of semiconductor business ecosystem—integrated device manufacturing (IDM), fabless (IC design), professional foundry (Fabs) and the hybrid model (Hurtarte, Wolsheimer, & Tafoya, 2007; Macher & Mowery, 2004). Minor business models in the ecosystem include, at least, semiconductor IP core vendors which develop design blocks to be licensed and incorporated in IC products, electronic design automation (EDA) companies which supply software tools for IC design, packaging and testing companies, photomask manufacturers, equipment manufacturers, and suppliers of wafers and special chemicals and logistics and distribution companies among others.

Table 4.1 Features of the three sub-industries in the overall semiconductor industry

	IC Design	**IC Manufacturing (fabrication)**	**Packaging and Testing (assembly)**
Skill-intensity	High	Mid	Low
Capital-intensity	Low	High	Mid
Economic scale	Low	High	Mid
Internationalization	1980s	1970s	1960s
FDI investment	Two-way	Two-way	US to South-East Asia
Requirement on infrastructure	High or Low	High	Low
Notes	■ Three stages are identified in design workflow—specification, logic design, physical design ■ Design processes differ between digital logic and analog circuits ■ Team size varies by project complexity, schedule, and resources available ■ Coding of related software requires compatibility and time efficiency ■ Internationalization allows access to specialized skills, engineer-customer interaction and 24-hour work cycle, but raises	■ In the US, labor is around 16% of total costs including depreciation in 200mm fabs and less than 10% in 300mm fabs; labor costs for 200mm fabs are 8% in Taiwan and 3% in China ■ Internationalization mainly for market access concern caused by trade barrier (rising non-US markets) ■ Asian foundries facilitated the fast growth of IC design firms in the 1990s ■ More advanced fabs require more technicians and engineers and a	■ As the final stage of production, it is functionally separate from other stages ■ Product diversity hinders automation due to scale diseconomy ■ Packaging types vary by the specific requirement of IC designs to ensure heat dissipation and performance in specified work conditions, withstanding heat, vibration, shock, humidity and other environmental conditions. ■ Asian suppliers in numbers offer a large array of packaging

	managerial challenges ■ IC design companies may retain internal test and packing facilities for specialized IC products	higher degree of automation which reduces human error ■ Two-way investments between US, EU, Japan and several other Asian countries	types ■ Firms may favor in-house facility for technological concern and volume production

Source: The table is mainly based on Brown et al. (2005) and revised with additional data from this research.

4.3.1 Integrated device manufacturing (IDM) model

IDM is the traditional business model in the semiconductor industry that internalizes most activities, establishing extensive ownership and retaining control over most resources for IC production and in-house design teams (Hurtarte et al., 2007). IDMs were the dominant business model in the population of semiconductor companies in the early days of the industry (Macher & Mowery, 2004). Although many of the largest semiconductors by global sales retain the IDM business model, rather than an indicator of superior profitability or innovativeness, their respectable sales revenues are the necessary condition for monumental capital expenditures on a regular basis. Because the costs are growing exponentially to build and upgrade semiconductor production facilities and to develop and implement cutting-edge manufacturing processes, this requirement on capital investments raises a high entry barrier for the IDM business model.

According to industrial studies, IDM companies create competitive advantages by internalizing production. Firstly, ownership-based control guarantees the supply of manufacturing capacity for own products, of which production is prioritized and closely monitored. Facility ownership also makes directly accessible production line information, which is essential for improving product quality and decision making (Buckley & Casson, 1985; Casson, 1997). The internal access to both production capacity and information—which improves product performance, yield rates and delivery time—is ingrained in vertically integrated companies but raises a barrier for fabless companies (Brown & Linden, 2009: 103).

Secondly, intra-firm coordination between in-house designers and manufacturing engineers greatly expedites manufacturing process refinement and innovation (Balconi, 2002; Dibiaggio & Nasiriyar, 2009; Macher & Mowery, 2004). Shared corporate culture and technological language facilitate inter-unit communication and implementation of design (Macher & Mowery, 2004; Monteverde, 1995). The familiarity of IC designers with the capability of internal facilities also reduces the time and resources spent on design revisions and new product introduction (Cheng & Cheng, 2005; Kapoor, 2012).

Thirdly, firm-specific manufacturing processes can be developed and refined in internal facilities according to the requirement of in-house designers. Internalization permits such asset-specific investments, and proprietary technologies are protected against leakage. For instance, IDMs adopting a niche-market strategy may design and manufacture highly specialized IC products with proprietary technologies (Kapoor, 2013). These niche-market IC products have unique specifications and applications, such as those use in aerospace and defense industries. Similar investments in specialized manufacturing processes and equipment would instead cause asset-specificity concern for external foundries (Leiblein, Reuer, & Dalsace, 2002).

In summary, internalization of manufacturing confers advantages from internal coordination, which include internal access to capacity and information, superior coordination between design and manufacturing, and firm-specific manufacturing processes. As a result, IDM companies tend to have better product quality and shorter time-to-market than fabless companies in same product categories (Dibiaggio & Nasiriyar, 2009; Kapoor, 2012). Also, the internal transfer pricing for manufacturing is relatively stable, while external foundries usually adjust service fees by capacity utilization rates and seasonal fluctuation. IDMs can, therefore, better ensure the required volume and delivery time of own products during unanticipated demand surges and new product introduction, while the fabless competitors queue and require higher fees.

From the strategic point of view, vertical integration and asset-specific investments create the capabilities and competitive advantages of internal production and coordination (Argyres, 2011; Kapoor, 2013). Leading IDM companies continue to improve internal coordination and leverage superior financial and human resources to fill capability gaps (Linden & Somaya, 2003) and generate systemic innovations (Kapoor, 2013).

The IDM model was the dominant business model in the early days of the semiconductor industry (Macher & Mowery, 2004). Many leaders of the semiconductor industry by global sales have retained this vertically integrated model. However, rather than an indicator of superior profitability or innovativeness, their respectable scale and sales are the requirement for monumental and regular capital expenditures. Because of the exponentially growing costs of semiconductor manufacturing facilities and cutting-edge manufacturing process R&D, the requirement on financial resources has raised a very high entry barrier for the IDM model, while the economic scale for mass production becomes even more challenging to reach (Brown & Linden, 2009). Moreover, fixed-cost and asset-specific investments on internal production make IDMs inflexible in adapting to emerging market demand and technological discontinuity (Macher & Mowery, 2004). At such scale, unforeseen change in demand can result in severe losses and affect the investment plans for future production capability.

4.3.2 Hybrid model

Against the volatile market demand, the hybrid business model reconfigures the IDM model by offering idle manufacturing capacity during sluggish demand for own IC products and utilizing external capacity for excessive demand (Hurtarte et al., 2007). The hybrid model creates a buffer for internal production facilities of which high fixed costs demand high utilization rates to spread the average cost. Prolonged facility construction times further hinder swift adjustments of efficient output levels at a reasonable cost. In fact, companies adopting the hybrid model were the initial suppliers of manufacturing capacity for early IC design companies until the emergence of the professional foundry model in the 1990s (Macher, Mowery, & Hodges, 1998).

Hybrid companies also use external capacity for specific IC products with shorter commercial lifecycles and uncertain production volumes. Professional foundries with flexible manufacturing capability and diverse processes achieve high utilization rates by aggregating multiple manufacturing contracts (Brown et al., 2005). Some hybrids also outsource small batches from professional foundries to benchmark the performance difference between internal production facilities and external facilities operated by manufacturing service providers (Hurtarte et al., 2007; Puranam, Gulati, & Bhattacharya, 2013). In other words, the hybrid model essentially opens up IDM companies and installs flexibilities in response to volatilities in both market demand and production.

On the downside, the key features of both the IDM and hybrid models—inherent priority on production (Casson, 1997), close coordination and communication between internal design and production (Ernst, 2005a) and product standardization (Krishnan, Prioletta, & Karls, 1998)—limit the mobility of these companies which operate semiconductor foundries. When the market demand for IC products shifted towards commercial and consumer applications, such as with the electronics manufacturers in East Asia (Langlois & Steinmueller, 1999), proximity to major markets and access to specialized skills became the main driving forces for R&D internationalization (Brown et al., 2005). As semiconductor MNEs began to expand their global presence and establish subsidiaries that may detect, access and operationalize local creative potentials (Ernst, 2005a; Papanastassiou & Pearce, 2009), vertically-specialized business models offered innovative solutions and unprecedented flexibilities in response to emerging and increasingly diverse market demand.

4.3.3 Professional foundry model

The professional foundry model, also known as semiconductor fabrication (fab), is adopted by companies providing contract manufacturing services to both hybrid and fabless IC design companies. Although recent statistics suggest that the majority of their sales are associated with fabless clients (Peng & Chen, 2010), professional foundries usually avoid direct competition with clients and tend to be viewed as neutral (Hurtarte et al., 2007). Taking a rather supportive role, professional foundries concentrate resources on developing production capability, acquiring and upgrading production facilities and process technologies in pursuance of scale economies and manufacturing excellence.

Specialized foundry companies, which offer manufacturing capacity to both IDM and IC design companies, have developed flexible manufacturing capabilities and several strategies to manage demand volatilities (Casson, 2000; Guo, Su, Chiu, Pai, & Yeh, 2007). (1) While the demand of individual companies varies and fluctuates, professional foundries reach economic scale by aggregating demands from multiple clients. (2) Foundries regularly adjust the manufacturing service fees, according to material costs, inflation rates, facility utilization rate, manufacturing processes and the yield rate of specific IC products. These pricing strategies encourage clients to improve demand forecasts and product design processes and thereby economize service purchases. (3) Foundries typically impose a set of design rules specific to each manufacturing process, which allow IC designers just enough flexibility in creating designs, while facilitating the implementation of designs, ensuring yield rates and lowering unit costs (Dibiaggio, 2007; Macher, Mowery, & Simcoe, 2002). (4) Foundries often collaborate with main clients in developing advanced manufacturing processes. Such R&D collaborations improve production capabilities and inter-firm coordination experience. Due to the increasing complexity of modern IC design, such experience and development of a common language are of particular importance to companies adopting vertically specialized models (Ernst, 2005a).

Industrial analyses suggest that foundries typically have higher production costs relative to IDM companies due to additional investments in developing flexible manufacturing capability, diverse offerings of manufacturing processes and nonrecurring engineering costs for each IC design entering the production line (Krishnan et al., 1998). These features of foundries are nevertheless critical for the production of less standardized and more customized IC products—designed for specific applications and manufactured in small batches, which elude scale economy and are shunned by hybrid companies and neglected by IDMs.

Substantial and continuous capital spending on manufacturing process R&D, including collaboration with equipment suppliers, allow a small number of leading foundries to compete fiercely to introduce cutting-edge manufacturing processes desired by companies designing high-performance IC products and willing to accept a higher service charge. The world-class manufacturing capabilities of leading professional foundries enable fabless IC design companies to capture most of the benefits of scale without internalizing the production of IC products (Teece, 2007).

4.3.4 IC design model

Outsourcing manufacturing from hybrid and foundry companies allows IC design to deliver products to business customers but avoid committing managerial resources and capital investments in production facilities. Because of high switching costs and intensive inter-firm coordination, IC design companies tend to establish long-term relationships with specific professional foundries and design products by the design rules and manufacturing processes of these foundries. Using an unfamiliar or less mature manufacturing process raises the requirement on inter-firm coordination between the vertical specialists and becomes a disadvantage relative to the vertically-integrated IDM model (Macher & Mowery, 2004). Large and resourceful design companies may use longer-term supply contracts, collaborate with professional foundries on developing new manufacturing processes or even enter manufacturing and R&D joint ventures. Only in rare cases may IC design companies internalize production, seeking superior intra-firm coordination via intra-firm information flows and direct supervision (Buckley & Casson, 1985; Casson, 1997).

Fundamentally different from the vertically-integrated IDM model, the IC design model aims to profit from fragmented, heterogeneous and interchangeable demand. IC design companies concentrate on designing and marketing products for emerging market demand and utilize external service providers for production (Hurtarte et al., 2007). Longitudinal analysis shows that IC design companies have more volatile financial performance relative to the vertically-integrated companies (Brown & Linden, 2009). Fragmented and interchangeable demand defies the rationale of longer-term planning and resource commitment for internalizing production (Casson, 1997).

The overall market demand may come from the industrial machinery, consumer electronics, computers, telecommunications, automobile, instrument and aerospace and defense industries, but geographically much of the market growth is in the rapidly growing and increasingly sophisticated East Asian markets (Adams et al., 2013; Ernst, 2005a). Prospering electronics manufacturers in East Asia mostly lacked the IC design capability internalized by incumbents in the West and Japan (Fuller, 2014). Moreover, before the proliferation of modern consumer electronics, IC and other semiconductor products supplied for industrial, defense and aerospace applications had longer commercial lifecycles, stable demand and lower price sensitivity, and the consumer electronics market was dominated by vertically-integrated electronics companies and conglomerates (Langlois & Steinmueller, 1999).

Instead, IC products for modern consumer electronic devices are characterized by price elasticity, shorter lifecycles, fragmented demand and customization, and the arrival of personal media players, civilian navigation devices and smartphones further reinforced this trend (Brown & Linden, 2009: 81). Facing fierce competition, electronics manufacturers seek novel, customized IC products to achieve greater performance and functionality in devices with short delivery times, while minimizing product dimensions and power consumption. Therefore, besides the emergence of the complimentary foundry model, IC design companies only bloomed in the 1990s by offering innovative and highly-customized IC products to the fast-growing IT and consumer electronics industry (Macher & Mowery, 2004).

4.4 Customized IC design process

Customized IC design typically begins with a discussion with business customers about the functions and working conditions expected for a potential IC product—also known as specification-making (Brown & Linden, 2009). According to experienced engineers interviewed by the author of this thesis, the discussion involves sales representatives and project managers with technological backgrounds and intends to clarify the functions and working conditions expected for a potential IC product (see Note 1). The participants then decide the functions and components to be built into the design and generate a detailed specification for design (Hurtarte et al., 2007). Specification-making has a direct impact on the methodology, function and performance requirements for IC design, and the IC design firms able to do so would possess profound knowledge of overall system architecture, control over product implementation and strong market influence (Chang & Tsai, 2002). Thereafter, based on the initial specification, a team of engineers would start the selection of IC components, also termed as IP blocks, IP cores or design modules, mostly from the firm-proprietary intellectual property library (IP library) and sometimes from third-party IP core suppliers, which are external suppliers of reusable design blocks with a certain extent of proven usability.

This highly value-adding process synthesizes the designers' understanding of customer demand and end product industry, technological expertise, and experience in designing similar products, often involving joint problem-solving with the specific business customer (Chang & Tsai, 2002). McEvily and Marcus (2005) suggest that joint problem-solving arrangements, including information sharing and trust, may facilitate the transfer of insights, experience and capabilities between customers and suppliers. Following the specification stage, the logic design stage uses symbolic abstractions to describe how signals will be processed within the IC at the register and gate level, and physical design is the final stage that involves the translation of the abstract designs into the layout of actual wires and devices in multiple layers. The later stages of IC design, which are less value-adding and often rely on special automated design software packages, are often outsourced to other design service companies (Brown et al., 2005).

In addition, system-on-a-chip (SoC) IC products, the current business focus of most leading semiconductor companies including IDM and IC design companies, combine multiple design modules and functions and provide further cost, size and energy efficiency advantages for end electronic products (Chang & Tsai, 2002; Linden & Somaya, 2003). SoC IC products usually involve larger design teams spreading across countries and time zones (Ernst, 2005b), and the design process of SoC IC products is disproportionately more complex and resource-consuming.

4.4.1 Geographical proximity to customers

Specification making for IC design requires a thorough understanding of customer demand and thus benefits from proximity to customers, which facilitates interpersonal communication and the transfer of tacit knowledge. In contrast with vertically-integrated IDM companies, market knowledge is given a higher priority in the R&D activities of IC design companies. The concerns for time efficiency and accurate knowledge of market demand outweigh the concerns for knowledge dissipation besides the strength of patent regimes and professional foundry companies' implicit commitment to avoid direct competition.

Because of the flexibility in product offerings allowed by their business model, IC design companies can effectively incorporate market knowledge in their customized IC design, and to timely deliver specialized IC products in a small volume, which are deemed uneconomic by the standard of most IDM companies. The capability to substantially customize IC products for specific customer demand can be enhanced by the relative ease in setting up small design offices in proximity to business customers, especially the electronics manufacturers in East Asia (Ernst, 2005a). Essentially, market information is prioritized in IC design companies' knowledge-creating synthesis in order to create the new product. IC design companies have coined the term *design-win* for decisions of business customers to incorporate their IC products into the customers' end product, and proximity to customers is influential to the decision-making (Ernst, 2005a).

Time efficiency is another critical concern because each customized design needs to be verified, tested thoroughly, prototyped and revised several times before entering mass production expecting full functionality and an acceptable yield rate (Krishnan et al., 1998). According to one firm's archives (PMC-Sierra in this case), the design process from conceptualization to a viable prototype can take between 12 and 24 months, and additional 3 to 18 months to be designed into business customer's end products and sold in mass production. Other firms have reported 6 to 24 month from the customer's decision to use the product offering to high volume production of the end product (Broadcom). The time length varies by specific business model and product offerings. Some IP core vendors, which focus on developing and licensing reusable design modules but do not directly participate in IC fabrication, would expect different processes. For instance, ARM reported 9-15 months from licensing, delivery to acceptance, although the development of ARM IP cores can take years.

The process can also be longer because of customers' special demands on quality assurance. For example, an interviewee with experience in designing power management IC mentioned that IC products for vehicles usually require extra design time for extensive testing to ensure durability and safety (see Note 1). The time period varies by specific business models and product offerings, while standardized IC products are much faster (Krishnan et al., 1998).

Therefore, to secure a *design-win* for IC products, design companies would participate as early as possible in customers' product development process, while sharing costs and risks.

4.4.2 Foreign market and R&D internationalization

Earlier studies based on the entire semiconductor industry suggest that locally bound knowledge development influence many MNEs' location decisions on the establishment of knowledge-seeking subsidiaries, encouraging their location in these geographic areas to acquire the latest technological technology (Almeida & Kogut, 1999). However, more recent industrial studies suggest that costs and operational concerns may have a more direct impact on location decisions. Brown and Linden (2005) suggest that a competitive advantage in the semiconductor industry relies on the firm's IP repertoire as well as access to location-specific advantages in resources and markets for cost reduction and new demand. Almeida, Song and Grant (2002) suggest that semiconductor companies need closer relationships with their business customers in various industries, including computers, defense, telecommunications, and consumer electronics. Since East Asia has become the main geographical region of production to meet the worldwide demand for personal computers, consumer electronics, internet-enabled devices, home appliances and many other end products using IC products, the strategic consideration for proximity to market has been driving the internationalization of IC design activities toward this region (Ernst, 2005a).

In the mid-1980s, IDM companies began to set up foreign design offices and hire talented local designers and engineers to customize IC designs for local markets. IC design companies also followed in the early 1990s. For instance, US-based IBM and LSI established design centers in major European and Asian markets to facilitate interactions between engineers and business customers, while developing reusable IP cores in other locations with cost or skill advantages (Brown et al., 2005). Design offices, as well as fully functional subsidiaries in the region, allow semiconductor companies to spot market trends and facilitate close collaboration with their current and future business customers. This observation corresponds to the categorization of different knowledge-creating mandates proposed in the international R&D literature (Cantwell & Mudambi, 2005; Cantwell & Piscitello, 2014; Frost, 2001). As the geographical locations of design and manufacturing proliferate, semiconductor companies and the industry as whole may gain an advantageous position to access and integrate technological knowledge as well as market knowledge from various locations worldwide.

On the other hand, although both IDM and IC design companies actively establish foreign R&D centers, the distribution of nationalities of IC design companies differs from that of companies adopting more traditional business models. For instance, IDM companies mostly originated in the United States, Japan and other developed countries, and professional manufacturing foundries operate mainly in East Asia (Fuller, Akinwande, & Sodini, 2005). However, among the Top 25 IC design companies worldwide in 2011, more than half have their headquarters outside the United States (IC Insights, 2012). This distinctive pattern results partly from the lower entry barrier of a fabless business model. It externalizes manufacturing capacity and avoids hefty investments in semiconductor fabrication facilities and future expenditures in developing advanced process technologies, which are now undertaken by professional foundry companies. Due to the small dimensions and high unit costs of IC products, transportation and labor costs seem to be minor concerns for R&D internationalization (Brown et al., 2005).

At the industry level, relinquishing production facilities and becoming smaller in size and lighter in assets, the fabless IC design model creates both the flexibility to customize and differentiate products and the dexterity to enter new product categories and new locations. Brown et al. (2005) suggest internationalization creates competitive advantages in the semiconductor industry with access to location-specific engineering expertise, lower-cost skilled labor and market demand. However, despite significant benefits of proximity to customers, IC design companies have met difficulties in coordinating geographically separated design teams. Brown et al. (2005) report multiple managerial challenges of the decentralized IC design process from assigning tasks to time zone differences, language issues, cross-culture communication, performance evaluation, insufficiently trained local engineers and regular traveling of managers. Linden and Somaya (2003) point out that poor communication between design teams serving different markets leads to redundant design work on similar functions. These coordination issues suggest that decentralized knowledge creation should not only reflect the source of customer demand but also consider internal information costs and the coordination between different subsidiaries and the headquarters.

4.4.3 Semiconductor industrial clusters

It is important to recognize that the modern semiconductor industry is global in the sense that it globally links local industrial clusters. Saxenian (1996) pioneered the research on renowned industrial clusters in the semiconductor industry. She analyzes various social networks in the US semiconductor industry by comparing the development of the Route 128 area in Boston and Silicon Valley in California. The Route 128 region is home to a number of vertically-integrated companies (IDMs), which are typically enormous in size and capital and stay independent and isolated from each other. Thence, in the Route 128 area a general culture is developed that encourages those big corporations to pursue stability and self-reliance. While corporate hierarchy and centralized organizational structure ensure vertical information flows, clear boundaries exist between and within companies, and between companies and other external organizations.

In Silicon Valley, conversely, Saxenian (1996) identifies a network-based industrial system that promotes collective learning and flexible adjustment between companies in a dense social network. Through informal communication and collaboration, numerous companies compete while learning from one another about the changing markets and technologies. Organizational boundaries within these companies are permeable, as are the boundaries between companies and other local organizations, such as trade associations and local universities. Instead of being confined to individual companies, knowledge flows span across companies and external knowledge sources.

Following the work by Saxenian, Almeida and his coauthors conduct a series of empirical studies on knowledge spillovers in the semiconductor industry based on patent data. They identify a number of factors that locally bound knowledge flows. These factors include geographical proximity and embeddedness (Almeida & Kogut, 1997), knowledge seeking and creation by foreign semiconductor companies and their subsidiaries (Almeida, 1996), and the relationship between the mobility of inventors and localized knowledge flow (Almeida & Kogut, 1997, 1999; Rosenkopf & Almeida, 2003). Other researchers also look deeper into the networks and sociological aspects; for instance, Rowley, Behrens, and Krackhardt (2000) argue that networks and weak ties in the semiconductor industry enhance firm performance because weak ties tend to be the conduit for transmitting novel information (Granovetter, 1973). In brief, the semiconductor industry is highly characterized by knowledge and patent intensiveness, and by leaving public traces of intra- and inter-organizational knowledge transfer in patenting and citation records. These features make the industry an ideal sampling ground for the subsequent industry- and firm-level empirical research.

In the UK, according to Athreye (2002), the Cambridge area in England closely resembles Silicon Valley albeit on a smaller scale. Since the 1980s, the Cambridge area has developed a number of institutes, university-industry links and local technology venture capital firms that have assisted in the development of several science-based industries. Renowned examples include Acorn Computers, which was founded in 1978 and later created ARM, and the Olivetti Research Lab, which was established in 1986 with computer scientists from Cambridge University (Myint, Vyakarnam, & New, 2005). The lab later became Olivetti & Oracle Research Lab and generated a series of spin-offs. On the other hand, the semiconductor industries in Asian NIE countries and, more recently, China and India, have benefited from knowledge spillovers and spin-offs from US subsidiaries, varying levels of government policy support and the presence of related activities (Chang & Tsai, 2002; Fuller, 2014; Mathews & Cho, 2007). In particular, Brown et al. (2005) suggest access to lower-cost engineering talents and the emergence of local subcontractors, startups and spin-offs of MNE subsidiaries have stimulated the growth of IC design industries in China, India and Taiwan.

4.5 Research sample

In order to compile a representative sample of IC design MNEs, this research collected data from several industrial reports and online industrial news published in the past two decades and built a historical list of leading IC design companies in the 2000s. The starting point is the *Leading (Top) Fabless IC Suppliers* list published annually by IC Insights based on its reporting and estimation of fabless IC companies' worldwide sales in the previous year. Founded in 1997, IC Insights is a leading semiconductor market research company and publishes *The McClean Report*, which annually reports the technological trends, market development and the rankings of semiconductor companies in booklets and CD-ROMs. It provides analyses of the semiconductor industry, top performing and emerging companies, different IC product segments and geographical segments, development and utilization of process technologies, and general outlook and forecasts of the semiconductor industry. This source has been used in previous studies to identify prominent semiconductor companies (Hsu & Ziedonis, 2013; Ziedonis, 2004).

Recent issues of The McClean Report were perused, and additional information was gathered from company annual reports and other online industrial news outlets, such as CNET, EE Times, Solid State Technology, and Wired among others. Based on the information from these sources, the original rankings published by IC Insights were further augmented to address several issues, such as substantial gaps between estimated sales and the actual figures later reported in company annual reports. Cross-referencing between these sources helped rebuild a relatively complete historical list of top IC design companies, which led the IC design industry during the period between 2001 and 2008 (see Table 4.2).

Table 4.2 Historical list of top IC design companies 2000-2011

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	Xilinx	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm	Qualcomm
2	Altera	Nvidia	Nvidia	Nvidia	Broadcom	Broadcom	Broadcom	Nvidia	Broadcom	AMD	Broadcom	Broadcom
3	Qualcomm	Xilinx	Xilinx	Broadcom	Nvidia	Nvidia	Nvidia	Broadcom	Nvidia	Broadcom	AMD	AMD
4	Broadcom	VIA	Broadcom	Xilinx	SanDisk	SanDisk	SanDisk	Marvell	Marvell	MediaTek	Marvell	Nvidia
5	VIA	Broadcom	MediaTek	ATI	ATI	ATI	Marvell	MediaTek	MediaTek	Nvidia	MediaTek	Marvell
6	Cirrus	Altera	VIA	MediaTek	Agere	Agere	Xilinx	Xilinx	Xilinx	Marvell	Nvidia	MediaTek
7	Nvidia	Conexant	Altera	SanDisk	Xilinx	Xilinx	MediaTek	LSI	LSI	Xilinx	Xilinx	Xilinx
8	PMC-Sierra	Cirrus	ATI	Altera	MediaTek	Marvell	Agere	Altera	Altera	LSI Corp	Altera	Altera
9	SanDisk	ATI	Conexant	Marvell	Marvell	MediaTek	Avago	Novatek	Avago	ST-Ericsson	LSI	LSI
10	Lattice	MediaTek	SanDisk	Conexant	Altera	LSI	Altera	Himax	Himax	Altera	Avago	Avago
11	ATI	Qlogic	Marvell	VIA	Conexant	Altera	LSI	CSR	Novatek	Avago	Novatek	MStar
12	SST	PMC-Sierra	Qlogic	Qlogic	VIA	Conexant	Conexant	Avago	CSR	MStar	ST-Ericsson	Novatek
13	MediaTek	SanDisk	Cirrus	GlobespanVirata	Sunplus	Novatek	Novatek	Conexant	QLogic	Novatek	MStar	CSR
14	Qlogic	Lattice	ESS	Silicon Labs	Novatek	VIA	Himax	QLogic	Conexant	Himax	Atheros	ST-Ericsson
15	GlobespanVirata	Marvell	Realtek	Sunplus	Intersil	Sunplus	CSR	Realtek	MegaChips	Realtek	CSR	Realtek
16	ESS	ESS	Sunplus	Novatek	CSR	Himax	VIA	PMC-Sierra	Realtek	CSR	Realtek	HiSilicon
17	Semtech	GlobespanVirata	SST	Realtek	Silicon Lab	CSR	QLogic	DSP Group	PMC-Sierra	HiSilicon	HiSilicon	Spreadtrum
18	Sunplus	SST	GlobespanVirata	SST	SST	QLogic	Sunplus	VIA	Atheros	Atheros	Himax	PMC-Sierra
19	ICS	Realtek	Lattice	PMC-Sierra	Qlogic	Silicon Lab	Silicon Lab	Zoran	Mstar	PMC-Sierra	PMC-Sierra	Himax
20	Realtek	Sunplus	ICS	ICS	GlobespanVirata	SST	PMC-Sierra					Lantiq
21		Semtech	PMC-Sierra	Lattice	Zoran	Solomon	SST					Dialog Semi.
22		Ali	Genesis Microchip	Ali	SiS	SiS						Silicon Labs
23		ICS	Novatek	Zoran	Solomon							MegaChips
24			Silicon Image	SMSC	Himax							Semtech
25			Ali	Genesis Microchip	PMC-Sierra							SMSC
26			Semtech		Realtek							
Industry total (Billion USD, Source: IC Insight)												
	17.0	**15.1**	**16.8**	**21.3**	**28.7**	**34.5**	**41.1**	**43.8**	**43.8**	**49.3**	**63.5**	**66.5**

Notes: 1. The table lists those satisfy the one-percent criterion; 2. Related mergers and acquisitions: (a) AMD acquired ATI in 2006; (b) LSI acquired Agere in 2007; (c) STMicro acquired Genesis Microchip in 2008; (d) Qualcomm acquired Atheros in 2011; (e) CSR acquired Zoran in 2011; (f) Microchip acquired SMSC in 2012; (g) MediaTek acquired MStar in 2014; (h) Avago acquired LSI in 2014; (i) Qualcomm acquired CSR in 2015; (j) Microsemi acquired PMC-Sierra in 2016; (k) Intel acquired Altera in 2015; (l) Avago merged with Broadcom in 2016; (m) Western Digital acquired SanDisk in 2016; (n) SoftBank acquired ARM in 2016. Source: IC Insights, company annual reports and online news archives.

In addition, the length of annual rankings originally published by IC Insights constantly varies between 25 and 50 over the years with no clear explanation for reduced or extended inclusion. Therefore, based on industrial statistics recently published, a one-percent threshold is imposed on the annual ranking to exclude less important companies, of which annual sales are less than 1% of the IC design industry worldwide sales. This imposed criterion retains the major members of the industry, while maintaining a level of consistency across the rankings of different years. Morover, with this criterion, the length of annual rankings is shortened to a range between 19 and 26 companies.

4.5.1 The 28 IC Design MNEs

From the historical list of leading IC design companies, 41 IC design companies, which entered annual ranking at least once, were identified between 2001 and 2008, and nine of them entered all years (see Table 4.3). Subsequently, a brief background survey was conducted on these 41 companies in order to distinguish those which are essential to the research interest of this thesis—international knowledge creation and transfer. This survey provides a basic knowledge of these 41 companies, including their founding, demise, and exact business model among others. It was found that one company remained private, and another was founded as late as 2007, while two others had complex histories of mergers and acquisitions. Data entries are either limited or less than clear about these two companies. Also, one company had its main source of sales revenues from other business at least in some years. These companies were excluded from subsequent analysis.

Table 4.3 List of Top IC design companies, 2001-2008

Name	Year founded	HQ	Reason for exclusion[1]	SUBS patent[2]	Total patent[3]
Agere	2000	US	Agere Systems, MNE#1	14.12%	1608
Ali	1987	TW	Ali Corporation; low R&D internationalization	-	-
Altera	1983	US	MNE#2	26.73%	1706
Atheros	1998	US	MNE#3	2.21%	181
ATI	1985	CA	ATI Technologies; MNE#4	37.95%	361
Avago	2005	SG	MNE#5	92.48%	758
Broadcom	1991	US	MNE#6	9.75%	5695
Cirrus	1981	US	Cirrus Logic; MNE#7	2.80%	357
Conexant	1999	US	Low R&D internationalization; complex history of spin-off and restructuring	-	-
CSR	1998	UK	MNE#8	58.76%	97
DSP Group	1987	US	MNE#9	46.51%	43
ESS	1984	US	ESS Technology; MNE#10	32.97%	91
Genesis	1987	US	Genesis Microchip; MNE#11	22.73%	88
Globespan	1993	US	GlobespanVirata, merged with Conexant in 2004.	-	-
Himax	2001	TW	Low R&D internationalization	-	-
ICS	1976	US	Integrated Circuit Systems, merged in 2005	-	-
Intersil	1967	US	Reincorporated in 1999; complex history of merger and acquistions and spin-off	-	-
Lattice	1983	US	MNE#12	2.01%	349
LSI	1980	US	LSI Corporation; MNE#13	11.63%	2519
Marvell	1995	US	MNE#14	19.49%	2288
MediaTek	1997	TW	MNE#15	8.93%	1154
MegaChips	1990	JP	MegaChips Corporation; low R&D internationalization.	-	-
Mstar	2002	TW	Mstar Semiconductor; went public in 2010	-	-
Novatek	1997	TW	Novatek Microelectronics; low R&D internationalization	-	-
Nvidia	1993	US	MNE#16	7.62%	1587
PMC-Sierra	1983	US	MNE#17	73.71%	175
QLogic	1992	US	IC design business is not main business	-	-
Qualcomm	1985	US	MNE#18	8.18%	4912
Realtek	1987	TW	MNE#19	14.42%	617
SanDisk	1988	US	MNE#20	25.35%	1653
Semtech	1960	US	MNE#21	28.79%	66
Silicon Image	1995	US	Low R&D internationalization	-	-
Silicon Labs	1996	US	MNE#22	3.72%	592
SiS	1987	TW	Silicon Integrated Systems; low R&D internationalization	-	-
SMSC	1971	US	Standard Microsystems Corporation; MNE#23	5.67%	141
Solomon	1999	HK	Solomon Systech, a spin-off of Motorola; low R&D internationalization	-	-
SST	1989	US	Silicon Storage Technology; low R&D internationalization	-	-
Sunplus	1990	TW	Sunplus Technology; low R&D internationalization	-	-
VIA	1987	TW	VIA Technologies; MNE#24	20.70%	1285
Xilinx	1984	US	MNE#25	5.50%	1872
Zoran	1981	US	Zoran Corporation; MNE#26	51.56%	128
ARM	1990	UK	ARM plc; MNE#27	36.09%	496
Dialog	1998	DE	Dialog Semiconductor; MNE#28	28.97%	145

Note: 1. MNE# suggests inclusion in the sample, and the reasons for the exclusion of others are noted. 2. Total Patent is the number of patents. 3. SUBS patent is the percentage of international patenting of the 28 IC design MNEs between 2001 and 2008; percentage of international patenting is computed based on the location of main headquarter and residence information of leading patent inventors. 4. Information about excluded companies is omitted due to a lower level of data accuracy. Source: company annual reports, USPTO and this research.

Furthermore, to have a picture of the international knowledge-creating activities of these companies, a comprehensive search was conducted with the USPTO patent database for US patents assigned to these companies. Because each published US patent is specified with detailed information about the application date and inventor residence, it was possible to precisely plot the geographical distribution of patents over the period between January 1, 2001 and December 31, 2008. This information showed that nine other companies were operating at a very limited scale and geographical scope of international knowledge creation, in the sense that the vast majority of their patented inventions originated in the home country. With the ratio of international patenting as an indicator of R&D internationalization, these companies are less qualified as representative IC design MNEs. On the other hand, given the rarity of their international patents, these companies were excluded from subsequent empirical analyses simply due to the impracticability to delineate knowledge flows by empirical investigation of their patenting records.

While this process successfully selected 26 IC design MNEs from the historical list of 41 leading IC design companies, a concern was raised on the international coverage of the sample. Because the majority of these 26 MNEs were based in North America and East Asia, a survey of more recent rankings and industrial reports indicated two European IC Design MNEs to be included in the sample. The first addition is *Dialog Semiconductors PLC* registered in the United Kingdom with operating headquarters in Germany. This dual-headquarter approach was more often observed among European MNEs. IC Insights ranked this company 33rd in 2010 and 21st in 2011. The second addition is *ARM PLC* based in the renowned Cambridge area in the United Kingdom. The company has been a leading IP core vendor and its IP core designs are used in the majority of worldwide mobile devices

(Source: http://www.zdnet.com/uk/inside-arm-the-british-success-story-taking-the-chip-world-by-storm-7000008437/). As previous noted, IP vendors adopt a slightly different business model from other IC design companies and typically specialize in designing reusable IC components, which are licensed and incorporated by other IC design and IDM companies into their designs.

Overall, these 28 IC design MNEs cover a wide geographical area both in terms of the home country locations of their corporate headquarters and the extended corporate networks of their knowledge-creating subsidiaries. The sample size is comparable to those in previous studies on MNE knowledge transfer but admittedly smaller than several studies on technological innovations in the semiconductor industry (e.g. Adams et al., 2013). This discrepancy can be attributed to the context-rich approach adopted in the first group of studies to analyze the organizational and social aspects of knowledge flows, while the second group tends to focus on the industrial and technological aspects. Although patent data based studies may potentially employ a sizable sample, the data collection for firm-level knowledge transfer is usually more challenging because it spans across multiple levels of analysis and incorporates different data sources (e.g. Di Minin & Bianchi, 2011).

A notable exception is the reverse knowledge transfer research by Frost and Zhou (2005), who have employed a sample of 104 MNEs from two industries with a wider sampling criterion. Their approach was not adopted because of the concern of differential patenting behavior and intensity between industries (ESA & USPTO, 2012; also see 3.2.4), and the clear focus on a single industry in this study.

4.5.2 Observation time period

The time period studied in this research covers the nine years from 2001 to 2008, an inter-crisis period between two recent worldwide economic downturns in the early 21st century. The burst of the dot-com bubble in the early 2000s caused severe losses in the semiconductor and IT industries as well as in many other industries that are generally the users of IC products. Both crises led to changes in the industry composition. Mergers and acquisitions and corporate restructuring were undertaken, while better performers expanded and acquired and others also adjusted their business strategies. Although the impact of the dot-com crisis is directly related to the semiconductor industry, significant structural change is observed in years after the 2008 financial crisis. As shown in the historical list of leading IC design companies, except for a small number of the market leaders, many companies have either changed places or entered the list in the years closely following both crises.

Their fabless nature and flexible product offerings allowed some IC design companies to adapt shortly after the crises, and some involve mergers and acquisitions. The IC industry also had new members from the IDM and electronic industries. For IDM companies and large electronic companies, business model changes would involve the externalization of either the fabrication facilities and equipment or in-house IC design teams. In some cases, in-house IC design business units and product divisions were sold to other IC design companies intending to increase the market share of existing product lines or to expand to new markets. In other cases, design teams were sold or spun off as part of a business unit, such as in the case of Avago, which was part of Agilent Technologies, a spin-off from Hewlett-Packard.

Besides structural changes at the industry-level, these crises also impacted the international knowledge-creating activities of IC design companies in several aspects. Firstly, it is likely that these merger and acquisition events have involved personnel mobility and the trade of patented inventions (Corredoira & Rosenkopf, 2010). Secondly, in response to changes in market demand after crises, companies may have adjusted product strategies and shifted the focus of R&D activities to different technological fields. Thirdly, while sales decline amid crises have caused cuts in R&D spending and resource commitment in the short term, all these can have longer-term impacts, such as the divestments of subsidiaries (Bradley, Aldrich, Shepherd, & Wiklund, 2011). R&D activities and related resource inputs generate patents as one of the observable outputs, which only emerge after a certain period of time. Therefore, sudden cuts and short-term adjustments in R&D activities in response to crises may leave traces in patenting records long after the crises. The exact nature and magnitude of the effects are less than clear and cloud the potential implications of research findings.

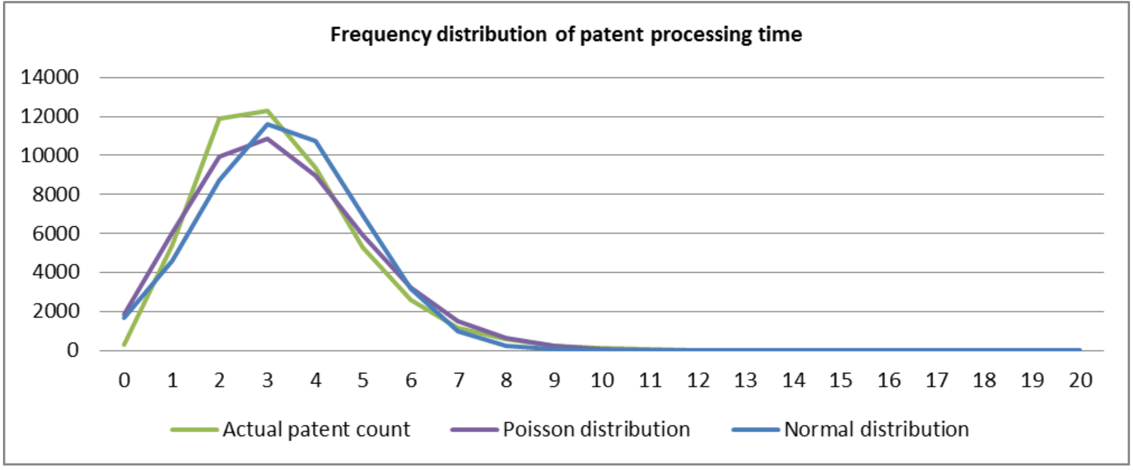
Lastly, a practical reason why the data collection of this thesis ends in the year of 2008 is patent processing time lag, which usually takes several years and results in right-truncated observations. Between the application and publication of a patent, there tends to be a time gap of several years, during which applications are thoroughly evaluated. Among the 49,221 patents assigned to these 28 companies and published by December 2013, the average processing time is 3.29 year with a standard deviation of 1.67 (see Table 4.4). According to the frequency distribution of observed processing time, the five-year gap between 2008 and the data collection at the end of 2013 likely limits the right truncation to around ten percent. Prediction based on Poisson and Normal distributions also suggest a similar percentage (see Figure 4.5). Therefore, given these reasons 2008 is considered a reasonable end of the data panel, which to some extent reduces the right-truncation issue. The following section explains the details of patent data collection.

Table 4.4 Frequency distribution of patent processing time

Process Year	Observed distribution	Poisson distribution	Normal distribution	Observed probability	Poisson probability	Normal probability
0	286	1829.545	1680.627	0.006	0.037	0.034
1	5397	6023.324	4580.784	0.110	0.122	0.093
2	11876	9915.154	8718.715	0.241	0.201	0.177
3	12302	10881.067	11588.017	0.250	0.221	0.235
4	9360	8955.807	10754.984	0.190	0.182	0.219
5	5277	5896.957	6970.348	0.107	0.120	0.142
6	2571	3235.713	3154.592	0.052	0.066	0.064
7	1140	1521.827	996.956	0.023	0.031	0.020
8	604	626.280	220.015	0.012	0.013	0.004
9	234	229.097	33.906	0.005	0.005	0.001
10	116	75.424	3.649	0.002	0.002	0.000
11	40	22.574	0.274	0.001	0.000	0.000
12	13	6.193	0.014	0.000	0.000	0.000
13	3	1.568	0.001	0.000	0.000	0.000
14	1	0.369	0.000	0.000	0.000	0.000
15	1	0.081	0.000	0.000	0.000	0.000
16	0	0.017	0.000	0.000	0.000	0.000
17	0	0.003	0.000	0.000	0.000	0.000
18	0	0.001	0.000	0.000	0.000	0.000
19	0	0.000	0.000	0.000	0.000	0.000
20	0	0.000	0.000	0.000	0.000	0.000
Sum	49221[1]	49221.000[2]	48702.880[3]	1.000	1.000	0.989[1]
Mean	3.292					
SD	1.669					

Note: 1. Total number of patents assigned to the 28 IC design MNE as of December 2013. 2. A frequency distribution shows minor under-dispersion assuming Poisson distribution. 3. Normal distribution is truncated at zero.

Figure 4.5 Frequency distribution of patent processing time



Note: 1. The diagram is based on 49,221 patents assigned to 28 IC design MNEs by December 2013. 2. Data query was conducted in December 2013. Source: this research. Source: This research.

4.6 Patent data search and filter

Due to the nascence of the IC design industry, the patent data collection was conducted by comprehensive search on a number of patent data websites providing public access to the USPTO patent databases in various digitalized formats. These databases include FreePatentsOnline, Google Patent Search and USPTO Patent Full-Text and Image Database for patent information and Free World Cities Database for location information. In other words, instead of relying on the established NBER database ended in the year of 2006 or other commercial databases, the database for subsequent analysis was originally built during months of manual and computer-assisted data query and compilation. Procedures involved in the construction of this database are explained in this section. Although data verification has been conducted repeatedly in various ways, it is acknowledged here that a negligible number of data entry errors and omissions may still be present in the final dataset.

The US Patent and Trademark Office (USPTO) patent database has been widely used in the past two decades in the empirical literature of knowledge spillovers (Alcácer & Chung, 2007; Almeida & Kogut, 1999; Jaffe & Trajtenberg, 1996; Jaffe et al., 1993; Singh, 2007), international R&D (Cantwell, 1995; Cantwell & Janne, 1999; Cantwell & Piscitello, 2002; Frost, 2001; Patel & Pavitt, 1991), subsidiary knowledge seeking and transfer (Almeida, 1996; Almeida & Phene, 2004; Frost & Zhou, 2005; Miller, Fern, & Cardinal, 2007), organizational learning and innovations (Ahuja & Katila, 2001; Phene & Almeida, 2008; Yayavaram & Ahuja, 2008), and others in various research settings. Patent documents contain detailed information about the inventors, assignees, classifications, examiners and both patented and non-patent prior arts. Location information of inventors and assignees, which could be one or more, and the exact dates of patent application and publication can be aggregated to reveal the patenting records of individuals and firms across industries, countries and time.

The semiconductor industry has one of the highest patent intensities, measured as the number of patents per thousand employees (ESA & USPTO, 2012), and IC design companies particularly benefit from a strong patent region and make comprehensive use of the intellect property protection it provides (Hall & Ziedonis, 2001). As the industry matures and competition intensifies, patenting can provide a useful legal instrument for transactions and litigation. Companies are advised to start patenting at an early stage of development, search for related patents owned by other firms and engineers, establish committees to review internal research projects and patentable inventions regularly, and establish close relationships with IP lawyers with good backgrounds in companies' technological fields (Hurtarte et al., 2007).

Patenting records cover most technological knowledge created in these IC design companies, which may include new circuits, algorithms, IC products, photomasks, materials, manufacturing processes and others. Several key functions of patents facilitate the industry by allowing IC design companies to license, commercialize their inventions, cooperate with other firms, conduct knowledge searches, engage in patent infringement litigation with competing firms, and establish their reputation as leading innovating firms (Crawford, Telesco, Nelson, & Botwin, 2009). Almeida et al. (2002) suggest that patent licensing is an especially important kind of knowledge transfer contract in the semiconductor industry to derive revenues from proprietary knowledge assets. Hall and Ziedonis (2007) suggest that stronger patent rights were particularly critical to IC design companies, which emergence coincides with the strengthening of the US patent regime in the early 1980s, in attracting venture capital funds and securing proprietary rights in niche product markets.

Therefore, although knowledge-based assets in the semiconductor industry may exist in several forms, including patents, copyrights, photomasks, trademarks or trade secrets, patenting remains the most critical approach for IC companies to protect their IPs (Hurtarte et al., 2007). In particular, as Phene and Almeida (2008) point out, because the US is both the major market and the major design and manufacturing location of semiconductor products, US intellectual property rights (IPRs) are considered most critical for all companies in the industry. Patent disputes can result in court issued injunctions against the sale of end products incorporating specific IC products.

4.6.1 Patent search

Database queries were conducted for all published US patents assigned to these 28 IC design companies by assignee name. Subsequent analysis of backward citations identified and added a small number of patents, which eluded the preliminary patent search. Overall, this process identified 49,221 patents, which were applied between 1971 and 2013 and assigned to these 28 companies as of December 2013, excluding patents with multiple assignees.

As shown in Figure 4.6, the patenting rate of these 28 companies picked up in the early 1990s as the overall IC design industry emerged. In addition to the right-truncation issue previously discussed, the slower growth in patenting since 2005 also relates to the consolidation in the industry (see Table 4.2). Meanwhile, the internationalization of the IC design industry is also demonstrated by the increasing number of patent country origins since the mid-1990s (see Figure 4.7). The number of patent classes, as the indicator of technological fields covered by the IC design industry, has also expanded continuously since the 1980s, even before the significant growth of the industry (see Figure 4.8). While both the geographical and technological scope stabilized in the 2000s, these figures reflect the flexibility and wide geographical and technological scopes of the industry.

On the other hand, it is interesting to see that the average number of inventors has remained stable since the emergence of the industry (see Figure 4.9), while the proportion of patents with a first inventor in host countries has made a significant increase since the late 1990s. Taking into account the stable geographical scope since the early 2000s, this may imply that the extent of internal coordination remained at a certain level, while a general shift towards decentralized knowledge creation takes place (see Figure 4.11). That the average number of country origins associated with each patent has largely remained stable suggests that the internationalization of the industry in terms of geographical scope may not equate with the internal internationalization of firm organizations. Assuming that internal interdependencies between subsidiaries and the headquarters indicate transnationality (Bartlett & Ghoshal, 1989; Frost & Zhou, 2005; Gerybadze & Reger, 1999; Morris, Hammond, & Snell, 2014; Pearce, 1999a), these figures may provide a different perspective from the level of actual R&D activities.

Figure 4.6 Frequency distribution by year of patent filing, 1970-2013

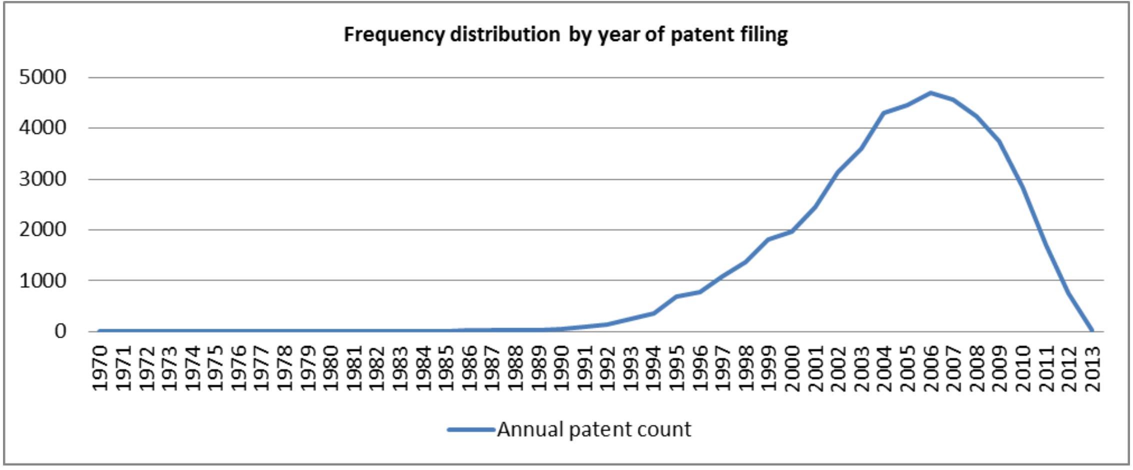
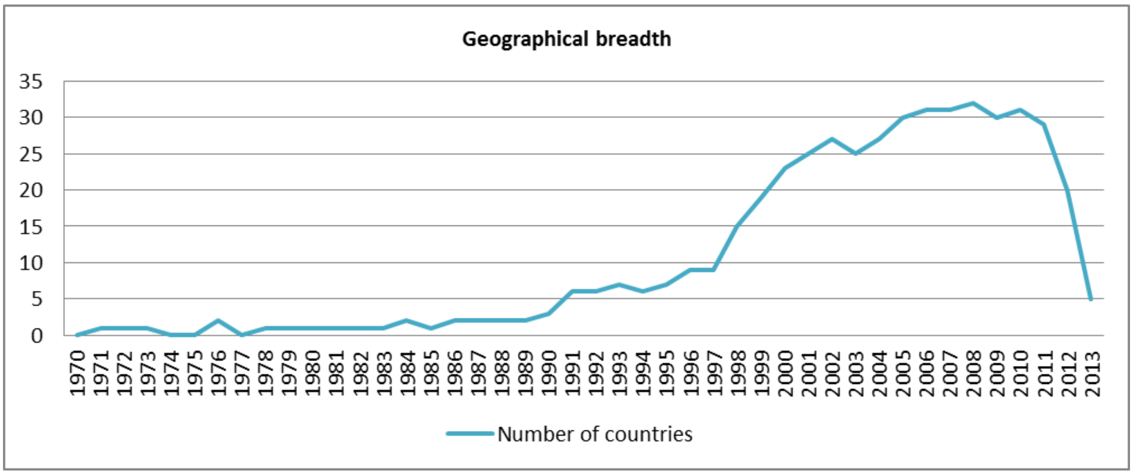


Figure 4.7 Number of source countries by year of patent filing, 1970-2013



Source: This research.

Figure 4.8 Number of primary classes by year of patent filing, 1971-2013

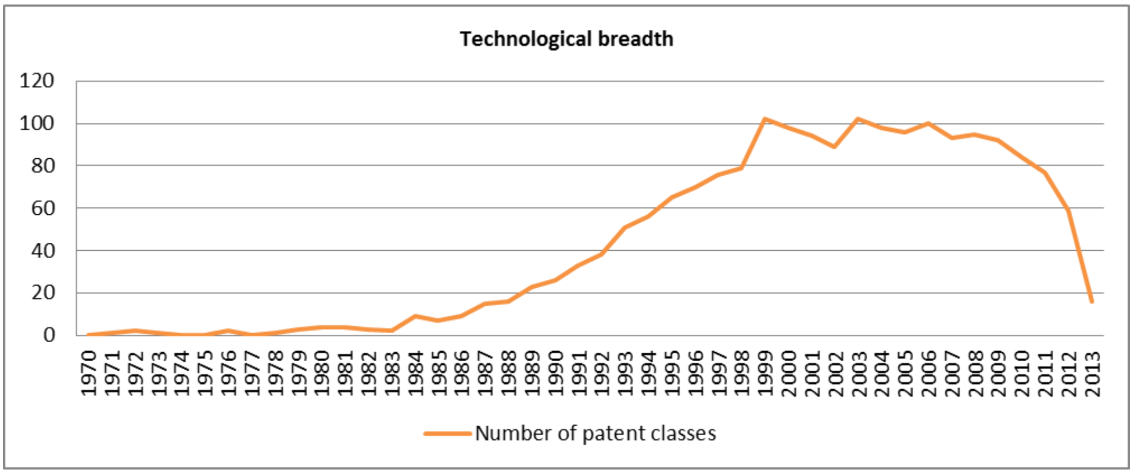


Figure 4.9 Average number of inventors per patent, 1980-2013

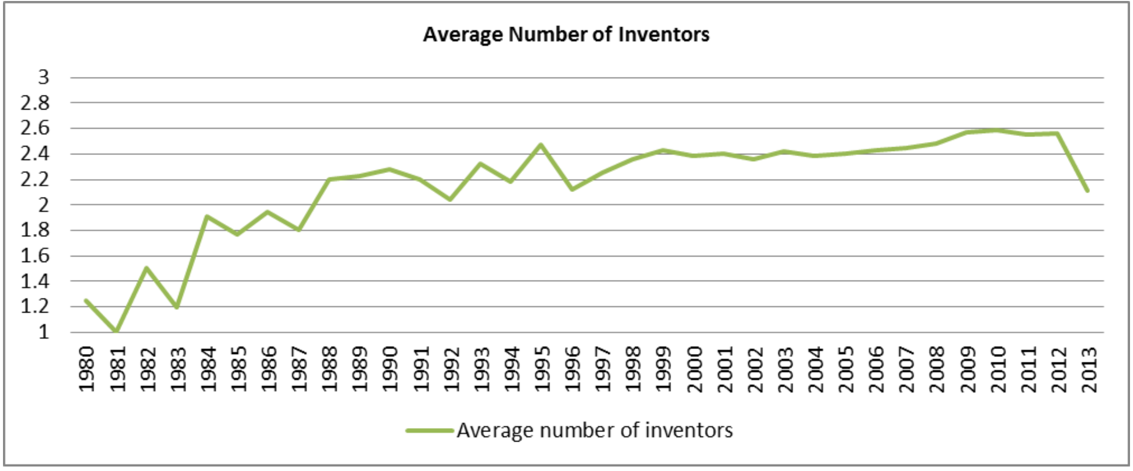


Figure 4.10 Ratio of international patenting, 1980-2013

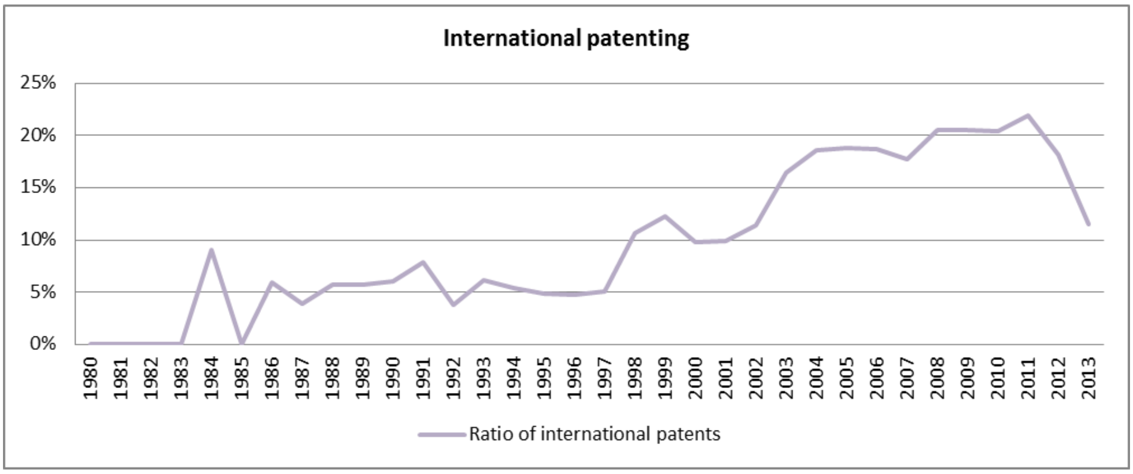
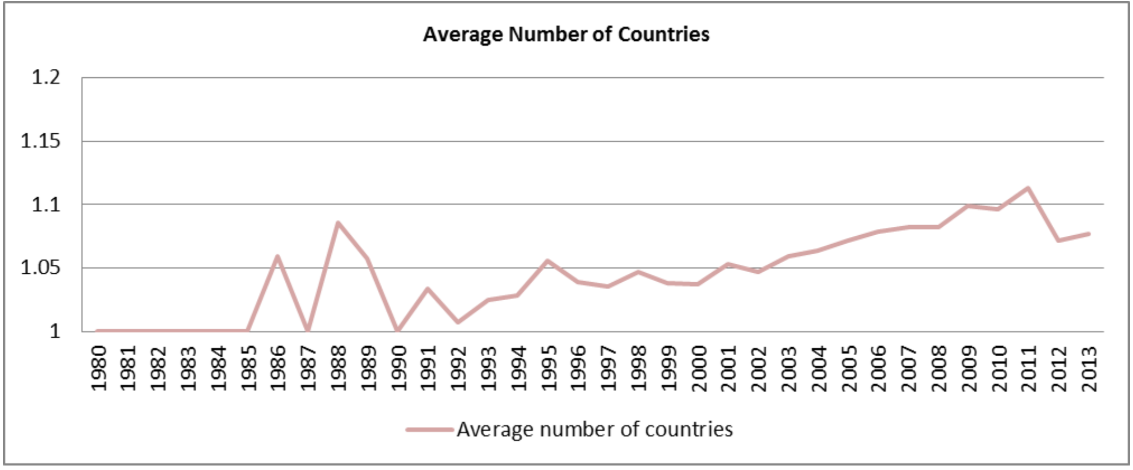


Figure 4.11 Average number of country origins per patent, 1980-2013



Source: This research.

4.6.2 *Searching and identifying patents by assignee name*

In this research, patented inventions were identified and labeled according to assignee name information, and there are a number of reasons why this approach was adopted. First of all, a large majority of the patenting records compiled for this research are more recent inventions that are not covered in the NBER patent database. Although this widely used data source covers the period between 1976 and 2006 by year of publication, 76.25% of the focal patents identified in this research were published after 2006. Therefore, it was not a feasible option, even though its use would avoid several limitations of patent assignee information discussed in the next section.

Secondly, some researchers have conducted patent searches by focusing on a selective list of patent classes, which are assumed to be related to the semiconductor industry. For instance, Ganco (2013) considered twenty-two 3-digit patent classes and calculated a mean complexity measure for each of them. However, relative to the overall semiconductor industry, IC design companies have incorporated a larger diversity of technologies and applications due to their highly flexible product offerings, and these twenty-two 3-digit patent classes only cover one-half of all patents identified, while the total number of patent classes is more than a hundred.

Thirdly, instead of relying on the subsidiary lists and SIC codes (e.g. Adams et al., 2013), this research analyzes international knowledge-creating activities by the residence information of patent inventors. Residence information was considered more reliable than subsidiary names for the identification of the original country location of patented inventions. Subsidiary locations of most companies are rather fluid and malleable and therefore less informative. In fact, subsidiary inventions are often assigned to the headquarters, which operates in different country locations (McCann & Mudambi, 2005). Whether subsidiary inventions were assigned to the subsidiary or the parent firm may depend on firm-specific IP management and the nature of research projects.

Lastly, previous studies have referred to lists of subsidiaries in annual reports and databases when compiling the patenting records of MNEs (e.g. Cantwell & Janne, 1999; Cantwell & Piscitello, 2002; Frost & Zhou, 2005; Yayavaram & Ahuja, 2008). This approach is less applicable to the IC design industry, due to highly frequent mergers and acquisitions of startups and subsidiaries (see 4.6.3 for further discussion). On one hand, the inclusion of patents created by entrepreneurial startups prior to acquisitions and patents by subsidiaries of other firms before ownership transfer may corrupt the observations of subsidiary knowledge creation. On the other hand, it was observed that subsidiaries carrying less identifiable names are likely portfolio investments unrelated to main business lines. Instead, acquired and related subsidiaries usually obtain names with clear connections to the parent MNE.

Notably, the lists of subsidiaries included in annual reports are highly problematic. These lists often include subsidiaries that were too short-lived to have any meaningful R&D activities, while omitting those controlled through limitedly disclosed holding subsidiaries. Also included are holding subsidiaries for patent procurement and trading. These subsidiaries tend to be differently named and assigned with patents acquired externally.

4.6.3 Limitations to searching by assignee information

While searching by assignee information is a widely used approach, it is nevertheless subject to several limitations. In a small number of cases, assignee information may be less accurate and affect the reliability of data collection. Firstly, some in-process R&D may have been transferred from the original developers to the acquiring firms, as part of corporate merger and acquisition deals. Because of delayed assignment, these inventions might be sold to others and omitted or acquired and included. As a result, the patent stock of a firm may not reflect the direct output of its internal R&D activities entirely. However, the decision to exclude companies with a complex history of mergers and acquisitions should avoid this issue to a certain extent.

Secondly, a search by assignee names can omit those patents assigned to differently-named subsidiaries. However, according to company annual reports, most acquired units were rapidly renamed, restructured and sometimes merged into other units of the acquiring firm. Patents reporting differently-named and less identifiable assignees are usually pre-acquisition inventions of acquired entities or those from unrelated diversification. These inventions are considered less relevant to the knowledge creation of the sampled MNEs. It is also a common practice among larger semiconductor companies to set up patent trading subsidiaries, which deal with patents sold from terminated firms and business units and sometimes traded multiple times among several entities. Although there are some evidence suggesting that these acquired patents might be more valuable than average patents, the implication and relevance of these patents to firm-specific knowledge-creating activities are less clear. In some cases, specific patents may have been acquired only to fend off IP litigation, such as in the case of VIA technologies.

Thirdly, and most applicable to the highly diversified companies, a smaller number of patents were assigned to acquired subsidiaries carrying very different names and operating in industries outside the core business of parent companies. These inventions might have been aimed at very different markets, involve separate IP management and therefore only provide limited information to this research. Lastly, assignee names can be misspelled or abbreviated, especially in earlier patent documents, such as those included in the NBER database. However, the patenting records analyzed in this research are more recently published and are less subject to such issues. These observations form the company annual reports and patent records also led to the decision to invalidate the information from the list of subsidiaries. These lists were often highly volatile and included disparately named subsidiaries.

In brief, potential biases caused by inaccurate assignee information are may result in less accurate patenting and citation records and less reliably-identified knowledge bases and flows. Considering that the IC design MNEs studied in this research are all highly successful knowledge-creating companies, these measures should significantly reduce the proportion of confounding patent information. Also, because the subsequent empirical analyses are mostly based on aggregated patent statistics, a sizable sample should render the impact of random noise immaterial.

4.6.4 Processing and filtering patent information

In order to attribute these patents to country origins, residence information of inventors was identified and verified with information from world city and country databases. Confounding and incomplete entries in inventor residence information were also corrected or imputed manually. These data errors are mostly found in patents published before the mid-2000s, and confusion sometimes arises from popular city names, such as Reading in Pennsylvania or the United Kingdom, and from indistinguishable state and country abbreviations, such as Canada and California. The latter issues were carefully examined, given that Canada, California, India, Indiana, Israel and Illinois are all important geographical sources of semiconductor technologies.

In brief, several manual and computer-assisted procedures were involved to solve these missing or confounding entries. Firstly, residence information in patents published before

2007 was compared with a reference list compiled from more recent records between 2007 and 2013, which were found more accurate. Secondly, all patents were then verified with the Free World Cities Database listing more than three million cities worldwide. Lastly, those that failed to obtain a clear match in the previous two steps were resolved by manual examination of the original patent document in PDF format. In many cases, corrections were made by cross-referencing other patenting records of the same inventors close in time.

Subsequently, the year of patent application was referenced as the point in time when the invention was generated, recognized and appropriated by the assignee MNE. It was found that some patents were filed before the company founding year and potentially associated with entrepreneurship events and the founders' personal efforts, which become the starting foundations of the firm. However, these inventions are less indicative of the knowledge-creating activities of these MNEs by either subsidiaries or the headquarters. On the other hand, primary patent class information as assigned by patent examiners was identified at 3-digit level to categorize the technological fields of patents (Henderson, Jaffe, & Trajtenberg, 2005). This information is critical for subsequent analysis on the knowledge-seeking scope and knowledge bases of subsidiaries and the headquarters.

Table 4.5 International patenting and R&D cooperation, 1970-2013

Patent origin	**Pre-founding**[1]	**Pre-crisis (-2000)**	**Inter-crisis (2001-2008)**	**Post-crisis (2009-)**
HQ patent	739	7,260	26,033	7,206
SUB patent	494	698	4,931	1,860
R&D Cooperation	**Pre-founding**	**Pre-crisis (-2000)**	**Inter-crisis (2001-2008)**	**Post-crisis (2009-)**
HQ-SUB	12	216	1,124	457
SUB-HQ	7	85	784	323
Sum (HQ and SUB)	1,233	7,958	30,964	9,066
International (%)	40.065%	8.771%	15.925%	20.516%

Note: 1. Pre-founding patents are those filed before the year of incorproation. Source: This research.

Finally, after restricting the dataset to the inter-crisis period between 2001 and 2008 and excluding pre-founding patents, this study identified 30,964 patents covering 153 patent classes, associated with 38 country locations and assigned to one of these 28 IC design MNEs.

The percentage of patents invented by first inventors outside the MNE home country is 15.93% (see Table 4.5). While the majority of patents originated from knowledge-creating activities in the headquarters, the percentage of international patenting increased over different time periods and reached 20.52% after the financial crisis, based on the limited number of observations available for this time period. Moreover, international R&D collaborations between the headquarters and subsidiaries also grew over time, suggesting a deeper form of decentralized knowledge creation (see the lower half of Table 4.5).

The relative prominence of different triad regions as geographical knowledge sources has also been changing over time, as shown in Figure 4.12 which aggregates the 38 countries into Triad regions. According to the patenting records of the 28 sampled MNEs, Europe became the largest host region during the inter-crisis time period, while Asia quickly gained more importance after the financial crisis. Lastly, Figures 4.13 and 4.14 show notable variations in international patenting rate and patent processing time is observed at the firm level. These firm-level heterogeneities may reflect the differences in firm organizations, technological fields and patenting behaviors (see Chapter 5).

4.6.5 Intra-MNE R&D collaboration

The residence information of first inventors is often prioritized when attributing patented inventions (Cantwell & Piscitello, 2002), and patents with multiple inventors in several country locations may reflect international activities and intra-MNE interactions (Bergek & Bruzelius, 2010). This research follows Frost and Zhou (2005) and identifies joint patents with co-inventors from both subsidiaries and the headquarters (see Table 4.5). Moreover, joint-patents are further distinguished by the location of first-inventors—subsidiaries or the headquarters, which results in four types of intra-MNE R&D collaborations (see Table 4.6). Further discussion on intra-MNE R&D collaboration can be found in Chapter 7.

Figure 4.12 Number of host region patents

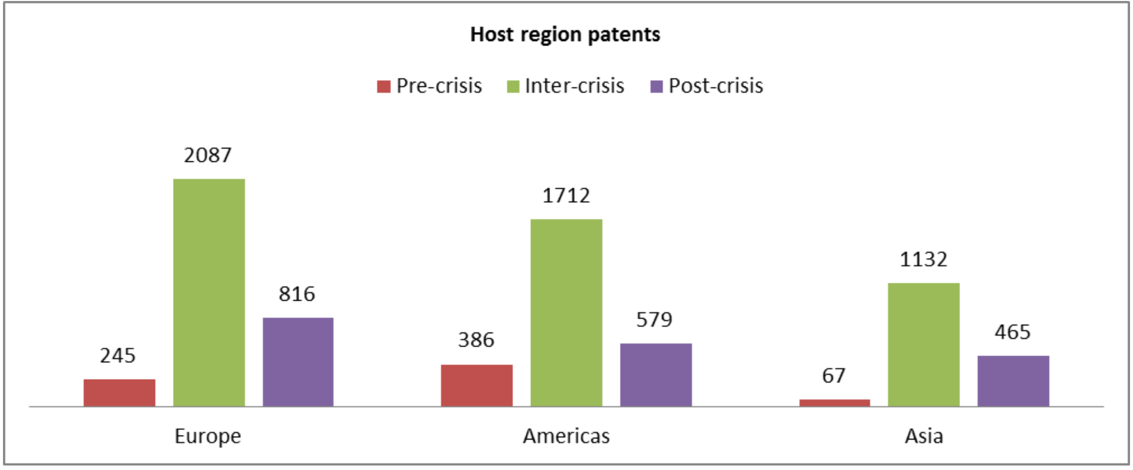


Figure 4.13 International patenting of sample firms

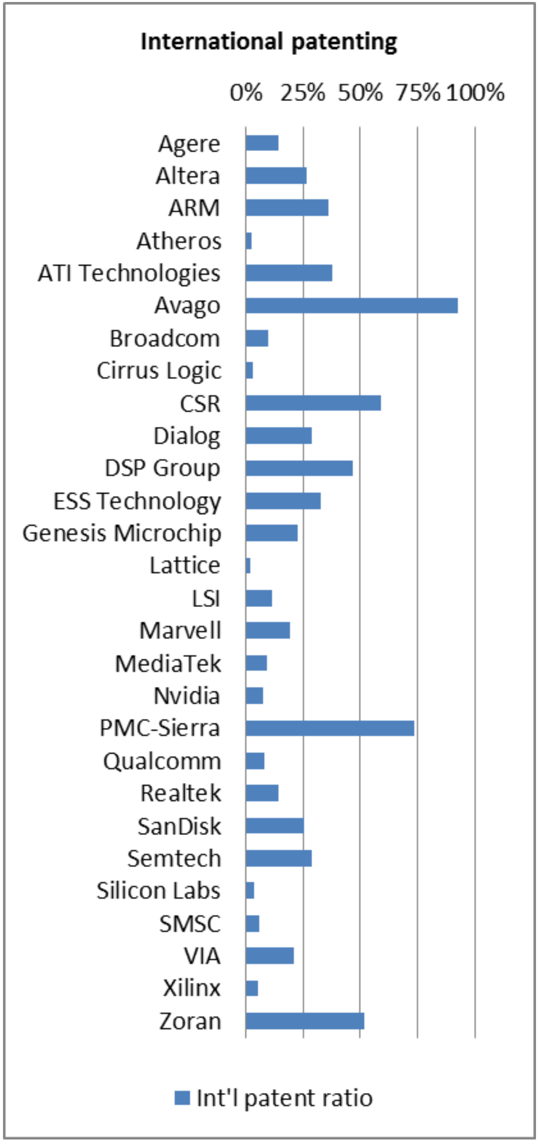
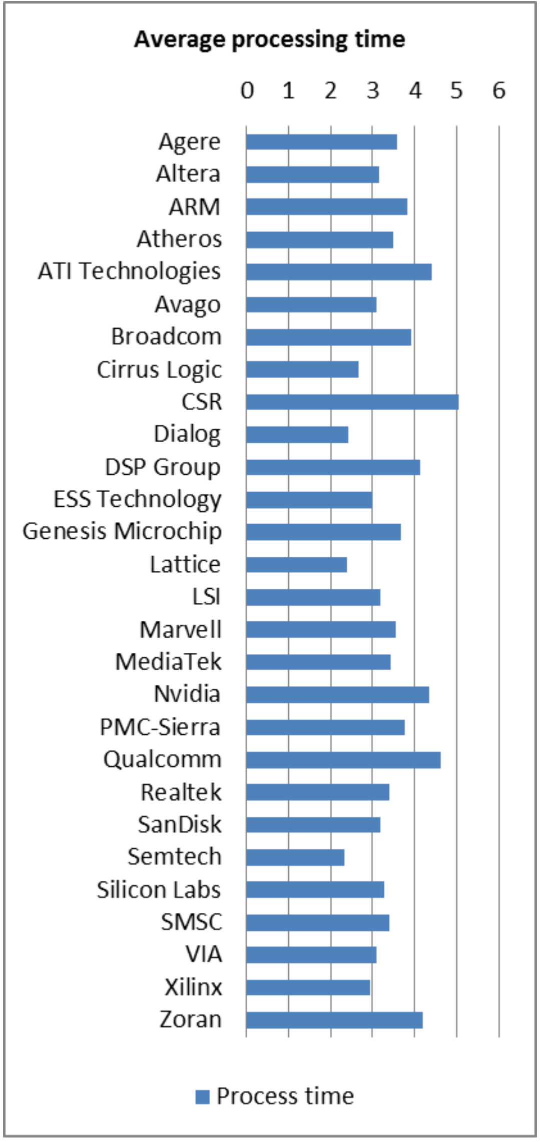


Figure 4.14 Patent processing time of sample firms



Note: 1. International rates vary over time. 2. Processing time is calculated by years and affected by the technological fields of each firm. Source: This research.

These joint patents may involve expatriation (Brown et al., 2005), but the implications are profound. Intra-firm R&D collaborations may establish an intra-firm network of inventors (Nerkar & Paruchuri, 2005), develop relative absorptive capacity between subunits (Frost & Zhou, 2005), and coordinate between centralized IP management and subsidiary knowledge creation (Di Minin & Bianchi, 2011). Various interactions and non-R&D activities may also occur between co-inventors during international R&D collaboration (Bergek & Bruzelius, 2010).

Table 4.6 Intra-MNE international R&D collaboration

		1st inventor country of residence	
		Home country	Host country
Other inventors	Host	HQ-Sub 1,124 (3.6%)	Sub-Sub 173 (0.6%) Sub-solo 3,974 (12.8%)
	Home	HQ-solo 24,909 (80.4%)	Sub-HQ 784 (2.5%)

Note: 1. HQ-Sub patents have first inventors in the headquarters and others in subsidiaries. 2. Sub-HQ patents have first inventors in subsidiaries and one of the co-inventors in the headquarters. 3. HQ-solo patents have all inventors in the headquarters. 4. Sub-solo have all inventors in same subsidiary locations. 5. Sub-Sub patents have inventors in multiple subsidiary locations. Source: This research.

Table 4.7 List of patent country origins

Firm-Country	**AT**	**AU**	**BE**	**BR**	**BY**	**CA**	**CH**	**CN**	**CY**	**CZ**	**DE**	**DK**	**EG**	**ES**	**FI**	**FR**	**GB**	**GR**	**HK**	**HU**	**IE**	**IL**	**IN**
Agere	0	19	1	0	0	1	5	8	0	0	44	0	1	9	0	0	13	1	0	0	4	7	17
Altera	0	0	0	1	0	215	0	0	0	0	0	0	0	0	0	2	170	0	0	0	0	0	0
ARM	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	45	317	0	0	0	0	0	4
Atheros	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0
ATI Technologies	0	0	0	0	0	224	0	0	0	0	1	0	0	0	2	0	1	0	0	0	0	0	0
Avago	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	22	0	0	0	0	0	2
Broadcom	0	0	30	0	0	86	10	2	0	20	3	0	0	1	1	5	110	26	0	0	1	78	94
Cirrus Logic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
CSR	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	1	40	0	0	0	0	5	0
Dialog	11	0	0	0	0	0	0	0	0	0	103	0	0	0	0	0	17	0	0	0	0	0	0
DSP Group	0	0	0	0	0	0	3	0	0	0	2	0	0	0	0	1	0	0	0	0	0	11	0
ESS Technology	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Genesis Microchip	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
Lattice	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	5	0	0	0	0	0	0
LSI	0	1	0	0	0	88	0	4	0	0	40	0	0	0	0	0	47	0	1	0	0	5	32
Marvell	0	0	0	0	0	0	16	12	0	0	17	1	0	6	0	1	0	0	6	0	0	202	16
MediaTek	1	0	0	0	0	1	1	0	0	0	0	6	0	0	0	0	11	0	0	0	2	0	0
Nvidia	0	2	0	9	0	8	9	8	1	0	10	0	0	0	4	1	22	0	0	0	0	0	28
PMC-Sierra	0	0	0	0	0	114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	1
Qualcomm	0	61	0	0	0	48	29	6	1	0	20	2	1	1	9	5	43	0	2	0	0	49	17
Realtek	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SanDisk	0	0	0	0	2	1	0	2	0	0	0	0	0	5	0	0	83	0	0	0	0	240	4
Semtech	0	0	0	0	0	3	5	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0
Silicon Labs	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	7	2	0	0	3	1	0	1
SMSC	0	0	0	0	0	2	1	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
VIA	0	0	0	0	0	0	0	24	0	0	1	0	0	0	0	0	11	0	0	0	0	0	0
Xilinx	0	0	1	0	0	12	0	0	0	0	3	0	1	0	0	8	36	0	3	1	25	0	3
Zoran	0	0	0	0	0	8	0	1	0	0	0	0	0	0	0	7	0	0	0	0	0	46	0
	AT	AU	BE	BR	BY	CA	CH	CN	CY	CZ	DE	DK	EG	ES	FI	FR	GB	GR	HK	HU	IE	IL	IN

(Table 4.7 continued)

Firm-Country	IS	IT	JP	KR	MY	NL	NZ	RU	SE	SG	TH	TR	TW	US	YU	Europe, Mid-East, Africa	Asia-Pacific
Agere	0	0	1	0	0	79	0	0	0	17	0	0	0	1381	0	Austria (AT)	China (CN)
Altera	0	0	0	0	64	1	0	0	0	0	0	0	3	1250	0	Belgium (BE)	Hong Kong (HK)
ARM	0	0	0	0	0	0	0	0	1	0	0	0	0	119	0	Belarus (BY)	India (IN)
Atheros	0	0	0	0	0	0	0	0	0	0	0	0	0	177	0	Cyprus (CY)	Japan (JP)
ATI Technologies	0	0	0	0	0	0	0	0	0	0	0	0	0	133	0	Czech Republic (CZ)	Malaysia (MY)
Avago	0	12	18	9	212	0	0	0	0	57	0	0	0	400	0	Denmark (DK)	Singapore (SG)
Broadcom	0	3	0	0	0	51	0	0	2	16	0	0	16	5140	0	Egypt (EG)	South Korea (KR)
Cirrus Logic	0	0	0	0	0	0	0	0	0	0	0	0	0	347	0	Finland (FI)	Taiwan (TW)
CSR	0	0	0	0	0	0	0	0	2	0	0	0	0	43	0	France (FR)	Thailand (TH)
Dialog	0	0	1	0	0	0	0	0	6	0	0	0	0	7	0	Germany (DE)	Australia (AU)
DSP Group	0	0	0	0	0	3	0	0	0	0	0	0	0	23	0	Greece (GR)	New Zealand (NZ)
ESS Technology	0	0	0	0	0	0	0	0	0	0	0	0	0	61	0	Hungary (HU)	
Genesis Microchip	0	0	0	0	0	0	0	0	0	0	0	0	0	68	0	Ireland (IE)	**Americas (3)**
Lattice	0	0	0	0	0	0	0	0	0	0	0	0	0	342	0	Israel (IL)	Brazil (BR)
LSI	0	6	7	1	1	0	0	59	0	0	0	0	1	2226	0	Iceland (IS)	Canada (CA)
Marvell	0	10	20	0	7	4	0	0	2	124	0	0	2	1842	0	Italy (IT)	The USA (US)
MediaTek	0	0	1	9	0	0	0	0	0	10	0	1	1051	60	0	Netherlands (NL)	
Nvidia	0	0	0	0	0	0	0	1	0	0	0	0	18	1466	0	Spain (ES)	
PMC-Sierra	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	Switzerland (CH)	
Qualcomm	0	16	11	21	0	15	15	0	0	1	7	0	22	4510	0	Russian Federation (RU)	
Realtek	0	0	0	0	0	0	0	0	0	0	0	0	528	85	0	Serbia (YU)	
SanDisk	0	0	67	0	0	0	0	0	0	0	0	0	14	1234	1	Sweden (SE)	
Semtech	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	Turkey (TR)	
Silicon Labs	5	0	0	0	0	0	0	0	0	0	0	0	0	570	0	The UK (GB)	
SMSC	0	0	0	0	0	0	0	0	0	0	0	0	0	133	0		
VIA	0	0	0	0	0	0	0	0	2	0	0	0	1019	228	0		
Xilinx	0	1	1	0	0	2	0	0	5	1	0	0	0	1769	0		
Zoran	0	0	0	0	0	0	0	0	4	0	0	0	0	62	0		
	IS	IT	JP	KR	MY	NL	NZ	RU	SE	SG	TH	TR	TW	US	YU		

Source: This research.

4.7 International patenting of 28 IC design MNEs

International patenting of these 28 IC design MNEs shows a considerable variation in their degrees of R&D internationalization (see Figure 4.13). The highest ratio of international patenting is found in the patenting records of Singapore-based Avago, a spin-off of Agilent. Notably, this ratio was not adjusted for the size of patent stock of each location. Thus it is inevitable that companies headquartered in the US tend to have a lower ratio, as a result of the size and strength of country-specific knowledge base in semiconductor, IT and other related technologies. Historically, the semiconductor industry and the IC design sub-industry also originated in the US. There are also exceptions, nevertheless. PMC-Sierra and Zoran, both headquartered in California, have conducted a significant percentage of their knowledge-creating activities in Canada and Israel. In fact, home country factors also fail to explain the difference between ARM and CSR, both headquartered in Cambridge and that between MediaTek and VIA, both from Taiwan.

The strength of IC design MNEs is in their ability to link external sources of technological knowledge, market knowledge and own knowledge-creating activities, which often spread across many locations worldwide. Close examination of the geographical distribution of their patenting records suggests that corporate history may have some roles in R&D internationalization (see Table 4.7). Knowledge-creating activities are found to be more common in nearby countries and countries with specific technological strength. The implication of this geographical distribution and how these IC design MNEs leverage their international knowledge seeking and creation are the focus of this thesis. The following discussion on the semiconductor industry in specific countries is based on the entries in Semiconductor Industry Yearbook, published by The Industrial Economics & Knowledge Center (IEK) in Taiwan (Source: http://ieknet-eng.iek.org.tw/).

4.7.1 Europe

Germany. Several renowned semiconductor country locations have appeared in the patenting records of these 28 companies. To begin with, Germany has a long history in semiconductor technology, especially the semiconductor cluster in the renowned Dresden area in Saxony (Weber, 2003). On the other hand, Siemens moved its headquarters from Berlin to Munich and started its business in IC manufacturing in the early 1950s. This event contributed to the development of the semiconductor industry and the high-tech region in Bavaria. Moreover, the renowned Fraunhofer Society, an applied research organization with various institutes throughout Germany, has been an important knowledge source for cutting-edge technologies in signal processing, communications and many other technological fields related to the semiconductor industry.

France. According to ter Wal (2013), the renowned IT sector in Sophia-Antipolis, characterized by local knowledge-based interactions among private firms and research institutes, began in the 1970s as pure colocation of high-technology firms, which were attracted by the pleasant local climate and policy supports. Firms locating there intended to conduct product adaptation R&D for the specific requirements of the European market. The reduced presence of larger MNEs in the 1990s then provided opportunities for the growth of spin-offs and start-ups in the local IT industry.

Sophia-Antipolis is also part of the French Secured Communicating Solutions cluster in the French Riviera in the Provence-Alpes-Côte d’Azur region, including Nice and Sophia-Antipolis Science Park. The cluster hosts several hundreds of small and medium-sized enterprises, research and higher education institutes, and several dozen large members, such as Alcatel Space, Atmel, France Telecom, HP, IBM, Philips, SAP, STMicroelectronics and Texas Instruments, covering microelectronics, telecommunications, software, and multimedia, from semiconductor technologies to applications (Dang, 2009). Among a number of local public research institutes which supply high-quality labor and new technologies (ter Wal, 2013), the European Telecom Standardization Institute (ETSI), which has been located in Sophia-Antipolis since 1989, is also critical to the development of modern telecommunication and related technologies (Di Minin & Bianchi, 2011). By the end of the 2000s, the IT cluster in Sophia-Antipolis had established a complete network of companies in various businesses, including infrastructure: equipment, networks, and hardware; platforms: interfaces and software; and applications and services (ter Wal, 2013).

United Kingdom. The history of the semiconductor industry in the UK began with the Royal Signals and Radar Establishment (RSRE), a scientific research unit of the British Ministry of Defence (von Hippel, 1976). However, over the decades the semiconductor industry in the United Kingdom did not grow to a comparable scale as it did in Germany or France, despite several rounds of government funding support. Instead, the renowned semiconductor cluster in Cambridge only emerged in the past two decades. In the 1990s, as the traditional semiconductor industry in the UK was vanishing, a micro-computer company founded by Hermann Hauser, Acorn, spun off its proprietary ARM microprocessor design as an independent business in Cambridge. According to company website (http://www.arm.com/), ARM’s IP cores and technologies are used in at least 95% of smartphones, 80% of digital cameras, and 35% of all electronic devices. The success of ARM encouraged a string of local semiconductor start-ups and attracted other top semiconductor companies to invest in the Cambridge area. In addition, Wolfson Microelectronics in Edinburgh has also developed into a substantial IC design company in the analog and mixed-signal product markets.

Russia. As one of the BRIC countries, Russia has a rather different development in the semiconductor industry. The country built its strong knowledge base in fundamental science and defense technology during the Soviet time but lacked the ability to commercialize its various cutting-edging technologies. The large number of highly-skilled engineers trained in the Russian defense industry, government research labs and universities have attracted investments from leading semiconductor companies worldwide. South Korean companies

Samsung and LG were among the early investors in Russia. Zelenograd, an area near Moscow, is an important location for the Russian semiconductor industry.

4.7.2 Asia

Taiwan. After a very long development, the Taiwanese semiconductor industry finally developed from the labor-intensive packaging and testing business to include an entire semiconductor value chain, including IC design, manufacturing, packaging and testing. Taiwan Semiconductor Manufacturing Company (TSMC) and United Microelectronics Corporation (UMC) are two world leading professional foundries of pivotal status in the global semiconductor value chain. Advanced Semiconductor Engineering (ASE) and Siliconware Precision Industries (SPIL) are both leaders in testing and packaging. Other companies also achieved a degree of success in related businesses, such as subcontract design services, mask-making, manufacturing equipment and material. These companies were mostly concentrated in Hsinchu and the greater Taipei area and only began to expand to the southern part of the island since the 2000s. While Hsinchu is home to MediaTek, Novatek and Realtek, many of the world’s leading semiconductor companies have set up offices in these two locations, which are a one-hour car drive from each other. Moreover, besides local access to various external service providers, Taiwanese IC design companies mainly serve domestic business customers in Taiwan and the enormous demand from the nearby Chinese manufacturing sector.

Singapore. The development of the semiconductor industry in Singapore began in 1987 with the establishment of the third professional foundry company in the world, Chartered Semiconductor Manufacturing (CSM), with support from the Economic Development Board (EDB), a government body. The company was a joint venture between government controlled ST Electronics and two American companies, National Semiconductor and Sierra Semiconductor. EDB also had other foundry joint ventures, including UMCi with UMC and Infineon, SSMC with Philips and TSMC, TECH with TI, Canon and HP. As shown in the case of the Taiwanese semiconductor industry, the presence of proximate local professional foundries is advantageous for the development of IC designs companies. The workforce in the Singaporean semiconductor industry is also supported by graduates from several renowned local schools and high-tech immigrants from nearby countries. In addition, nearby Malaysia, with the establishment of IC testing and packaging facilities in the 1970s, was one of the earliest investment locations, especially the city of Penang. The Malaysia Institute of Microelectronic Systems (MIMOS) was founded in 1985 with government support.

India. The semiconductor industry in India is unique in that it has emerged from providing IC design and software coding outsourcing services for IDM companies in the 1980s. Current investors in India represent various parts of the global semiconductor value chain, including IDM and IC design companies, IP suppliers, EDA companies and others. The majority of domestic IC design companies are headquartered in Bangalore, followed by Hyderabad and Chennai. On the other hand, local infrastructure and government policy have limited the growth of professional foundries and testing and packing businesses.

Israel. Finally, Israel has been recognized as an early leading country in the semiconductor industry, with IBM, Intel and HP investing in local R&D centers in the 1980s. Tower Semiconductor, a professional foundry company, was founded in 1993 with customers mostly in the US. Israel currently has a large number of domestic IC design companies and IP suppliers, which constantly attract acquisition investment from the US. Patenting records of several IC design companies are found to have originated in the area close to Yissum Research Development Company (http://www.yissum.co.il/), the technology transfer company owned by the Hebrew University of Jerusalem.

4.8 Discussion and conclusion

Patent data has been a unique data source used by empirical researchers and presented in academic publications in a wide range of disciplines, including economic geography, economic sociology, economic development, R&D management, innovation studies, strategic management, organizational learning, and international business, among others. Workshops and research seminars to promote potential applications and address methodological issues of patent data are commonplace.

For this research, leveraging patent data analysis has several benefits. Firstly, although the use of patent data originated from a specific branch of economic studies, its flexibility allows researchers to incorporate patenting records with other firm-, industry- and country-level data in novel research designs. It is also possible to strengthen ongoing research projects by expanding existing datasets with patenting records, which are publicly available. Secondly, the reliability and continuity of patent data are ensured by patent regimes, which regularly publish and update patenting records online. For longitudinal studies, this allows follow-up observations and future analysis. Thirdly, because of the wide use and increasing applications, the limitations of patent data and validity of patent metrics are continuously reviewed and discussed in academia and other public and private research organizations. These efforts continue to improve existing methodologies, provide new viewpoints, reject false interpretations, and thereby maintain the reliability of patent data analysis.

Finally, the last part of this chapter reviews the semiconductor industries in a number of countries. Their significance as the sources of advanced semiconductor technologies is reflected in the patenting records of the 28 IC design MNEs. It is important to find agreement between patenting records and other descriptive information, which indicates the validity of patenting records. Although patent data have been used to infer the technological advantages of countries and firms, much of the contextual information and crucial details can only be read from references and archives. Indeed, the following chapter will examine in detail the context of the IC design industry and the stories of these 28 IC design MNEs.

Appendix to Chapter 4

Notes

1. In private interviews taken place in person or online, four individuals have provided valuable insights on several of these topics. Each of these individuals has more than five years of experience in the IC design industry. They are either project managers or IC designers in public research institutes, consumer electronics and automotive electronics. The transcript and notes of these interview session are available by request, but the identities of interviewees are kept confidential and excluded from the document.

5 THE 28 IC DESIGN MNES AND THE IC DESIGN INDUSTRY

5.1 Introduction

Following an overview of the semiconductor industry, this chapter reviews the histories of these 28 IC companies and a number of issues within the context of the IC design industry. The chapter consists of a series of short case studies: in each case, the history of a company is summarized and attached with a brief discussion on a specific topic. A specific topic is selected and attached, when it emphasized in company annual reports and when it is also associated or applicable to several other companies. These themes include, for instance, the decision to relinquish manufacturing and become fabless, the entrepreneurs who chose the fabless business model, business concerns in the IC design process, business risks of the fabless business model, the decision to establish and manage an international R&D network, and the relationship between the IC design industry and other industries, universities and governments.

These case studies also further touch upon some points directly related to subsequent analysis, such as the coordination and decision-making challenges of IC design MNEs, locations of knowledge creation, and relevant knowledge sources. The discussion incorporates a decade of annual reports, industrial reports, patenting records, news archives and previous studies on the semiconductor industry. It intends to provide deep and context-rich understanding of the industry, which will help clarify the pertinence of this thesis to practitioners and the generalizability of its findings in other industrial contexts.

Lastly, an important piece of information—locations of knowledge creation—is manually collected from the full text of annual reports from 2000 to 2009. While engaged in fierce innovation competition, the majority of publicly-traded IC design companies regularly report the geographical locations for knowledge creation. The actual terminologies referring to these sites vary between companies, which may declare R&D centers, design centers, engineering centers, and product development activities, as well as technological service and support and field engineering office, among others. The variation in terminology may reflect the business statement of each R&D site as well as the administrative heritage of individual companies regarding how they describe R&D. These evolution and implication of different labeling of knowledge-creating units are really beyond the scope of this research, and therefore readings and searches in the full-text of company annual reports were conducted with a broad criterion to register all active and identifiable sites that can potentially create technology knowledge.

5.2 Stories of the 28 IC design MNEs

The company operations discussed in this series of shorts case studies is mainly regarding the period from 2001 to 2008 (see Table 5.29 for a summary). Companies tend to explain in length their focused technological areas and applications. Several companies also mentioned their organization, strategies, and main concerns for knowledge creation. All these provide a lens into their business and industry and indicate the relevance of knowledge creation for them. Changes in the corporate profile of knowledge-creating locations are sometimes explained in greater detail, including potential implications on business operation and corporate strategies.

These case studies are mainly based on the information disclosed in company annual reports and patenting records during the inter-crisis period. Meanwhile, company websites also provide more updated information for companies that remain in business. About those who provided limited information, ceased to function or become acquired business, other information sources were referred, such as earlier annual reports, industrial reports, new archives and the entries in International Directory of Company Histories published by St. James Press (1988-). Although corporate information disclosed in company websites and annual reports is by nature self-reported data, auditing by certified accounting agencies and cross-referencing reports from adjacent years have ensured the reliability of information to a certain extent. For the major events involving other large public companies, the viewpoints presented in their annual reports were also considered at times.

At the end of each case study, a table details the locations mentioned in the annual report, patenting by inventors from these sites and the floor space whenever available. Floor space is specified as *thousands square footage* owned or leased, and the patenting records are noted as *patenting in total (patenting in new patent class/ in assisting in patenting in new patent class)*. Patenting records in new patent classes provide some indication that the knowledge-creating activity in a specific location could be pioneering and entrepreneurial. Further discussion on this information is provided in 5.3.4.

5.2.1 Agere Systems and internal facilities

Agere Systems (NYSE: AGR) was incorporated on August 1, 2000, as a subsidiary of Lucent Technologies. The company made a public offering in 2001 and spun off from Lucent in the following year. After going through a series of restructurings and consolidation, Agere gradually became focused on IC products for storage devices, mobile phones, high-speed communications systems and personal computers. The company also had a foundry joint venture, Silicon Manufacturing Partners, with Chartered Semiconductor Manufacturing (CSM), and operated a manufacturing facility in Singapore since the late 1990s. Agere relied mostly on the joint venture while decommissioning its internal foundry facilities in Pennsylvania and Spain. However, for certain IC products that required advanced manufacturing processes, manufacturing activities were sourced externally from CSM and Taiwan Semiconductor Manufacturing Corporation (TSMC). Both CSM and TSMC were the leading professional foundries that were able to operate with scale economy while affording the hefty capital investments on developing and implementing cutting-edge IC manufacturing processes. On the other hand, Agere continued to utilize its internal assembly and testing facilities in Singapore and Thailand for the majority of its IC products.

Partially operating or taking an equity share of internal facilities can be justified by prioritized access to capacity, quality assurance and time efficiency based on the enhanced coordination of and direct control over internalized activities. Direct control and prioritized access help achieve faster delivery time for IC products and therefore faster time-to-market for business customers' products. Close coordination between designing and manufacturing effectively improves manufacturing yield rates as well as the implementation of designs that may require multiple revisions during the process. Internalized testing and assembly activities, on the other hand, allow IC companies to use and safeguard valuable proprietary technologies, such as special testing equipment and specialized packaging for certain IC products. In the case of Agere and several other IC design companies, internal testing and assembly facilities serve to expedite delivery time and ensure quality control. Several companies that supply to the defense and aerospace industries also tend to use internal testing and assembly facilities to achieve higher quality assurance and provide specialized packaging for specific IC products (Crawford et al., 2009).

While some larger and more mature IC design companies continued to maintain internal facilities and conduct a part of manufacturing and testing and packing activities internally, Agere's annual reports explained the challenges of maintaining these internal facilities. Firstly, because material and labor costs are lower than the capital investment in manufacturing equipment, clean rooms and so on, the manufacturing costs of IC products entail mostly fixed costs and relatively lower variable costs. Hence, high utilization rates of foundries and other facilities, product standardization and scale economies are the essential conditions to internalize these activities.

These conditions are, however, not satisfied in most cases as most IC design companies compete in responsiveness to changeable demand, product customization and small-volume niche markets (see 5.2.13 LSI). It is also difficult to accurately predict product demand for more than a few years (see 5.2.16 NVidia). If a sudden surge in market demand exceeds the capacity limit of internal facilities, companies will have to contract with external service providers at the costs of extra service charges and performance transition fees. Finally, advanced manufacturing processes, which are employed to maintain the performance edge of high-end IC products, require hefty and continuous capital investments to develop and implement. It is often the case that initial capital investments are funded by venture capital firms or government-sponsored sources. However, further and sustainable investments on manufacturing process R&D and on buying cutting-edge equipment rely on market demand and revenues staying at high and stable levels in future time periods, which are often not the case.

Table 5.1 The geographical distribution of Agere's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Australia						X	X				19 (0/0)	2005
Austria							X				0 (0/0)	
Canada						X	X				1 (0/2)	2005
China						X	X				10 (0/0)	2000
Germany						X	X				52 (10/0)	2000
India				X	X	X	X				17 (2/0)	2003
Ireland						X	X				4 (3/0)	2002
Israel						X	X				7 (0/0)	2006
Japan						X	X				2 (0/0)	2000
Korea						X	X				0 (0/0)	
Mexico		X	X								0 (0/0)	
Singapore		X	X	X	X	X	X				23 (2/3)	2000
Spain						X	X				10 (1/5)	2000
Taiwan						X	X				1 (0/0)	2000
Thailand		X	X	X	X	X	X				1 (0/0)	2000
UK				X	X	X	X				16 (1/2)	2000
US		X	X	X	X	X	X				1781 (189/10)	2000

Note: 1. Agere only reported its international R&D sites by country. 2. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.2 Altera Corporation and international R&D sites

Altera Corporation (NASDAQ: ALTR) was founded in 1983 in San Jose, California. Altera and its main competitor, Xilinx, were both early members of the IC design industry. Rodney Smith, the corporate founder, was a British engineer and former employee of Fairchild Semiconductor. Other founding members also had considerable industrial experience before joining the company. In 1983 Altera developed the re-programmable logic device (PLD), which created a new market segment in the semiconductor industry. PLDs are relatively standardized IC products as opposed to highly customized, application-specific integrated circuit (ASIC) (see 5.2.25 Xilinx). In terms of applications, the company focused on communications, electronic data processing, industrial, and consumer applications with high-density PLDs. More recently, the company also supplied PLDs to manufacturers of defense products, aerospace products, avionics and medical equipment. Initially, Altera sourced manufacturing capacity through agreements with Intel, Texas Instruments, and Sharp, and invested in Cypress Semiconductor in exchange for guaranteed supply. Since the mid-1990s, the company began to work with TSMC and WaferTech—a manufacturing joint venture between TSMC, Altera and others to build a professional foundry in the US.

Altera’s international R&D sites are listed in the following table, which reports the active years and floor space in thousand square feet if available in annual reports. The last two columns of the table report the number of patents received between 2001 and 2008, the starting year of effective knowledge creation based on the year of first successful patenting, and in parentheses the number of entries into new patent classes. The table suggests that Altera’s international R&D sites were relatively stable over the years, except a Vietnamese site in the Tan Thuan Export Processing Zone, which was briefly mentioned in the company's 2007 and 2008 annual reports. In an earlier annual report in 1998, Altera mentioned its European technology center in High Wycombe, UK, and Asian design center in Penang, Malaysia, for lowering R&D costs and conducting round-the-clock development activities.

Notably, this relative immobility of international knowledge-creating activities is likely due to the characteristics of PLD IC products, which are suitable for flexible use but are themselves relatively standardized IC products (also see 5.2.20 SanDisk). Business customers can configure these IC products for their specific applications in their manufacturing sites, using software tools and technology supplied by the company. While companies designing highly-customized ASIC products tend to establish and utilize their international sites to work closely and exchange information with business customers in proximity (see 5.2.13 LSI), PLD IC suppliers may rationalize, aggregate and conceptualize international knowledge-creating activities in a small number of locations. In fact, the same phenomenon was also observed in two other companies—Lattice and Xilinx—both of which supply PLD IC products and are discussed in the following sections.

Table 5.2 The geographical distribution of Altera's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Canada (Toronto)[3]	X	X	X	X	X	X	X	X	X	X	221 (3/0)	1998
Canada (Ottawa)[3]	X	X	X	X	X	X						
Malaysia (Penang)[1]	62	240	240	240	240	240	240	240	465	465	64 (0/0)	2001
UK (High Wycombe)[2]	X	X	X	X	X	X	X	X	X	X	173 (1/2)	2000
Vietnam (Ho Chi Minh)								X	X		0 (0/0)	
US (San Jose, CA)	500	500	500	500	500	500	500	500	500	500	1801 (61/1)	1984

Note: 1. The Penang site conducted both designing and testing activities. 2. Patent inventors were found living in multiple locations in Southern England. 3. The company reported Toronto Technology Center and Ottawa Technology Center in these locations. 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.3 *Atheros Communications and complementary technologies*

Headquartered in Santa Clara, California, Atheros Communications (NASDAQ: ATHR) was founded as T-Span Systems Corporation in 1998 by two faculty members of Stanford University, Teresa Meng and John Hennessy. It went public in 2004 and was acquired by Qualcomm in 2011. In particular, Teresa Meng, a Taiwanese immigrant, was a researcher in digital signal processing and radio frequency technologies with her professorship in the Department of Electrical Engineering at Stanford University. This personal expertise later became the core technological areas of the company when she became an entrepreneur. Based on its proprietary technologies in wireless communication and others, Atheros designed and supplied IC products for manufacturers of personal computers, networking equipment and consumer electronics devices.

Moreover, Atheros's knowledge-creating activities closely followed the development of mobile devices, mobile connectivity and various mobile services, expanding its product offerings and functionality with complementary technologies. Atheros expected that their business customers—the manufacturers of mobile devices—intended to incorporate wireless connectivity and other functions into their products, such as mobiles phones for Internet browsing, mobiles devices with Wi-Fi and Bluetooth connections, and mobile navigation devices based on Global Positioning System (GPS) technology. High-speed Wi-Fi connection allows consumers to connect to the Internet for browsing and using various online services; Bluetooth connection, which has the advantage of lower power consumption, enable wireless access to peripheral devices, such as headsets, mouse, keyboard and others. Finally, the GPS technology, which uses a series of satellites to determine the location information of the users, could be combined with wireless connections to provide tracking and location-related services.

While significantly expanding the functionality of mobile devices, the design effort to incorporate these technologies into the end product hinged on the availability of advanced IC products. The costs, functionality, size and power consumption of IC products are rightly the factors that affect the cost, functionality, dimension and power consumption of mobile devices. Atheros and other competing IC design companies, therefore, fiercely competed in their capability to develop IC products with the specifications required by mobile device manufactures, and in combining more technologies to make redundant those extra IC products needed for additional functions. IC design companies that come up with the best IC products may achieve *design-win*—business customers' decision to purchase and incorporate IC products into their end products. Moreover, the sales of extra IC products needed for additional functions would be affected, and the survival of IC companies supplying them compromised.

Table 5.3 The geographical distribution of Atheros's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Canada										X	0 (0/0)	
China (Shanghai)						X	X	X	X	X	0 (0/0)	
Finland (Tampere)								X	X	X	4 (1/0)	2005
India (Chennai)				X	X	X	X	X	X	X	0 (0/0)	
India (Bangalore)								X	X	X		
Taiwan (Hsinchu)							X	X	X	X	0 (0/0)	
US (Irvine, CA)								X	X	X	196 (33/0)	1999
US (Santa Clara, CA)[1]				X	56.34	87.33	87.33	137.53	X	X		
US (FL)										X		

Note: 1. The entry includes nearby Sunnyvale, California. 2. The company started to publish its annual report in 2003. 3. The 2009 annual report also mentioned Canada and Florida, the US. 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.4 ATI Technologies and manufacturing processes adoption

ATI Technologies (NASDAQ: ATYT; TSE: ATY) was founded as Array Technology in 1985 and by the end of the same year renamed as ATI Technologies. Until its acquisition by Advanced Micro Devices (AMD) in 2006, which gradually retired the former's brand name, ATI and its main competitor NVidia were the leading suppliers of graphics IC products. As the demand for computer graphics and multimedia applications continued to grow in the consumer electronics market, ATI, NVidia and several lesser known IC design companies fiercely competed to introduce revisions and new generations of graphic processing unit (GPU) IC products. Both companies competed to introduce new flagship products and update their product offerings in accordance with the schedule for qualifying and shipping products as well as the seasonal demand increase in the spring and fall seasons. A flagship product would last between six and eighteen months—a rather short commercial lifecycle given the amount resources required to design and manufacture such IC products. Moreover, amid this fast-paced R&D competition, both companies would also regularly evaluate and conduct the transition into cutting-edge manufacturing processes available from professional foundry companies. Effectively harnessing latest manufacturing process innovations is critical to maintaining the performance edge of IC products and hence the competitive advantage of these IC design companies, which supply relatively standardized high-performance IC products.

ATI's annual reports explained the technical and managerial challenge of utilizing cutting-edge manufacturing processes. In semiconductor manufacturing, process technologies define the minimum size of features, including transistors and other components. Advanced process technologies create smaller features that allow more components to be built in an IC and more ICs per wafer, increasing functionality while cutting the unit cost. However, fabrication using cutting-edge manufacturing processes often involves new technologies and new equipment that are not yet familiarized by either IC design companies or professional foundry companies or both, which causes time-consuming revisions and low manufacturing yield rates. Moreover, because manufacturing yield rates are contingent on specific IC designs and manufacturing processes utilized, solving yield rate problems requires cooperation and communications between IC design companies and their manufacturing service providers. However, for most IC design companies, the geographical distance to service providers concentrated in East and Southeast Asia would often complicate the process (see also 5.2.23 SMSC and 5.2.19 Realtek).

Table 5.4 The geographical distribution of ATI's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Barbados		X	X	X	X	X					0 (0/0)	
Canada (Markham, Ontario)[1]		179	240	240	240	240					510 (53/0)	1992
China (Shanghai)					X	X					0 (0/0)	
Germany (Starnberg)			X	X	X						2 (0/0)	1996
Hungary			X	X	X	X					0 (0/0)	
India						X					0 (0/0)	
Korea					X	X					0 (0/0)	
Ireland (Dublin)[2]		35	35								0 (0/0)	
US (Santa Clara, CA)		104	104	104	104	104					349 (24/1)	1994
US (Marlborough,		60	60	60	60	75						

MA)			
US (Newtown, PA)	34	34	35
US (Langhorne, PA)		13.5	

Note: 1. There were several other sites in Markham, Ontario, for different purposes. 2. Logistic, software, manufacturing and technical support for the European market. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.5 *Avago Technologies and industrial and automotive applications*

Headquartered in Yishun, Singapore, Avago Technologies (NASDAQ: AVGO) was, from 1961, the semiconductor business of Hewlett-Packard and later became a part of Agilent Technologies, from which Avago became an independent business entity as a spin-off in 2005. Its operation in the Asia-Pacific area, which started as early as the 1970s, created proximity to business customers and the center of worldwide electronics supply chain. Avago maintained internal fabrication facilities for some of its IC products, utilizing innovative and non-standardized materials and manufacturing processes. While using internalization to protect its proprietary technologies, the company continued to invest and develop its internal manufacturing capability. Applications for Avago’s IC products could be found in consumer products, personal computer peripherals, data networking and telecommunications equipment, enterprise storage and servers, factory automation and military electronics.

Avago mainly served four markets, including industrial and automotive electronics, wired infrastructure, wireless communications, and consumer and computing peripherals with an enormous product portfolio consisting of thousands of analog, mixed-signal and optoelectronic IC products. However, relative to the diverse and changeable demands in the consumer electronics market, IC products for industrial and automotive applications typically have longer commercial life cycles and more stable average selling prices (see also 5.2.28 Dialog). Longer commercial life cycles relate to complexities in arduously designing and comprehensively testing IC products for the industrial and automotive market in which the end products are themselves costly to design and test. Between designing and testing, different manufacturing materials, special manufacturing processes and specialized packaging may be employed. In addition, industrial and automotive applications tend to contain highly fragmented and idiosyncratic industrial standards, which are relatively unified for most consumer electronic devices. Hence, for the IC design companies and their business customers in these markets, close relationships as well as high switching costs arise from all these concerns and carry over to the design work for future IC products.

Table 5.5 The geographical distribution of Avago's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Malaysia (Penang)[1]							515	439	439	318	212 (39/4)	2005
Germany (Boeblingen)							21	21	19	19	26 (7/0)	2005
Germany (Regensburg)[1]								21	21	21		
Italy (Turin)[1]							59	59	59	43	12 (2/1)	2005
Korea (Seoul)							28	28	36	55	9 (1/0)	2005
Singapore (Yishun)[1]							234	234	176	144	57 (26/0)	2005
Singapore (Depot Road)[1]							52					
Singapore (Senoko)[1]							52					
US (Ft. Collins, CO)[1]							1058	1058	883	833	400 (150/8)	2005
US (San Jose, CA)							183	183	183	148		

Note: 1. Avago externally sourced at least 75% of its manufacturing capacity but reported several internal facilities in these locations. 2. Frequent adjustment in subsidiary mandates was observed during the time period. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.6 Broadcom and university connections

Broadcom Corporation (NASDAQ: BRCM) was founded by Henry Samueli and Henry Nicholas III in Los Angeles, California, in 1991 and later moved to Irvine in 1995. During its early years, the company offered various customized IC designs for a wide range of applications and later became focused on IC products for computer networking and broadband internet access. Broadcom supplied IC products and software solutions to manufacturers of computing and networking equipment, digital entertainment, broadband access products and mobile devices. Notably, following its public offering in 1998, Broadcom pursued an acquisition-based growth strategy rather aggressively. Between 1999 and 2008, the company conducted more than three dozen business acquisitions and another dozen in the years following the financial crisis. These acquisitions were mostly targeted at smaller companies and business units with technological expertise related to Broadcom’s core product lines. Moreover, some these acquisitions, including international acquisitions and acquisitions of small MNEs, became the starting point for Broadcom’s international knowledge-creating activities, such as HotHaus Technologies in Canada and Armedia in India, among others. According to Broadcom’s annual reports, these specific acquisitions resulted in its international R&D sites in Belgium, Israel, Taiwan and the United Kingdom.

Universities and faculty with special expertise are important sources of cutting-edge technological knowledge (Thursby & Thursby, 2006), and both Broadcom and another giant IC design company, Qualcomm, have had connections to renowned research universities since their founding. Henry Samueli was a Professor at University of California, Los Angeles (UCLA), and Henry Nicholas III was a PhD alumnus of the same university. Qualcomm was founded by Irvine Jacob, a Professor in University of California, San Diego (UCSD), and Andrew Viterbi, a Professor at UCLA and UCSD; both were also alumni of Massachusetts Institute of Technology (MIT). Without any accepted indicator for whether these relations have translated into better access to scientific knowledge created in these universities, patenting records of both companies in the inter-crises time period, nevertheless, have included a large number of backward citations to patents assigned to the Regents of the University of California—the governing board of the University of California. Arguably, these knowledge inflows might have resulted from their geographical proximity to these universities. However, Qualcomm, whose founders also graduated from MIT in the East Coast of the US, made a lot more citations to MIT patents than did Broadcom: 30.1% of Qualcomm’s backward citations to university patents are associated with MIT patents, while only 8.0% of Broadcom’s citations to university patents are the case.

Table 5.6 The geographical distribution of Broadcom's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Belgium	X	X	X	X	X	X	X	X	X	X	33 (0/0)	2000
Canada	X	X	X	X	X	X	X	X	X	X	100 (0/0)	1999
China			X	X	X	X	X	X	X	X	2 (0/0)	2005
Denmark						X	X	X	X	X	0 (0/0)	
France					X	X	X	X	X	X	5 (0/0)	2006
Greece						X	X	X	X	X	26 (0/0)	2002
India	X	X	X	X	X	X	X	X	X	X	97 (1/0)	2000
Israel	X	X	X	X	X	X	X	X	X	X	79 (0/0)	2000
Japan						X	X	X	X	X	0 (0/0)	
Korea						X	X	X	X	X	0 (0/0)	
Netherlands	X	X	X	X	X	X	X	X	X	X	54 (1/2)	1999
Singapore[1]	X	X	X	X	X	X	X	X	X	X	16 (0/0)	2002
Spain									X	X	1 (0/0)	2008
Taiwan	X	X	X	X	X	X	X	X	X	X	16 (0/0)	2001
UK	X	X	X	X	X	X	X	X	X	X	119 (6/0)	1999
US (Tempe, AZ)	X	X	X	X	X	X	X	X			5465 (126/1)	1994
US (San Diego, CA)	X	X	X	X	X	X	X	X	X	X		
US (Los Angeles, CA)	X	X	X									
US (Pleasanton, CA)	X	X										
US (Santa Clara, CA)[2,4]	X	X	X	X	X	X	X	X	X	X		
US (Irvine, CA)[4]	X	X	X	X	X	X	X	690	750	800		
US (Colorado Springs, CO)[3]						X	X	X				
US (Duluth, GA)	X	X	X	X	X	X	X	X				
US (Andover, MA)					X	X	X	X				
US (Germantown, MD)					X	X	X	X				
US (Bloomington, MN)								X				
US (Morrisville, NC)								X				
US (Nashua, NH)				X	X	X						
US (Matawan, NJ)			X	X	X	X	X	X				
US (Glen Rock, NJ)								X				
US (Lancaster, PA)								X				
US (Austin, TX)						X	X	X				
US (Dallas, TX)	X	X	X									
US (Seattle, WA)	X	X	X	X	X	X	X	X				

Note: 1. The distribution center in Asia. 2. Various locations in California were gradually consolidated in Santa Clara since 2002. 3. The entry includes nearby sites in Fort Collins and Longmont, Colorado. 4. Following a restructuring plan in 2008, only two main sites in California were mentioned in annual reports. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.7 Cirrus Logic and corporate restructuring

Cirrus Logic (NASDAQ: CRUS) was founded as Patil Systems in Utah by Suhas Patil, a former faculty member of MIT and University of Utah, in 1981, and was later reincorporated as Cirrus Logic in 1984 after moving to Fremont, California. Initially, the company focused on designing controller IC products for computer hard drives and entered the area of computer display in the 1990s. Following its initial public offerring in 1989, it quickly expanded its technological expertise through a series of merger and acquisitions. Due to its rapid growth, the company faced integration and communication problems and made the decision to restructure and decentralize in the 1990s in order to expedite its R&D activities and new product delivery.

On the other hand, although the company was founded with the fabless business model, as a large number of IC design companies jostled for a limited supply of manufacturing capacity in the 1990s, Cirrus Logic went beyond longer-term supply contracts with service providers and made investments in foundry facilities. To ensure the level of manufacturing capacity available, the company was briefly engaged in a number of manufacturing joint ventures with IBM, Lucent Technologies and UMC, respectively. However, when slow product development and stagnated sales resulted in low utilization rates, these manufacturing joint ventures ended with hefty financial losses, which sent the company into another series of corporate restructurings in late 1990s. After the second relocation of its headquarters to Austin, Texas, in the early 2000s, the company exited several markets, conducted another series of mergers and acquisitions and gradually became a supplier of IC products for consumer, professional and automotive entertainment and industrial measurement applications.

The progressive restructuring of Cirrus Logic is reflected by the changes in it R&D sites reported over the years. The number and geographical spread of these sites often expanded as a result of merger and acquisitions and then waned during consolidations. The company's

R&D labor force was more than halved, while several product lines were terminated and the company gradually developed more standardized product offerings. For example, in the several years following the decision to relocate its headquarters to Austin, Texas, Cirrus Logics phased out most R&D sites in the US by mid-2000s. Then in 2007, the company added Tucson, Arizona, to the list as a result of the acquisition of Apex Microtechnology, an IC design company specialized in industrial and aerospace applications. The site also housed facilities to conduct testing and packaging activities internally, because manufacturers in these markets often demanded special packaging and additional testing for IC products (see Section 5.2.1 Agere for more discussion). The site was later closed in late 2012, after the company sold the business and relocated the remaining employees, primarily R&D personnel, to its headquarters in Austin, Texas.

The fluidity observed in the history of Cirrus Logic is not uncommon in the IC design industry. Companies sometimes deviated from an unadulterated fabless business model and participated in manufacturing joint ventures or R&D joint ventures in the hope of securing their access to manufacturing capacity and advanced manufacturing processes. Corporate headquarters were relocated to reflect the changes in business focus, and the geographical distribution of knowledge-creating activities would also be realigned accordingly. New sites were added as a result of corporate development and new business operations for burgeoning markets, while mergers and acquisitions seemed to be an effective means for such changes.

Table 5.7 The geographical distribution of Cirrus Logic's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
China (Beijing)[1]		X	X	X	X	X	X				0 (0/0)	
China (Shanghai)[1]		X	X	X			X	X				
China (Shenzhen) [1]		X	X	X	X							
Hong Kong				X							0 (0/0)	
India (Pune)	X	X	X								12 (0/0)	2000
Japan (Tokyo)	X	X	X	X							4 (0/0)	1996
Korea (Seoul)				X	X						0 (0/0)	
Singapore	X	X	X	X							5 (0/0)	1998
Taiwan (Taipei)				X	X						0 (0/0)	

US (Tucson, AZ)[2]								54	54	54	1111 (74/0)	1987
US (Fremont, CA)[3]	54	100	77	167	167							
US (Boulder, CO)[4]	X	X	X	X	X	12						
US (Boca Raton, FL)	X	X										
US (Ft. Wayne, IN)	X	X	X	4								
US (Austin, TX)	248	215	197	197	197	144	144	144	181	176		

Note: 1. The company did not report the exact location of its Chinese R&D sites in 2001 and 2002. 2. The sites also hosted testing and assembly activities. 3. Floor spaces in Fremont, California, the company's former headquarters were mostly subleased. 4. The entry included nearby Broomfield, Colorado. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.8 CSR and the Cambridge cluster

CSR (LSE: CSR) was formerly Cambridge Silicon Radio based in Cambridge, the United Kingdom. CSR was a leading supplier in the wireless communication market with its Bluetooth IC products designed to enable short-distance, wireless data and voice communication in a wide range of end products. Bluetooth technology has the advantage of low power consumption in a shorter distance, and CSR offered IC products that also incorporated Wi-Fi technology for longer distance wireless communication. As a key source of its competitive advantages, the company owned the expertise in combining these related but different wireless communication technologies in one electronic device without compromising the performance of either function. The company went public in 2004 and extended its product lines to include GPS IC product (see also 5.2.3 Atheros). During a series of acquisitions between 2007 and 2009, the company acquired SiRF Technology, the once world's largest supplier of GPS IC products. CSR's technologies were widely adopted in devices such as mobile phones, wireless headsets and input devices, laptops, personal computers, automobile and personal navigation and other personal and commercial tracking devices.

CSR was founded in 1998 and spun off in the following year from Cambridge Consultants, a private research company formed by alumni of the University of Cambridge in 1960. After spinning off in 1999, CSR quickly grew from a few dozen people to more than a thousand employees in 2007 with business operations in eleven countries. Cambridge Consultants and Acorn computer were the founding companies and early success in the renowned Cambridge hi-tech cluster. Over the years, the Cambridge cluster developed and hosted a complete network of entrepreneurs, researchers, research consultancies and companies, technology startups and venture capital firms (Myint et al., 2005). Companies in the cluster mostly operated in the biotechnology, electronics and software industries, and many were connected to the University of Cambridge. Acorn computer, a British computer company founded in Cambridge in 1978, later gave rise to ARM and Conexant, two top IC design companies.

Table 5.8 The geographical distribution of CSR's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
China (Shenzhen)						X					6 (2/0)	2008
Denmark (Aalborg)					X	X	X	X	X		0 (0/1)	
France (Sophia Antipolis)						X	X	X	X	7.5	1 (0/1)	2008
India (Bangalore)						X	X	X	X	26.5	0 (0/1)	
India (Noida)										9.2		
Sweden (Lund)						X	X	X			2 (0/1)	2007
Sweden (Stockholm)								X	X	5.2		
US (Phoenix, AZ)										26.3	43 (14/1)	2003
US (Santa Ana, CA)										12.6		
US (San Jose, CA)										48.0		
US (Cedar Rapids, IA)										7.4		
US (Detroit, MI)						X	X	X	X	X		
US (Richardson, TX)[1]	X				X		X	X	X			
UK (Cambridge)					X	X	X	X	X	51.0	44 (17/0)	2000

Note: 1. A nearby site in Dallas, Texas, was also reported in some years. 2. The company's international R&D site expanded significantly following the acquisitions of Clarity Technologies in 2005 and SiRF Technology in 2009. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.9 DSP Group and acquisition entry

DSP Group (NASDAQ: DSPG) was founded in 1987 with headquarters in San Jose, California. The company was specialized in IC products for signal processing and wireless communications, mainly in short-distance, home applications. In early 1999, DSP group acquired the radio-frequency cordless telephone business unit from AMD, bringing in two groups of engineers in Israel and the US. This specific acquisition, which later became the main business focus of DSP Group, expanded not only the company's knowledge-based assets and R&D labor force but also its international R&D activities to Israel. Notably, quite a few US-based IC design companies operated in this Middle-Eastern country, which has developed a strong indigenous semiconductor industry, including several other companies studied in this research. DSP Group's Israeli subsidiary actually hired more engineers than those in its corporate headquarters in California. At the height, its Israeli site in Herzelia Pituach employed more than eighty percent of the company's worldwide R&D labor force and occupied more floor spaces than the headquarters in Santa Clara, California. The company also indicated in annual reports that tax benefits were granted by the Israeli government by the Law for the Encouragement of Capital Investments.

Similar policy support was provided by several small open economies, such as Canada, Ireland, Scotland, Singapore and Taiwan, as reported by several companies. However, in the case of the IC design industry, the actual effect of policy support is sometimes ambiguous because the fabless business model has much lower demand for capital and labor and the flow of tangible intermediate goods occurs mostly in other countries.

Table 5.9 The geographical distribution of DSP Group's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Israel (Herzelia Pituach)	29.8	29.8	19.6	19.6	X	X	X	17.7	58.1	58.1	21 (11/0)	1988
US (Palo Alto, CA)	X	X									38 (15/0)	1997
US (Rancho Cordova, CA)					X	X	X	X	X	X		
US (Santa Clara, CA)[1]	15.7	14.3	14.3	14.3	12	12	12	3.8	3.8	3.8		
US (Colorado Springs, CO)					X	X	X	X	X	X		
US (Chicago, IL)[2]	X	X	2.1	2.1								
US (Minneapolis, MN)[3]					X	X	X	X	X	X		

Note: 1. The entry includes nearby San Jose, California, where DSP Group was formerly headquartered. 2. The entry includes nearby Schaumburg, Illinois. 3. The entry includes nearby Bloomington and Minnetonka, Minnesota. 4. Patenting records are noted as total patent count (new patent class patent/new patent class participation). Source: This research.

5.2.10 ESS Technology and the loss of competitive advantages

ESS Technology (NASDAQ: ESST) was founded in Fremont, California, in 1984. It was a pioneer in designing IC products for audio functions with some remarkable success in the 1990s. The company later entered the then emerging digital video market and gradually expanded to applications in a wide range of consumer electronics, such as DVD, VCD, MP3 and other digital media players, digital camcorders, mobile phones and personal computers. Unfortunately, when these markets gradually matured and became saturated, ESS lost its competitive advantages against competing IC design companies from East Asia, falling into decline in the mid-2000s. Before it was delisted from NASDAQ in 2008, the company's annual report explained the several challenges facing it. Firstly, different IC products markets began to coalesce, while an increasing number of functions were built into IC products (see 5.2.8 CSR and 5.2.3 Atheros). Secondly and relatedly, different electronic devices also combined and caused the consolidation of electronics manufacturers. Thirdly, facing the erosion of familiar markets, ESS failed to find new niche markets while existing product lines became commodities. Finally, as reckoned in ESS's annual reports, IC design companies in East Asia, especially those from China and Taiwan, had developed the expertise in designing advanced products and forced ESS out of several markets while having significant cost advantages over the company (see also 5.2.19 Realtek).

While other examples abound, a recent case of market consolidation came from the emergence of the mobile phone as the principal mobile device for accessing and transmitting digital content. Particularly in the past decade, modern mobile phones, or so-called smartphones, have incorporated various functions for work and personal entertainment, which used to be the features of a list of devices such as personal digital assistant (PDA), MP3 Players, and portable DVD players. Smartphones literally substituted for all these devices and consolidated these once separated end product markets. Moreover, when these end products merged and retired others, competition in different end product markets fused and coalesced competing electronics manufacturers as well as the IC design companies in their supply chains. Electronics manufacturers began to demand IC products with more integrated functions, purchasing fewer IC products in larger quantities (see 5.2.3 Atheros for a discussion). The technological expertise and design capability to incorporate different technologies and integrate multiple functions into IC products thus became critical for the viability of businesses in the now consolidated market (see also 5.2.8 CSR).

In the case of ESS, its market shares were gradually replaced by East-Asian competitors with abundant financial and human resources, the advantages derived from their country locations, and by North American competitors with greater technological expertise and superior design capability. An alternative strategy would be to develop or acquire new product lines and seek opportunities in other underserved markets, and several other IC design companies have indeed done so with success (see 5.2.11 Genesis Microchip and 5.2.26 Zoran). Several such attempts by ESS were, however, largely unsuccessful. The company failed to increase its scale and technological domains through capital investments or mergers and acquisitions. In 2007, the company decided to close its VCD/DVD-related IC product lines, which accounted for more than 80 percent of its revenues. It then licensed and sold its proprietary technologies to three IC design companies based in China and Taiwan.

Table 5.10 The geographical distribution of ESS's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
China			X	X	X	X	X	X			0 (0/0)	
France						X					0 (0/0)	
Hong Kong	X	X	X	X	X	X	X	X			0 (0/0)	
Japan			X	X	X	X					0 (0/0)	
Korea			X	X	X	X	X	X			0 (0/0)	
Taiwan	X	X	X	X	X	X	X	X			0 (0/0)	
US (Fremont, CA)[1]	93	93	93	85	102	170	170	170			94 (24/0)	1993

Note: 1. The floor space of the site remained the same, while a varying proportion of it was subleased. 2. The only foreign country origin observed in the patenting records of ESS is Canada: 30 (2/0), which is not mentioned in company annual reports. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.11 Genesis Microchip and organization of R&D activities

Genesis Microchip began as a Canadian firm in Markham, Ontario, in 1987 and reincorporated in Delaware with its new headquarters in Alviso, California, in 2002. Genesis Microchip mainly focused on digital image processing technologies until the late 1990s, and then gradually expanded with a series of mergers and acquisitions of companies with complementary technologies (see also 5.2.6 Broadcom). According to its annual reports, through the acquisition of Paradise Electronics, it was able to combine analog and mixed signal technologies of the former with its digital image processing technology; through the acquisition of Sage Inc., it entered the market of flat-panel monitors and other emerging display applications. Hence, before its acquisition in 2007 by STMicroelectronics, an Italian-French IDM company headquartered in Geneva, Switzerland, the company had successfully shifted its business focus to display controller IC products, which would receive and process video and images for viewing on flat-panel display devices, such as flat-panel televisions and computer monitors.

Interestingly, the company's annual reports also explained its organization of R&D activities and division of R&D labor force. There were three specialized R&D groups, each performing a specific set of assigned duties. Firstly, the Algorithm Development Group was tasked with developing high-quality image processing technologies and fostering the implementation of these technologies in actual IC design. Then, the Product Development Group conducted design activities for standardized IC products for business customers. Thirdly, the Software Engineering Group would develop the software tools to assist these business customers in incorporating IC products into their end products. The company's annual reports suggested that its patenting activity covered various aspects of algorithms, architectures, IC designs and software tools. In addition, the company also hired field engineers stationed worldwide to work with sales and marketing personnel. Field engineers would not only participate in the discussion of product specifications with business customers but also assist with incorporating

IC products into their products (see 5.2.22 Silicon Labs). Genesis Microchip indicated in annual reports that field engineers accounted for more than one-third of the employment in sales and marketing offices, and around one-fifth of its overall engineering and R&D labor forces. The company also constantly reviewed the overall process of R&D and product planning from the managerial perspective to improve the quality of its IC designs.

Table 5.11 The geographical distribution of Genesis Microchips' knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Canada (Thornhill)[1,2]	X	X	X	X	X	X	X				27 (7/0)	1993
China (Shanghai)				X	X							
China (Shenzhen)		X	X	X	X	X	X				0 (0/0)	
China (Suzhou)			X									
Germany						X	X				0 (0/0)	
India (Bangalore)[1]		X	X	X	X	X	X				11 (0/0)	2002
Japan (Tokyo)		X	X	X	X	X	X				0 (0/0)	
Korea (Seoul)		X	X	X	X	X	X				0 (0/0)	
Singapore					X	X	X				0 (0/0)	
Taiwan (Taipei)	X	X	X	X	X	X	X				0 (0/0)	
Turkey (Izmir)							X				0 (0/0)	
US (Alviso, CA)[1,3]	X	X	X	X	X	X	X				97 (28/1)	1997

Note: 1. The company's main R&D centers were located in Canada, India and the US. 2. Corporate headquarters until 2002. 3. This entry includes several nearby locations in California, including Milpitas, San Jose, Santa Clara and Sunnyvale. 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.12 Lattice Semiconductor and cross-licensing agreements

Lattice Semiconductor Corporation (NASDAQ: LSCC) was founded in 1983 as Lattice International in Oregon. After several years of struggling as a startup, restructuring and finally reemerging from bankruptcy, Lattice relocated its headquarters to in Hillsboro, Oregon, and went public by the end of the 1980s. The company mainly supplied PLDs and related software tools for original equipment (OEM) manufacturers in the communications, computing, consumer, industrial, automotive, medical and defense markets (see also 5.2.2 Altera). Unlike highly-customized ASIC and ASSP IC products, PLDs are relatively standardized IC products sold and purchased in a blank state and then configured into various functions by software programming tools (see Table 5.2 in Appendix for a summary of main categories of IC products). Competing with Altera and Xilinx, the two leading firms in this product category, Lattice positioned its product offering in low-performance and low-power consumption applications. With moderate rationalization of its international R&D activities, the company largely maintained the same strategy over the years and acquired several business units that were relatively close to its core business. These acquisitions successfully increased the company's market share, accelerated the entry into several related product segments and added to its knowledge-based assets and R&D labor force.

Acquisitions and transfer of business units between companies often involve intellectual properties licensing—one of the mechanisms facilitated by the IP regime, which establishes markets for information and techniques, while infringement litigation is another (Mazzoleni & Nelson, 1998). Several IC design companies and IP suppliers have generated significant revenues from technology licensing (see 5.2.27 ARM and 5.2.18 Qualcomm). Moreover, competing companies with overlapping product lines may at certain times enter cross-licensing agreements. Examples may include the transfer of technologies alongside business mergers and acquisitions as well as the negotiation of settlement agreements to end patent infringement litigation (see also 5.2.24 VIA Technologies). In particular, Teece (2000) points out that cross-licensing is usually less concerned with technology transfer but more related to the exchange of rights to use technologies, which promotes the development and exploitation of innovations and prevents infringement claims from patent holders in the same technological area.

Lattice's annual report provided information on several such cases. In 1999, Lattice entered a cross-licensing agreement with AMD after acquiring Vantis Corporation, AMD's wholly-owned subsidiary in PLD business. The agreement allowed the mutual access to each other's proprietary technologies related to PLD IC products on a worldwide, non-exclusive and royalty-free basis. Additionally, due to patent infringement litigation, which began in 1994 between AMD and Altera, after acquiring Vantis and replacing AMD as a party, Lattice also entered a comprehensive cross-licensing agreement with Altera in 2001 as a part of the settlement agreement. Lastly, in 2002, as a part of the acquisition agreement of Agere's FPGA business, Agere's FPGA related patents, trademarks, software and other IPRs and technologies were assigned or licensed to Lattice, which then licensed back to Agere the rights in these intangible and knowledge-based assets.

Table 5.12 The geographical distribution of Lattice's knowledge creation

R&D Center	**'00**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**	**Patent**	**Since**
China (Shanghai)	13	13	29	29	29	29	27	27	37	37	1 (0/0)	2008
UK (Chippenham)[1]	X	X	X	7.5	7.5	7.5					6 (0/1)	1998
US (San Jose, CA)	133	133	133	133	133	133	133	99.5	66.4	66.4	444 (32/0)	1985
US (Broomfield, CO)[2]		X	X	X	X	6.3						
US (Colorado Spring, CO)	7	X										
US (Naperville, Il)[3]		X	X	X	X	6.4	6.4	6.4	6.4	6.4		
US (Hillsboro, OR)	200	200	200	200	200	200	200	200	200	189		
US (Bethlehem, PA)[4]		X	X	X	X	36	36	36	20	20		
US (Austin, TX)	40	X	X	25	25	25						
US (Salt Lake City, UT)		X	X	X	X	13.4						

Note: 1. The entry includes nearby Corsham, the UK. 2. The entry includes nearby Boulder, Colorado. 3. The entry includes nearby Downers Grove, Illinois. 4. The entry includes nearby Allentown, Pennsylvania. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.13 LSI Corporation and product customization

LSI Corporation (NASDAQ: LSI) was founded as LSI Logic Corporation in Milpitas, California, in 1980, and later reincorporated in Delaware in 1987. After acquiring Agere Systems in 2007, the company was renamed as LSI Corporation, and finally, in 2014 it was acquired by Avago Technologies, another IC design company studied in this research. LSI was founded by Wilfred Corrigan, a British engineer and former chairman of Fairchild Camera and Instrument Company, with an innovative business focus on the niche market of application-specific IC (ASIC) products, based on the more flexible gate-arrays technology and the anticipation that the demand for highly customized products would expand in the coming years. He planned to enter a small niche segment of the semiconductor industry supplying small batches of half-finished IC products, which would be customized for each customer later on. In contrast with the standardized product offering from large US and Japanese IC companies in the 1980s, these customized IC products help business customers to achieve product differentiation. From 1980 to its acquisition in 2014, LSI Corporation was a microcosm of the modern history of the US semiconductor industry, including its reconfiguration in the 1980s to develop design-intensive, higher-margin and highly-customized IC products in response to emerging competition from NIEs (Langlois & Steinmueller, 1999).

The design process of ASIC products requires intensive person-to-person communication, usually involving engineers from both IC design companies and their business customers (see 5.2.22 Silicon Labs). Field engineers from IC design companies work closely with engineers from business customers before proceeding to the stages of design simulation, verification, synthesis and finally fabrication. Business customers receive technological assistances during the entire process in order to optimize the performance and stability of customized ASIC products intended for specific applications. To achieve the *design-win* of their IC products, design companies try to participate as early as possible in customers' product development process and share some costs and risks. McEvily and Marcus (2005) suggest such joint problem-solving arrangements, including information sharing and trust, facilitate the transfer of insights, experience and capabilities between customers and suppliers.

According to LSI's annual reports, its worldwide design centers, in which were stationed experienced field engineers, were located in proximity to major markets, in order to interact with business customers' engineering management and system architects and to develop designs and to provide continuous customer support (see also 5.2.11 Genesis Microchip). While the terminologies vary—other IC design companies also used engineering center technology services offices—proximity to customers and joint problem solving are critical to win out in the competition of design-intensive IC products (see also 5.2.22 Silicon Labs).

Another important part of the historical evolution of the US semiconductor industry has been the sourcing of external manufacturing capacity. Initially, like most semiconductor companies at the time, LSI invested in its own foundry and assembly facilities and conducted manufacturing and testing and packing activities internally in California. In the late 1980s, LSI also invested in Nihon Semiconductor, a manufacturing joint venture with Kawasaki Steel Corporation in Japan. Because of its early involvement in semiconductor manufacturing, LSI was one of the fourteen founding members of Semiconductor Manufacturing Technology Consortium (SEMATECH)—a research consortium supported by the US Government to advance semiconductor manufacturing technologies in the US (Browning et al., 1995; Irwin & Klenow, 1996). LSI, however, left the consortium in 1992 due to financial difficulties and divergent goals: SEMATECH's aim to develop technologies for standardized, high-volume manufacturing conflicted with LSI's business focus on highly specialized and customized IC products for niche market customers (Los Angeles Times, January 1992). In 2001, the company announced its R&D collaboration and foundry supply agreement with Taiwan Semiconductor Manufacturing Company (TSMC) on an advanced semiconductor manufacturing process, initiating its transition into the fabless business model.

Table 5.13 The geographical distribution of LSI's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Canada (Etobicoke)[1]	X	X	X	X	X	X	X				94 (0/1)	1995
China					X	X	X	X	X	X	4 (0/0)	2004
France								X	X	X	14 (0/0)	1996
Germany		X	X	X	X	X	X	X	X	X	47 (0/1)	1991
India					X	X	X				32 (0/0)	2004
Israel							X				6 (0/0)	1996
Italy							X	X	X	X	6 (0/0)	2003
Japan (Tokyo)[1]	24.3	X	X	X	X	X	X	X	X	X	25 (1/0)	1990
Russia					X	X	X				70 (0/2)	1997
Singapore								X	X	X	0 (0/0)	
Sweden								X	X	X	0 (0/0)	
Taiwan						X	X				1 (0/0)	2005
United Arab Emirates (Dubai)						X	X				0 (0/0)	
UK (Bracknell)[1]	70	X	X	X	X	X	X	X	X	X	100 (2/1)	1991

US (Milpitas, CA)[1,2]	503.6	X	642.4	594	527	527	460	X	X	X	4304 (160/0)	1982
US (Colorado Spring, CO)[3]	415.6	X	X	X	X	X	180	180	180	180		
US (Fort Collins, CO)[3]	270	X	X	X	X	X	150	170	170	150		
US (Gresham, OR)[3]	532.4	X	492	588	588	588						
US (Norcross, GA) [1]					X	X	X					
US (Wichita, KS)[3]	332	X	345	345	330	330	330	330	330	330		
US (MD)			X	X	X	X	X					
US (MN)			X	X	X	X	X					
US (Allentown, PA)								600	600	600		
US (TX)			X	X	X	X	X					

Note: 1. LSI reported locations mostly by countries except for a number of specific sites. 2. Before 2004, several other nearby locations were mentioned in company annual reports, including Fremont, San Jose and Santa Clara, California. 3. These sites were significantly downsized during LSI's transition to the fabless business model, which involved the sale or closure of manufacturing and assembly facilities in these sites. 4. The list of R&D locations reported by the company changed significantly in 2007, while the list of its subsidiaries has expanded from 44 to 67. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.14 Marvell Technology Group and inventor residence information

Marvell Technology Group (NASDAQ: MRVL) was incorporated in Bermuda in 1995 with its corporate headquarters in California. Founded by a Chinese immigrant couple, the company initially focused on supplying IC products for enterprise and consumer storage devices. It later entered the technological area of broadband communication, supplying highly integrated mixed-signal IC products for computers, communications-related equipment and consumer devices for high-speed data storage, transmission, and management. After the initial public offering in 2000, Marvell conducted a series of merger and acquisitions, adding businesses, products and technologies complementary to its existing product lines, and quickly expanded the company's market coverage and technological capabilities. Along with Broadcom and Qualcomm, the company remained one of the largest IC design companies, even beyond the inter-crises period.

One unique aspect of Marvell would be its registration and official headquarters in Bermuda, a well-known business and tax-friendly British overseas territory. In the meanwhile, several other companies studied in this research also had their official headquarters and several R&D sites allegedly located in the business and the tax-friendly state of Delaware. Some explained in their annual reports that subsidiaries in these locations were managing and financing international knowledge-creating activities. Whether the practice was intended for international internal finance or other managerial purposes is beyond the scope of this research; however, it did complicate the investigation of these companies' international knowledge-creating activities entirely by reading annual reports. Fortunately, the empirical approach adopted in this research—identifying the country origin of a patented invention by its inventor residence information—has been particularly useful in such cases. For example, although Marvell had the vast majority of its patents assigned to the headquarters in Bermuda, instead of its operating headquarters in California, the residence information reported in patent documents provided a rather detailed picture of the geographical distribution of its knowledge-creating activities.

Table 5.14 The geographical distribution of Marvell's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Bermuda		X	X	X	X	X	X	X	X	X	0 (0/0)	
Canada							X	X	X	X	0 (0/0)	
China (Shanghai)		X	X	X	X	X	X	X	X	X	12 (1/0)	2006
Finland						X	X	X	X	X	0 (0/0)	
Germany			X	X	X	X	X	X	X	X	17 (1/0)	2003
India							X	X	X	X	16 (0/0)	2005
Italy						X	X	X	X	X	10 (0/0)	2007
Israel (Moshav Manof)	33	32	92	101	228	228	409	409	361	361	206 (9/0)	1999
Japan	X	X	X	X	X	X	X	X	X	X	20 (0/0)	2003
Korea				X	X	X	X	X	X	X	0 (0/0)	
Malaysia (Penang)							X	X	X	X	7 (0/0)	2004
Netherlands										X	4 (0/0)	2008
Singapore[1,2]	13	20	22	39	39	39	51	51	X	X	127 (1/0)	2000
Switzerland (Etoy)						X	X	X	X	X	16 (1/0)	2005
Taiwan	X	X	X	X	X	X	X	X	X	X	2 (0/0)	2008
UK	X	X	X	X	X	X	X	X	X	X	0 (0/0)	

US (Santa Clara, CA)[3]						876	993	993	993	993	1908 (97/2)	1995
US (Sunnyvale, CA)[3]	97	213	213	213	213							

Note: 1. Marvell started its operation in Singapore much earlier. However, according to the company's annual report, official R&D activity in the country started when a new regional headquarters was completed in 2008. 2. The Economic Development Board (EDB) of Singapore granted Pioneer Status to Marvell's Singaporean subsidiary in 1999 along with tax exemption, and in 2006 extended the term to fifteen years. 3. The company relocated its headquarters from Sunnyvale, California, to the neighboring Santa Clara in 2005. 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.15 MediaTek and emerging country markets

Found in Taiwan in 1997, MediaTek became the most successful spin-off of UMC, which was once an IDM company but later became one of the largest IC manufacturing companies in the late 1990s. Initially, MediaTek focused on designing IC products for optical storage devices and became one of the top suppliers in this product category, particularly DVD drives, which emerged in the early 2000s. Many of the company's IC products entered the supply chains of large electronics and IT companies, such as Sony and Microsoft, through OEM companies that provided electronics manufacturing services for them. On the other hand, the company's Taiwanese headquarters and base in East Asia proved to be advantageous against its main competitors in the West, such as ESS and Zoran (see 5.2.10 ESS and 5.2.19 Realtek). Moreover, according to MediaTek's annual reports, since the early 2000s the company had invested in and operated several knowledge-creating subsidiaries in California, in proximity to the most advanced industrial cluster of electronics companies as well as the largest single market for consumer electronics. Finally, in the late 2000s, MediaTek became renowned for its chipset IC products for mobile phones, especially those designed and manufactured by small startup companies in China (see also 5.2.10 ESS).

In 2004, as a latecomer to a market dominated by Western companies, MediaTek launched in China its IC product line for mobile phones. IC companies, including the market leader, QUALCOMM, and other potential entrants expected that future mobile phones would incorporate multimedia, navigation and other novel functions. These companies knew that all these additional functions could only be achieved with highly-integrated IC products (see also

5.2.3 Atheros and 5.2.8 CSR). While most IC companies were collaborating with leading phone manufacturers, such as Ericsson, Nokia, and Samsung among others, MediaTek instead focused on a neglected market segment occupied by numerous Chinese start-ups designing and producing low-priced phones in minuscule batches and varying designs. These low-price mobile phones were targeted at the nascent Chinese consumer market—emerging but relatively small at the time—relative to the established markets in the developed countries.

Because these tiny start-ups had very limited design and engineering capabilities and lacked resources and scale to conduct more R&D, MediaTek decided to incorporate a complete set of functions into its IC design and offer the product at low price (Hu, Wan, & Zhu, 2011). It even provided reference phone designs, detailed documents, design tools and training programs for these entrepreneurial start-ups. Its synthesis of market information led to an IC product that enabled these start-ups to create phones with comprehensive functionality, flexibility and competitive pricing. Moreover, MediaTek's technological support greatly shortened the phone design process to several months, which drastically lowered the requirements on R&D and financial resources and allowed more Chinese designers to focus on adding novel features catering for various local demands (Hu et al., 2011). These included dual-SIM—a novel feature first popularized in China based on MediaTek's IC products and only adopted by Western competitors until years later (Wired, February 2003).

Dual-SIM phones were designed to simultaneously access two carrier networks with two SIM cards, allowing phone calls to go through networks operated by either of the two carriers supplying the SIM cards. Though less appreciated by consumers in developed countries, the feature was well received by Chinese consumers, who used to switch between networks by swapping SIM cards in order to use favorable call rates. Dual-SIM let consumers call people and countries through different networks at different times and occasions or use one line for work and one for private use. In some countries, such as Brazil, multi-SIM phones may use up to four SIM cards (Wired, February 2003). This feature later became the favorite of business travelers, who must remain connected to home country carrier network while accessing foreign carrier networks. When large phone manufacturers started to design similar products, many chose MediaTek's products. Prioritizing on market information and applying the unique flexibility of fabless business model, MediaTek developed an expertise in the Dual-SIM feature and complementary technologies years before its competitors.

Table 5.15 The geographical distribution of MediaTek's knowledge creation

R&D Center	**'00**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**	**Patent**	**Since**
China (Beijing)[1]							X	X	X	X	0 (0/0)	
China (Hofei) [1]				X	X	X	X	X	X	X		
China (Shanghai)										X		
China (Shenzhen) [1]				X	X	X	X	X	X	X		
Denmark (Aalborg Oest)								X	X	X	6 (0/0)	2002
India (Noida)					X	X	X	X	X	X	0 (0/0)	
Ireland								X	X	X	2 (0/0)	2005
Japan (Yokohama)								X	X	X	1 (0/0)	2006
Korea (Seoul)								X	X	X	9 (0/0)	2004
Singapore					X	X	X	X	X	X	10 (0/0)	2006
Taiwan	X	X	X	X	X	X	X	X	X	X	1062 (79/0)	1997
UK								X	X	X	11 (1/1)	2003
US (Irvine, CA)[2]				X	X	X		X	X	X	64 (13/1)	1997
US (Sunnyvale, CA)[2,3]				X	X	X	X	X	X	X		

Note: 1. MediaTek's R&D sites in China were mostly set up to assist business customers locally. 2. The company reported two other knowledge-creating subsidiaries registered in the US without further location information. 3. This entry included another R&D site in nearby San Jose, California. 4. Most of the company's foreign subsidiaries were managed through Gaintech Co registered in the Cayman Islands. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.16 NVidia Corporation and supply chain hazards

Headquartered in Santa Clara, California, NVidia Corporation (NASDAQ: NVDA) was founded in 1993 by Jen-Hsun Huang, who was an IC designer in LSI and AMD, and Chris Malachowsky and Curtis Priem, who worked for Sun Microsystems. NVidia was founded in a time when several dozen companies were competing for the emerging computer graphics market, as the demand for multimedia functions via personal computers was quickly expanding. With its initial public offering in 1998, the company became a recognized market leader at roughly the same time. However, because the company was actually a late entrant to this market, it struggled in the beginning to gain access to advanced manufacturing processes, a critical source of competitive advantages for IC design companies supplying Graphics IC products (see section 5.2.4 ATI for more discussion). NVidia's fortunes were boosted when SGS-Thomson Microelectronics, a French-Italian IDM company, agreed to become one of NVidia's initial suppliers of manufacturing capacity and advanced manufacturing processes. Later, NVidia began working very closely with TSMC, one of the few professional foundry companies that continued to develop and implement cutting-edge manufacturing processes.

Although the strategic importance of gaining access to advanced manufacturing processes differs depending on specific IC products, securing the supply of manufacturing capacity is a critical concern shared by all IC design companies. In particular, seasonal fluctuations and economic cycles can cause varying levels of disruption to the semiconductor supply chain. During downturns of demand for IC products, service providers can suffer from low utilization rates of their facilities as well as financial hardship. As a result, some service providers may scale back investment in manufacturing capacity expansion and manufacturing processes development, restricting the manufacturing capacity, quality of manufacturing processes and costs in future time periods. Conversely, during the upturns, unanticipated demand surges may not be met due to capacity constraints of IC design companies and their supplier networks. When a large number of design companies are bidding for additional capacity, procurement of additional capacity may not be feasible or only possible at a price premium. Moreover, additional fees can be charged for shorter delivery time when there are long queues of orders at the suppliers' side, while business customers' inventories are running low.

In addition to using warehousing as a buffer for relatively standardized products, IC design companies may adopt various strategies to ensure timely and adequate supply of manufacturing capacity, such as long-term supply contract, pre-payment, multiple-sourcing and internal or customer-supplied demand forecasts. Some companies—especially those who used to operate internal foundry facilities—also enter joint ventures with professional foundry companies to conduct manufacturing process research or to take an equity share of foundry facilities. However, a fundamental constraint in the semiconductor supply chain is the high switching costs between different service providers, which may include the search costs for an alternative service supplier, the qualifications of service providers and the transition of service performance. Alternative service providers may also need to be certified by business customers. The entire process can be very costly and time-consuming and can take more than a year in some cases.

Table 5.16 The geographical distribution of NVidia's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
China (Shanghai)[1]								X	X	X	8 (0/0)	2006
China (Shenzhen)[1]						X	X	X	X	X		
France (Paris)	X	X	X								1 (0/0)	2001
Germany (Wurselen)[1]	X	X	X		X	X	X	X	X	X	10 (0/1)	2003
Hong Kong			X								0 (0/0)	
India (Bangalore)[1]						X	X	X	X	X	28 (2/0)	2004
India (Hyderabad)[1]							X	X	X	X		
India (Pune)[1]						X	X	X	X	X		
Japan (Yokohama)	X	X	X								0 (0/0)	
Korea (Seoul)			X								0 (0/0)	
Singapore	X	X	X								0 (0/0)	
Taiwan[1]	X	X	X					X	X	X	18 (1/0)	2005
UK (Theale)	X	X	X								23 (1/0)	2000
US (Madison, AL)							X	X	X	X	1574 (79/0)	1995
US (Chandler, AZ)	X	X	X	X	X	X						
US (Berkeley, CA)[2]				X	X	X	X	X	X	X		
US (Marina Del Ray, CA)									X	X		
US (Santa Clara, CA)[6]	117	500	500	X	X	X	X	X	X	X		
US (Fort Collins, CO)[3,6]		4	X	X	X	X	X	X	X	X		
US(Honolulu, HI)			X		X							
US (Bedford, MA)	X	X	X	X	X	X	X	X	X	X		
US (Saint Louis, MO)									X	X		
US (Charlotte, NC)							X					
US (Durham, NC)[6]	6.7	25	X	X	X	X	X	X	X	X		
US (Beaverton, OR)[4,6]		11	X	X	X	X	X	X	X	X		
US (Greenville, SC)		X	X	X	X	X	X	X	X	X		
US (Austin, TX)	X	X	X	X	X	X	X	X	X	X		

US (Houston, TX)						X	X	X	X	
US (Salt Lake City, UT)									X	X
US(Bellevue, WA)[5,6]	X	X	X	X	X	X	X	X	X	X

Note: 1. Since 2004, NVidia reported these locations as its principal international R&D sites. 2. The entry includes nearby San Francisco, California. 3. The entry includes nearby Boulder, Colorado. 4. The entry includes nearby Portland, Oregon. 5. The entry includes nearby Bothell, Kirkland and Redmond, Washington. 6. The company identified these locations as its principal design centers in the US and suggested that other states or locations in the US might be secondary R&D locations mainly for sales and administration. 7. The company also mentioned Pennsylvania in its 2001 annual report, but its R&D location information was in general less clear prior to 2004. 8. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.17 PMC-Sierra and delayed profit generation

PMC-Sierra (NASDAQ: PMCS) was founded in 1983 in San Jose, California, as Sierra Semiconductor. The company initially focused on the personal computer modem chipset business and later acquired Pacific Microelectronics Centre in Burnaby, British Columbia, in 1994. In 1997, following the decision to exit the personal computer modem chipset business and enter the market of networking equipment, the company restructured around its acquired Canadian subsidiary and became PMC-Sierra. From then, the restructured PMC-Sierra operated with dual headquarters in Santa Clara, California, and Burnaby, British Columbia. The transition and new configuration were reflected by the geographical distribution of PMC-Sierra’s R&D sites and by the company’s patenting records. As shown in the following table, while the patenting by Canadian first inventors only started in the 1990s, by 2008 the number of patents originated in Canada already doubled that in the US. Moreover, the numbers of patents in new patent classes were roughly on par.

In PMC-Sierra’s annual reports, it explained an interesting phenomenon which is common in the IC design industry with some variations—a large time gap between R&D activities and actual profit generation. In the case of PMC-Sierra, from initial product conceptualization to a viable prototype, it usually took between 12 and 24 months. Afterward, it would take another 3 to 18 months for the IC products to be designed into business customers’ networking equipment and sold in production quantities. During the process, IC designers might change the design multiple times for various reasons, such as unacceptable manufacturing yield rates of prototypes, business customers' decision to redefine their products and so on. These revisions could cause further delay in volume production and sometimes obsolesce of the planned product. Lastly, the time required to complete the manufacturing of IC products would be between 12 and 16 weeks in terms of PMC-Sierra's IC products. Based on demand forecasts and delivery schedules, production planners should send purchase orders to service providers to arrange for manufacturing and testing and packaging activities, ensuring the availability of finished IC products at the agreed delivery time.

In most cases, finished IC products are shipped directly to business customers' internal or external facilities for the manufacturing or contract manufacturing of end products. However, these lengthy sales cycles have caused significant time delays between the spending on R&D activities, sales and administration and the actual generation of revenues. Although the fabless business model is inherently asset-lite and less prone to inventory cost and under-utilized manufacturing capacity, these contingencies could damage the profit margin of IC design companies and increase their financial risks. In fact, it also has implications for empirical academic studies based on the industry, since the time lag between R&D expenditure and performance is typically assumed as 12 months.

Table 5.17 The geographical distribution of PMC-Sierra's knowledge creation

R&D Center	**'00**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**	**Patent**	**Since**
Canada (Burnaby)[1]	260	254	241	192	184	147	147	173	173	149	198 (17/0)	1991
Canada (Kanata)[2]	90	90	90	90	90	90						
Canada (Montreal)	X	X	X	X	X	X	X	X	X	X		
Canada (Saskatoon)	X	X	X	X	X	X	X					
Canada (Toronto)	X											
Canada (Winnipeg)	X	X	X	X	X	X	X					
China (Shanghai)							X	X	X	X		
India (Bangalore)						X	X	X	X	X	4 (0/0)	1999
India (Pune)[3]	X	X	X									
Ireland (Galway)[3]	X	X	X								0 (0/0)	
Ireland (Dublin)[3]	X	X	X									
Israel (Herzliya)							X	X	X	X	14 (1/0)	2002
US (Santa Clara, CA)[4]	412	462	431	149	108	108	108	108	108	108	98 (16/0)	1986
US (Gaithersburg,	84	X	X									

MD)[3]										
US (MN)									X	X
US (PA)		X	X	X	X	X	X	X	X	X
US (Portland, OR)	42	X	X	X	X	X	X	X	X	

Note: 1. This entry includes the nearby Vancouver, British Columbia. 2. This entry includes the nearby Ottawa, Ontario. 3. A number of design centers in Maryland, Ireland and India were closed in 2003. 4. This entry includes the nearby San Jose, California. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.18 Qualcomm and industrial standards

Headquartered in San Diego, California, Qualcomm (NASDAQ: QCOM) has been a leading developer and supplier of CDMA-based communication IC products and system software, enabling various wireless devices, particularly mobile phones and infrastructure equipment. The company was founded by Irwin Jacobs, a Professor at UC San Diego, and Andrew Viterbi in 1985 with an early business focus on commercial applications of digital satellite communication and wireless communication. Qualcomm designed and supplied wireless communications equipment and ASIC products based on its Code Division Multiple Access (CDMA) technology, while in the meanwhile generating a part of its revenues from licensing the technology to major telecommunications equipment suppliers that adopted the technology in their wireless communications products.

According to Qualcomm’s annual report, the demand for mobile telecommunications dramatically increased after the commercialization and wide availability of mobile phones and other emerging mobile telecommunications services in the mid-1980s. In 1989, the company introduced its CDMA technology to compete with an alternative technology developed by Ericsson and already adopted by the industry. Following the introduction, Qualcomm committed significant financial resources to building infrastructure and test networks and made licensing and development agreements with numerous electronics and telecommunication companies worldwide. The gradual shift occurred in 1993 when the CMDA technology was adopted as a technological standard for mobile telecommunication by the US Telecommunications Industry Association, a trade association representing the global information and communications technology (ICT) industry through standards development, policy initiatives, business opportunities and other activities. In the meanwhile, several carriers in East Asia and many emerging countries worldwide were beginning to adopt this new technological standard to improve their communication infrastructures in local areas.

However, it was only after more years and several lengthy litigation battles that CDMA technology finally became accepted as the primary technological standard behind the third generation (3G) mobile telecommunication and various mobile services. Subsequently, Qualcomm continued to lead the commercialization and improvement of CDMA technology and generated a considerable IP portfolio underlying different versions of the technology. During the inter-crises period, as the company mainly profited from supplying IC products based on its proprietary technologies, royalty and licensing fees income increased to more than one-third of its annual revenues. Moreover, according to the European Telecommunication Standards Institute (ETSI), a standardization organization recognized by the European Commission, Qualcomm also developed and owned a significant portion of the essential patents behind the new technological standard for the next, fourth generation (4G) mobile telecommunication.

Related to the company's effort to promote the technological standard and related products, the internationalization of Qualcomm included substantial investments in various telecommunication operators worldwide, including early participation in telecommunication infrastructure development in China, India and Latin America. While other IC design companies also provided assistance to emerging business customers (see 5.2.15 MediaTek and 5.2.27 ARM), Qualcomm's strategy was rather unique among IC design companies, which were usually small and lacking the financial resources to participate in end product markets with equity shares. However, while remaining fabless, Qualcomm also owned several other successful businesses and had grown to a size and revenue scale comparable to the largest IDM companies. Hence, although the company's patenting records suggested that less than ten percent of its patents originated outside its home country, its global reach remained significant by the breath and absolute volume of its intellectual properties.

Table 5.18 The geographical distribution of Qualcomm's knowledge creation

R&D Center	**'00**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**'08**	**'09**	**Patent**	**Since**
China		55	55	73	86	83	88	88	98	105	6 (0)	2001
UK	13	13	17	21	33	52	62	71	71	71	43 (1)	2001
Germany					22	22	31	31			21 (0)	1999
India					60	97	210	296	309	343	18 (0)	2000
Israel	53	45	38	38	38	38	49	51	51	67	79 (1)	1991
Korea					51	60	71	65	75	75	23 (0)	2000
Netherlands	14	20	15	20							15 (0)	2003
Singapore									47	46	1 (0)	2006
Taiwan								47	47	134	22 (3)	2003
US (San Diego, CA)[1]	1952	2034	2252	2215	2699	3092	4076	4310	4817	5264	5585 (102)	1986

Note: 1. Part of the US site has manufacturing function. 2. Most sites have sales and marketing function. 3. Notably, in addition to the R&D sites reported in annual reports, patenting records suggested a number of other locations, which might have been reported as other international. These include Australia: 74 (4/1), Canada: 49 (1/0), Finland: 10 (0/0), Italy: 19 (0/0), Japan: 11 (0/0), New Zealand: 15 (2/0) and Switzerland: 35 (0/0). 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.19 Realtek Semiconductor and the Taiwanese semiconductor industry

Realtek Semiconductor was founded in 1987, making it one of the earliest IC design companies in Taiwan. The company supplied IC products for consumer electronics and personal computers, and its products lines covered applications in network connection, personal computer peripheral devices and multimedia functions. The company's home region, East Asia, hosted a large number of electronics companies and OEM manufacturers, which allowed Realtek to serve and collaborate with many of its business customers due to geographical proximity (see also 5.2.13 LSI). In part, the common language and shared culture between Taiwan, Hong Kong, Singapore and China, in particular, gave Realtek and other IC design companies based in the region a significant advantage in relation to its counterparts in the US and Europe. Local access and knowledge acquisition from business customers not only facilitate the exchange of ideas but also benefit new product development and technological advantages. Yli-Renko, Autio and Sapienza (2001) suggest that extensive social interactions between a technology-based company and its key customers enhance the exchange and processing of information as well as the recognition and evaluation of pertinent knowledge, and thereby help the transfer of technological and market knowledge from the customer. Moreover, since Realtek mostly focused on personal computers and consumer electronics in East Asia, this local and direct access bypassed knowledge-creating subsidiaries and avoided much of the managerial costs of a global network of R&D subsidiaries.

Besides the proximity to business customers, Realtek also benefited from the concentration of service providers in the region, especially in Taiwan where many of the largest service providers were based (also see 5.2.23 SMSC). The leading professional foundry companies, TSMC and UMC, and top testing and packing companies, such as ASE and SPIL, were all founded and headquartered in Taiwan. Hundreds of other smaller IC design companies and service providers were based on the island, especially in the Hsinchu Science and Industrial Park and several nearby locations. Moreover, like most other Taiwanese IC companies, Realtek hired from a sizable local pool of high-quality labor. According to the company's annual reports, although the number of employees in its headquarters tripled between 2001 and 2008, the percentage of employees with undergraduate degrees remained above 90%, while the percentage of those with post-graduate degrees increased from 50% to 61%. Within Taiwan, the presence of a complete semiconductor supply chain and abundant human capital, accompanied by a large number of electronics manufacturers on the eastern coast of China, created a favorable environment in the home region from which several Taiwanese IC design companies successfully engaged global competition.

Internationally, in contrast with South Korea and Japan where business conglomerates diversified into the semiconductor business, the semiconductor industry in Taiwan has been highly fragmented and diversified. Scores of startups and spin-offs competed and specialized in different sections of a vertically disintegrated semiconductor value chain. Before the emergence of a complete indigenous semiconductor industry, Taiwan was for years an offshore site for IDM and IC design companies in the US, especially for testing and packaging activities. In the mid-1970s, the Electronics Research and Service Organization (ERSO)—a subdivision of the government-sponsored Industrial Technology Research Institute (ITRI)—obtained technology licensing from RCA, which at the time led an emerging technological trajectory of IC manufacturing but soon afterward left the industry (Chen & Sewell, 1996). ERSO and ITRI later spun off as well as assisted many Taiwanese companies in the semiconductor industry, including TSMC and UMC that conducted manufacturing activities for most of the top IC design companies worldwide. Therefore, less a competitor with the US semiconductor industry than a symbiotic extension of it in many respects, the Taiwanese semiconductor industry emerged in a porous environment that promoted FDIs and cooperation with foreign companies and encouraged the international mobility of engineers (Langlois & Steinmueller, 1999).

Table 5.19 The geographical distribution of Realtek's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
China (Shenzhen)[1]					X	X	X	X	X	X	3 (1/0)	2006
China (Suzhou)[1]				X	X	X	X	X	X	X		
Hong Kong[1]	X	X	X	X	X	X	X	X	X	X	0 (0/0)	
Japan (Yokohama)		X	X	X	X	X	X	X	X	X	0 (0/0)	
Sweden (Södra Sandby)								X	X		0 (0/0)	
Switzerland (Zurich)			X	X	X						1 (0/0)	2004
Taiwan	X	X	X	X	X	X	X	X	X	X	540 (64/3)	1996
US (Irvine, CA)			X	X	X	X	X	X	X	X	86 (11/0)	2000
US (San Jose, CA)[2]	X	X		X	X	X	X	X	X	X		

Note: 1. Subsidiaries located in these locations were mainly for technology support for business customers. 2. This entry includes an earlier site in nearby Milpitas, California. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.20 SanDisk Corporation and manufacturing joint venture

SanDisk Corporation (NASDAQ: SNDK) was founded as SunDisk in California in 1988; in 1996, the company went public and changed its name to SanDisk. SanDisk had since its early years focused on flash memory storage devices for consumer electronic devices as well as industrial and aerospace applications. Different from traditional storage devices based on rotating magnetic disks, the technology of flash memory storage allows digital information to be stored in durable and compact solid-state devices based on IC products. The advantages of such devices—smaller dimensions, lower power consumption and a high tolerance for shock and vibration—make flash memory storage devices ideal for applications in small and portable electronic devices. As the market pioneer and technological leader of flash memory storage devices, SanDisk led the industry and supplied some of the earliest flash memory storage devices to IBM and NASA based on its technologies. For instance, by the end of 2013, one of its key patents filed in 1989—US Patent No. 5,602,987, which allows flash memory storage devices, based on IC products to function like traditional storage devices—has received more than 400 forward citations, an indicator of valuable inventions. The company also worked closely with digital camera and electronics manufacturers to establish the technological standards and formats of various end products based on flash memory IC products. These included the introduction of MultiMediaCard with Siemens, Secure Digital card with Toshiba and Panasonic, Memory Stick with Sony, and CompactFlash with Canon. Including having a well-known brand name, a number of key patents on USB Drives and other proprietary technologies in flash memory manufacturing processes, these intellectual properties allowed the company to generate around 10% to 15% of its annual revenues from licensing activities in the first decade of the 21st century (also see 5.2.18 Qualcomm).

Relative to other IC products discussed previously, flash memory is a unique category of IC products. It is relatively standardized but involves a different set of manufacturing processes (see Table 5.2 in Appendix for a summary of IC products). In part, similar to companies focusing on PLD IC products, less variation was observed in the geographical distribution of SanDisk’s knowledge-creating activities (see 5.2.2 Altera). On the other hand, properties of flash memory IC products and related technologies and market conditions influenced the company’s supply chain decisions, including the use of equity control over foundry facilities and the internalization of testing and packaging activities.

For the better part of the 1990s, SanDisk followed the asset-lite strategy adopted by most fabless IC design companies—to concentrate on undertaking R&D activities for which design companies were advantageous and avoid owning and operating foundry facilities for IC manufacturing (see 5.2.1 Agere). While testing activities for finished wafers were conducted internally at its then headquarters in Sunnyvale, California, wafers were mostly sourced from Matsushita Electronics Corporation and NEC in Japan and LG Semicon in South Korea. SanDisk relied on accurate demand forecasts and IP litigation to ensure its competitive advantages and rights. However, since flash memory IC products are relatively standardized products, scale economies and advanced manufacturing processes are vital in the competition to improve product quality while lowering costs (see also 5.2.4 ATI). Competition intensified when a myriad of IDM companies entered the market under technology licensing and exploited scale economies by mass production and better intra-firm coordination. In response to mounting competitive pressure, by the end of the 1990s, SanDisk started to change its strategy and became further involved in the R&D of manufacturing processes and the expansion of manufacturing capacity.

Along with its business model change, SanDisk intended to maintain a balanced mix of internal and external manufacturing capacities by sourcing mainly from its manufacturing joint ventures with Toshiba and by supplementing with external service suppliers such as Samsung Electronics. Therefore, after resolving legal disputes with Samsung and Toshiba, SanDisk entered a long-term supply agreement in 2002 with Samsung Electronics to purchase flash memory IC products from Samsung's foundry facilities in South Korea. Moreover, between 2000 and 2006, SanDisk joined Toshiba and held 49.9% ownership position in each of their three manufacturing joint ventures—FlashVision, Flash Partners and Flash Alliance—located at Toshiba's operations in Yokkaichi, Japan. Both companies also agreed to collaborate on R&D activities in these facilities. In 2006, SanDisk also started constructing its own assembly facility in Zizhu Science-Based Park near Shanghai, China, conducting internally a part of the testing and packaging activities of end products based on flash memory

IC products. At the same time, the company continued to source external manufacturing capacity from other service providers in East Asia. During this time period, SanDisk drastically increased its capital spending, rebalanced the mix toward more internalized manufacturing activities, and eventually left the list of top fabless IC suppliers in 2007 (see Table 4.2), but remained as one of the world leading IC companies by sales, especially in the flash memory market.

The decision to enter manufacturing joint ventures and obtain equity control over manufacturing capacities provided SanDisk certain cost advantages, better and more consistent product quality as well as better control over its proprietary technologies. Unfortunately, the company and its new business model suffered a severe setback in 2008 due to the overexpansion of manufacturing capacity and global economic downturns. The longer-term demand forecasts that justified the ownership position in manufacturing joint ventures were confronted by weak global demand following the financial crisis. Although the company avoided using external sources in 2008, inventory positions still grew due to the increasing output from these foundry facilities. To revert to its intended strategy and maintain an ideal mix of internal and external manufacturing capacities, SanDisk soon sold a significant portion of the capacity from two of the three joint ventures to Toshiba, keeping some flexibility in allocating and scheduling capacity between both parties. The joint venture partners also agreed to lower the utilization rate of these facilities during 2009.

Table 5.20 The geographical distribution of SanDisk's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
India (Bangalore)						X			X	X	4 (0/0)	2006
Israel (Omer)							X	X	X	X	240 (19/2)	2001
Israel (Petah Tikva)					X	X	X					
Israel (Kfar Saba)							148	157	157	157		
Israel (Migdal Tefen)	X	X	X	X	X	X	X	X	X	X		
Spain (Madrid)							X	X	X		5 (0/0)	2004
UK (East Kilbride)			X	X	X						83 (1/0)	2003
UK (Edinburgh)						X	X	X	X	X		

US (Milpitas, CA)							444	444	444	444	1387 (50/4)	1989
US (Sunnyvale, CA)	104	104	104	104	205	206						

Note: 1. In end of 2006, SanDisk acquired the inventor of USB drives, msystems, with its headquarters in Kfar Saba, Israel and substantial operations in the country. 2. SanDisk also operated a number of support offices in China, India and Taiwan. 3. Patenting records are noted as total patent count (new patent class patent/new patent class participation). Source: This research.

5.2.21 Semtech Corporation and the role of the US government

Like LSI Corporation, Semtech Corporation (NASDAQ: SMTC), now headquartered in Camarillo, California, had a long history which very much reflected the evolution of the US semiconductor industry. The company was founded in 1960 in Newbury Park, California, to manufacture power rectifiers—an electronic component which would convert alternating current to direct current—primarily for the defense and aerospace industries. At the time, the defense and aerospace industries in the US were the main source of domestic demand for semiconductor devices. Moreover, while most products sold to the defense and aerospace industries had to be qualified by the US Department of Defense, the company also went through auditing routinely and complied with changing specifications announced by the Department in order to maintain these qualifications.

The role of the defense sector was unusual in the sense that customers in the sector were willing to afford the high prices of earlier semiconductor devices in order to achieve the technological goals of miniaturization and reliability (Langlois & Steinmueller, 1999). The superior performance of IC products, rather than their costs, was the main concern for technology adoption in the defense sector at the time. Therefore, although the demand from the industrial and consumer markets was also growing, in the 1960s nearly half of the demand came from the defense sector, including aerospace and military, which provided significant direct and indirect support from the US Government for the US semiconductor industry (Langlois & Steinmueller, 1999). Even after several other countries also developed their own manufacturing capabilities during the 1990s, the US Government remained concerned with the capabilities of the US semiconductor industry for domestically designing and manufacturing IC products to be used in critical applications (Crawford et al., 2009).

The US Government also supported SEMATECH, a research consortium founded in 1987 by AT&T Microelectronics, AMD, IBM, Digital Equipment, Harris Semiconductor, HP, Intel, LSI, Micron, Motorola, NCR, National Semiconductor, Rockwell International and TI. To reverse the capability decline of the US semiconductor industry in the 1980s, the US Department of Defense agreed with the proposal by Semiconductor Industry Association (SIA) for a research consortium modeled on the Japanese VLSI project between 1975 and 1985. The consortium would be funded equally with private and federal sponsoring, and member companies would assign their engineers to SEMATECH's facility in Austin, Texas, for 6 to 30 months (Browning et al., 1995; Irwin & Klenow, 1996). Initially, the research consortium was aimed at advancing semiconductor manufacturing technology in the US by expanding semiconductor research and enabling knowledge sharing among member firms. Later, its direction was shifted toward assisting semiconductor equipment manufacturers and coordinating between equipment manufacturers and semiconductor manufacturers (see also 5.2.13 LSI)

However, coinciding with the decline of the US semiconductor industry and shrinking defense budget in the 1980s, the company suffered severe revenue losses and went through a series of restructurings that refocused its business on the market for commercial applications. The company diversified into the commercial IC product market with its technologies in analog IC products, which were difficult both to design and to manufacture at the time. Before the mid-1990s, Semtech largely focused on supplying the defense and aerospace industries. However, by the first decade of the 21st century, the company generated around two-thirds of its annual sales from computer, communication and consumer markets, while keeping the product lines for defense, aerospace, medical, and industrial applications. Langlois and Steinmueller (1999) point out that, when specialization and globalization became the driving forces of the global semiconductor industry, many US companies began to concentrate on higher-margin, design intensive IC products and competed on innovativeness and responsiveness. These qualities proved to be the very strength of the fragmented US semiconductor industry relative to the European and Japanese semiconductor industries, which were vertical-integrated and highly concentrated.

Table 5.21 The geographical distribution of Semtech's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Switzerland (Neuchatel)[1]						X	X	X	X		5 (1/0)	2003
UK (Glasgow)	X	X	X	X	X	X	X					
UK (Swindon)					X	X	X				13 (6/0)	1999
UK (Southampton)[2]	X	X	X	X	X	X	X	X	X	X		
US (Camarillo, CA)[3]		85	85	85	85	85	85	85	85	85		
US (Oxnard, CA)	X	X										
US (San Diego, CA)	X	25	25	25	25	25	25	25	25	10		
US (San Jose, CA)[4,6]	X	13.3	13.3	X	15	X	X	X	X	X	64 (21/1)	1995
US (Raleigh, NC)[5]	X	X	X	X	X	X	X	X	X	X		
US (Austin, TX)		X	X	X								
US (Corpus Christi, TX)[6]		44	44	44	44	44	44	44				

Note: 1. Semtech managed its international operations through its European regional headquarters in St. Gallen, Switzerland. The regional headquarters controlled subsidiaries in France, Germany, Malaysia, Switzerland, and the UK, and branch sales offices in Taiwan, Korea, Japan, and Shanghai and Shenzhen, China. 2. This entry includes the nearby Romsey, the United Kingdom. 3. Before 2002, the company was headquartered in Newbury Park, California. 4. This entry includes the nearby Santa Clara, California. 5. This entry includes the nearby Morrisville, North Carolina. 6. The company ended manufacturing activities in Santa Clara, California, in 2001, and Corpus Christi, Texas, in 2002. 7. The company's internal facilities in Reynosa, Mexico, produced rectifiers for defense, aerospace and other specialized applications. 8. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.22 Silicon Laboratories and the role of senior engineers

Silicon Laboratories (NASDAQ: SLAB), or Silicon Labs, was founded in Austin, Texas, in 1996. The company supplied mixed-signal IC products for a broad range of applications in communications, consumer electronics, automotive electronics, industrial equipment, medical devices and power management devices. Because traditional mixed-signal designs were based on numerous, complex discrete analog and digital components, some electronics manufacturers facing intensified competition began to appreciate those IC companies that could supply mixed-signal IC products with greater functionality, smaller size and lower power consumption while achieving lower costs and shorter time-to-market.

In its annual reports, Silicon Labs explained the importance of experienced engineers and their deep understanding of both market knowledge and technological knowledge. Firstly, the design of mixed-signal IC products requires that engineers understand business customers' products, values and engineering capabilities and evaluate the technical feasibility of a particular IC product based on their knowledge of performance requirements and evolving industrial standards. Secondly, the design process requires engineers with specific expertise and creativity as well as experience to deliver a high-performance mixed-signal IC product, which operates under strong digital interference and can be manufactured within the constraints of standard manufacturing processes. Relative to advanced processes and specialized, specific-purpose processes, standard manufacturing processes usually have higher yield rates, shorter delivery time and lower costs, because of the mature technology and the familiarity with the technology (see 5.2.4 ATI). However, to achieve all these requirements, engineers with the specific expertise are required to create the mixed-signal IC design; such expertise is developed through years of practical design work under the guidance of senior engineers, and, consequently, engineers with the required level of skill and expertise are often in short supply.

In its annual reports, Silicon Labs emphasized the merits of standard manufacturing processes that allow higher yield rates and shorter delivery times at lower prices, while explaining its coordination with geographically distant service providers. While IC design companies usually communicate and collaborate electronically with their geographically distant service providers, many also invest in offices or subsidiaries in proximity to service providers in order to facilitate the coordination between designing and manufacturing activities. Previous studies in the semiconductor industry suggest that analog IC product has higher coordination requirements between design and production, which may result in asset-specific investment in communication techniques (Leiblein et al., 2002; Monteverde, 1995). In the case of Silicon Labs, it also relied on senior engineers, with their familiarity with the intricacies of designs suitable for volume production, to direct and coordinate teams of less experienced engineers. Senior engineers with expertise in technological integration and team coordination allow for the replication of successful applications as well as the creation of new integrative IC products that combine functions usually performed by separate components in less efficient ways. Lastly, to accelerate the incorporation of IC products into customers’ products, experienced engineers were also assigned to work closely with customers to support their end product design and provide technological assistance (see also 5.2.11 Genesis Microchip).

Table 5.22 The geographical distribution of Silicon Labs’ knowledge creation

R&D Center	**‘00**	**‘01**	**‘02**	**‘03**	**‘04**	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**Patent**	**Since**
China				X	X	X	X	X	X	X	2 (0/0)	2008
France				X	X	X	X	X	X	X	7 (0/0)	2005
Germany					X	X	X	X	X	X	0 (0/0)	
Hong Kong					X	X					0 (0/0)	
Hungary									X	X	3 (0/0)	2005
India							X				1 (0/0)	2004
Japan		X	X	X	X	X	X	X	X	X	0 (0/0)	
Korea				X	X	X	X	X	X	X	0 (0/0)	
Malaysia			X	X	X	X					0 (0/0)	
Portugal							X		X	X	0 (0/0)	
Singapore					X	X	X	X	X	X	0 (0/0)	
Taiwan				X	X	X	X	X	X	X	0 (0/0)	
UK (Kenilworth)	X	X	X	X	X	X	X	X	X	X	2 (2/1)	2004
US (Nashua, NH)[1]	2.8	5.6	5.6	5.6	X	X					653 (79/0)	1997
US (Austin, TX)[1,2]	69.2	107	124	124	200	230	220	150	190	190		

Note: 1. Silicon Labs’ annual reports suggested that there were other smaller facilities in the US. The 2000 annual report mentioned the following locations: Allentown, Pennsylvania; Atlanta, Georgia; Broomfield, Colorado; Columbia, Maryland; and San Jose, California. 2. Floor space reported after 2000 include testing facilities. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.23 Standard Microsystems Corporation (SMSC) and supplier concentration in East Asia

Headquartered in Hauppauge, New York, Standard Microsystems Corporation (NASDAQ: SMSC) was founded in 1971 by Paul Richman, an MIT-trained engineer. SMSC had since its beginning focused on intensive R&D activities and had a number of cross-licensing agreements with large IT companies, such as IBM, Intel, Micron, NEC and Toshiba, from which licensing fee income had been a stable secondary source of revenues. The company suggested in annual reports that its business was based on several key aspects—the ownership of substantial patented technologies, access to peer companies' technologies, extensive experience in integrating designs into systems, the ability to work closely with business customers and the cability to manage a global network of suppliers. While most of these aspects were already discussed in previous sections, SMSC, in particular, discussed at length the potential business risks caused by the concentration of service providers in East and South East Asia.

For various historical reasons, including an abundant supply of high-quality labor as well as government support, a significant portion of leading professional foundry companies, testing and packing companies and others, have been operating in China, Hong Kong, South Korea and Taiwan as well as Malaysia, Singapore, Thailand and the Philippines. Besides the concentration of service providers, the region spreading across East and South East Asia is also home to a large number of electronics manufacturers that generate an enormous rising demand for IC products (see also 5.2.19 Realtek). Aside from IC design companies, their business customers and service providers, there are also wholesalers as well as logistics centers owned by design companies, which usually operate in Hong Kong and Singapore and transport IC product between parties—from foundry facilities to assembly facilities, from service providers to internal final testing or directly to business customers. While flows of goods and information are international, the clustering and geographical concentration in the region nevertheless exposes a large part of the global semiconductor supply chain to various potential natural and political hazards in the region. For example, many companies studied in this research expressed an extensive list of shared concerns in their annual reports. Large earthquakes in Taiwan and the Pacific Rim have in the past caused disruptions to the semiconductor supply chain, especially in the delicate procedure of wafer fabrication.

Hurricanes and flooding have affected companies in Taiwan, Thailand, the Philippines and southern and coastal provinces of China. Currency exchange rates in the region have had some violent fluctuations, such as the appreciation of Chinese yen and the sharp depreciation of Korean won and Thai baht during the Asian financial crisis. Moreover, the occasional military tensions between North and South Korea and between China and Taiwan, comparable to the situation of Israel, also pose potential threats to the supply of manufacturing and testing and packaging capacity. Other companies also discussed past and future business disruptions potentially caused by pandemic diseases, such as SARs and avian influenza.

Table 5.23 The geographical distribution of SMSC's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Germany (Karlsruhe)[1]						38.7	38.7	38.7	38.7	38.7	5 (1/0)	2004
Japan (Osaka)						0.33		0.33	0.33	0.36	0 (0/1)	
Japan (Tokyo)						9.0	9.0	8.59	8.59	15.3		
Singapore[2]									0.33		0 (0/0)	
Sweden (Gothenburg)							2.0	2.0	2.0	2.0	0 (0/0)	
US (Phoenix, AZ)	X	X	X	X	X	16.0	12.1	17.2	17.2	17.2	209 (44/1)	1971
US (Tucson, AZ)	X	X	X	X	X	8.0	29.0	10.9	10.9	26.9		
US (San Jose, CA)	X	X										
US (Hauppauge, NY)[3]	130	130	130	130	130	80	200	200	200	200		
US (Austin, TX)	X	X	X	X	X	43.2	43.2	97.2	63.1	63.1		

Note: 1. Acquisition of OASIS, a privately-held IC design company based in Karlsruhe, Germany, in March 2005 is an earlier observed event of the company's R&D internationalization. 2. The site was mainly for sales and marketing except in 2008. 3. There was other floor space for manufacturing facilityies. 4. Main design centers were located in Arizona, New York, Texas and Germany. 5. A series of acquisitions in 2009 added Chennai, India, Pforzheim, Germany, Ottawa, Canada, to this list. The company also mentioned a new site in Sofia, Bulgaria. 6. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.24 VIA Technologies and intellectual property right litigation

First founded in Fremont, California, in 1987, VIA Technologies moved its headquarters to Taiwan in 1992 to benefit from the proximity to the business market in Taiwan and the then emerging manufacturing bases in China. As an affiliate of a renowned Taiwanese business group, Formosa Plastics Group, VIA focused on designing IC products used in personal computers, especially motherboard chipsets from which the company had significant commercial success between the late 1990s and early 2000s. In a personal computer for example, a motherboard chipset is a set of IC products designed to bridge between microprocessor IC products and other devices on a motherboard, communicating between different electronic components and controlling the functioning of a large part of the personal computer hardware. Because motherboards were mostly supplied by electronics companies based in Taiwan, VIA had advantageous geographical proximity to its main business customers (see also 5.2.19 Realtek). In addition to its motherboard chipset business, the company also conducted several business acquisitions in the US to extend its product lines and strengthen its patent portfolio. Among others, the acquisition of the microprocessor business of National Semiconductors enabled VIA's entry into microprocessor IC product market; a joint venture with S3 Graphics allowed VIA to obtain the former party's graphics IC business and to strengthen its patent profile against a prolonged legal dispute with Intel, an IDM company and the leader in the microprocessor IC product market.

While working smoothly with its nearby business customers, VIA struggled to gain the permission and technological assistance from the IDM company supplying microprocessor IC products necessary for VIA's motherboard chipset IC products to function properly as well as legally. According to the annual reports of VIA and Intel and coverage by CNET, an industrial news website, Intel consecutively initiated two series of IPR litigation against VIA. Intel filed lawsuits in the US, Europe and Asia, alleging that VIA's IC products violated a previous licensing agreement and infringed Intel's patents. Intel claimed VIA, which was licensed in 1998 to supply chipset IC products compatible with several of Intel's microprocessors, had gone beyond the licensing agreement and supplied chipset IC products that used different technological standards and supported microprocessors unspecified in the agreement. In particular, VIA introduced a unique range of chipset IC products containing a less advanced technological standard, which was based on a mature technology and compatible with some less expensive electronic components. Meanwhile, Intel’s chipset IC products adopted an alternative technological standard, which was more advanced but only compatible with some expensive electronic components. In response, VIA filed countersuits against Intel in Taiwan and the US and acquired the graphics IC business of S3 Graphics, which held a considerable patent stock and a license to manufacture chipset IC products for Intel’s microprocessor IC products.

Although this alternative and newer technological standard, together with compatible electronic components, would provide superior performance for computers, motherboard manufacturers—the main business customers of chipset IC products—were mostly reluctant to adopt the newer and more expensive solution in their motherboard products. In April 1999, CNET reported that nearly every motherboard manufacturer introduced some products using VIA’s IC products in COMPUTEX Taipei, one of the largest international trade expos of ICTs since the 1980s. However, despite the support from compatriots, the lawsuits between Intel and VIA still threatened to material impact the course of business, particularly if the court ruled and upheld prohibitions on importing and selling of end products containing disputed IC products. According to the annual reports of other companies studied in this research, such injunctions are frequently sought in IPR litigation. By April 2003, VIA and Intel entered a settlement agreement and together dismissed approximately a dozen lawsuits worldwide. The confidential settlement agreement included a decade-long cross-licensing agreement covering a range of each company’s products, subject to certain terms and limitations (see also 5.2.12 Lattice).

Table 5.24 The geographical distribution of VIA’s knowledge creation

R&D Center	‘00	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	Patent	Since
China (Beijing)[1]		X	X	X	X							
China (Hangzhou)[1]			X	X	X						30 (2/0)	2002
China (Shanghai)		X	X									
India (Bangalore)[2]							X				0 (0/0)	
India (Mumbai)[2]								X				
Japan (Tokyo)	X	X	X	X	X	X	X	X	X	X	0 (0/0)	
Sweden (Lund)[3]				X	X						3 (0/0)	2000

Sweden (Stockholm)[3]			X	X	X	X	X	X	X	X		
Taiwan	X	X	X	X	X	X	X	X	X	X	1125 (92/1)	1998
UK (London)		X									11 (0/0)	2004
US (Fremont, CA)[4]	X	X	X	X	X	X	X	X	X	X	234 (11/0)	1995
US (Dover, DE)[5]			X	X	X	X	X	X	X	X		
US (Austin, TX)	X	X	X	X	X	X	X	X	X	X		
US (Plano, TX)	X	X	X	X	X	X	X	X	X	X		

Note: 1. VIA's annual reports identified most of its subsidiaries in China as sales offices. 2. The two R&D centers in India were briefly mentioned in the company's news releases. 3. In 2001, VIA made a collaboration agreement with Acreo, a Swedish research institute for electronics and communication technologies. 4. The company owned a number of R&D subsidiaries in multiple sites in Fremont, California. 5. The subsidiary in Delaware also managed the licensing of microprocessor-related IPs. 6. These R&D sites were identified by the location of the company's R&D subsidiaries, most of which were equity-controlled and managed through a subsidiary registered in the British Virgin Islands. 7. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.25 Xilinx and the demand for flexibility

Xilinx (NASDAQ: XLNX) was founded in Silicon Valley in 1984 by former semiconductor engineers of Zilog, a subsidiary of Exxon at the time. Xilinx and its main competitor, Altera, were the world's leading suppliers of PLD IC products, which allowed business customers to program the product with software tools for the performance of desired functions. Therefore, the product offering of Xilinx was comprised of several aspects—IC products, software tools to program the PLDs, predefined system functions loaded by customers as software, design services, customer training and field engineering and technical support.

Both Xilinx and Altera emerged during a trend in the semiconductor industry in the mid-1980s towards customized IC products for specific applications (see also 5.2.13 LSI). These highly-customized and design-intensive ASIC products are costly to design and to manufacture in small batches. However, semiconductor companies at the time were mostly vertically-integrated IDM companies—less flexible but advantageous in the mass production of standardized IC products with scale economies and better intra-firm coordination (see also 5.2.20 SanDisk). Because of the reluctance of IDM companies and the higher design costs of customized products, revisions to a flawed IC design and changes in customer requirements would usually take weeks or months to implement. This inflexibility can cause problems for business customers whose end products were supplied in smaller volumes and greater diversification, because any revision to their desired IC products could potentially result in costly delays in the design and manufacturing schedule of end products.

Seeking a new solution, Ross Freeman, one of the founders of Xilinx, proposed the novel idea to develop a ‘blank state’ programmable IC product that would not only reduce the risk of faulty designs but also allow greater flexibility for business customers. This unique flexibility of PLD IC products gave business customers and end product designers the means to achieve product diversification more quickly and easily, especially if the design of highly-customized ASIC products was costly and time-consuming. Though less efficient compared with custom-built ASIC products, PLD IC products could be easily reconfigured in the case of end product revision and redesign, shortening time-to-market for diversified end market products. Moreover, according to Xilinx’s company website, the product performance and unit cost of its PLD products had been quickly improving and were becoming comparable to ASIC products in some applications, as a result of the development of advanced manufacturing progress.

Table 5.25 The geographical distribution of Xilinx’s knowledge creation

R&D Center (ft^2)	**‘00**	**‘01**	**‘02**	**‘03**	**‘04**	**‘05**	**‘06**	**‘07**	**‘08**	**‘09**	**Patent**	**Since**
Canada (Toronto)									X	X	12 (0/0)	2002
France (Grenoble)						X	X	X	X	X	8 (0/0)	2002
India (Hyderabad)									X	X	3 (0/0)	2008
Ireland (Dublin)[1]	100	100	228	228	228	228	228	228	228	228	28 (1/1)	1999
UK (Edinburgh)						X	X	X	X	X	68 (1/0)	1993
US (San Jose, CA)	588	588	588	588	588	588	588	588	588	588	2534 (81/1)	1984
US (Boulder, CO)2	60	60										
US (Longmont, CO)	130	130	130	130	130	130	130	130	130	130		
US (Minneapolis, MN)				X	X	X						
US (Albuquerque, NM)	45	45	45	45	45	45	45	45	45	45		
US (Portland, OR)									X	X		
US (Austin, TX)				X	X	X	X	X				

Note: 1. Xilinx had regional headquarters in Dublin and Singapore for product testing and distribution. 2. The facility was relocated to the neighboring site in Longmont, Colorado. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting).

5.2.26 Zoran Corporation and the concentration of sales revenues in East Asia

Zoran Corporation was founded in California in 1981 with a business focus on digital signal processing applications for the defense industry. In 1989, the company changed its strategy and started to design and market IC products for the emerging multimedia market. With greater functionality and performance, IC products and related technologies for digital signal processing allowed digital audio and video signals to be edited, compressed, stored and transmitted in various digital formats introduced by international committees and groups, such as the Joint Photographic Experts Group (JPEG), which developed standards for high quality still images, and the Moving Pictures Experts Group (MPEG) for digital audio and video. During the inter-crises period, Zoran designed IC products for digital entertainment and digital imaging, such as video players, movie and home theater systems, digital cameras, video editing, set-top boxes for television, and printers and scanners. Like several of its main competitors, such as ESS Technologies and MediaTek, it also designed IC products for mobile phones when this unique portable personal electronic device became popular and created fast-growing demand for IC products with high performance, low-power consumption and multimedia functions (see 5.2.3 Atheros and 5.2.10 ESS). In 2011, Zoran merged with CSR, another company in the sample.

To work with leading manufacturers in the commercial and consumer markets and identify the market segments with growth potential, Zoran established sales offices near key customers and strategic partners worldwide (see also 5.2.19 Realtek). These companies supplying IC products for consumer electronics devices shared a feature—the very high concentration of sales revenues in East Asia, where a vast number of consumer electronics manufacturers and their factories operated and created a significant demand for IC products. Therefore, similar to ESS Technology, Zoran expanded its presence and opened half a dozen technological support offices in East Asia, while competition increasingly came from Asian IC design companies, such as MediaTek Novatek and Sunplus (see Table 4.2). Despite their relative technological disadvantage, Asian IC design companies had not only cost advantages but also historical relationships with and geographical proximity to consumer electronics manufacturers and service providers in the region (see 5.2.19 Realtek). Also, a unique aspect of Zoran was the significance of its R&D activities in Haifa, Israel, where the company operated its largest design center in terms of floor space and the number of R&D personnel. The company also had R&D agreements with the Israeli Ministry of Industry and Trade Department and the Israel-United States Binational Industrial Research and Development Foundation, which would provide partial funding for approved research projects.

Table 5.26 The geographical distribution of Zoran’s knowledge creation

R&D Center	‘00	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	Patent	Since
Canada (Toronto)[1]			X								8 (0/0)	2001
China (Shanghai)				X	X	X	X	X	X	X	1 (0/0)	2007
China (Shenzhen)	X	X	X	X	X	X	X	X	X	X		
France (Paris)									X	X	7 (0/0)	2002
Germany (Dortmund)				X	X	X	X	X			0 (0/0)	
Hong Kong		X	X	X	X	X	X	X	X	X	0 (0/0)	
Israel (Haifa) [1]	20	20	27	27	61.4	61.4	109.7	109.7	109.7	109.7	62 (10/1)	1986
Israel (Kfar Netter) [2]	3	3					16.1	16.1	16.1			
Japan (Tokyo)	X	X	X	X	X	X	X	X	X	X	0 (0/0)	
Korea (Seoul)		X	X	X	X	X	X	X	X	X	0 (0/0)	
Sweden (Linkoping)											4 (3/0)	2007
Taiwan (Taipei)	X	X	X	X	X	X	X	X	X	X	0 (0/0)	
UK (Manchester)				X	X	X	X	X	X	X	0 (0/0)	
US (Phoenix, AZ)				X	X							
US (Sunnyvale, CA)[1,3]	24	24	24	89	89	89	89	89	89	89	92 (34/3)	1983
US (Burlington, MA)[1]				X	X	X	X	X	X	X		

Note: 1. Main design centers. 2. This entry includes a nearby location in Kfar Saba, Israel. 3. This entry includes the company’s previous headquarters in Santa Clara, California. 4. This entry includes a nearby location in Woburn, Massachusetts. 5. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.27 ARM Holdings and IP cores licensing

ARM Holdings (LSE: ARM; NASDAQ: ARMH) is a world-leading IP vendor based in Cambridge, the UK. Formerly Advanced RISC Machines, the company was formed as a joint venture between Acorn Computers and Apple Computer in 1990 and later renamed as ARM in 1998, and went public in the same year. In the past decade, the company had significant growth through investments and mergers and acquisitions. ARM devised several partner programs to assist some of its less capable business customers, especially smaller IC design companies based in emerging economies (see also 5.2.15 MediaTek). For example, the ARM Approved Design Center Program provided qualification and training for design companies planning to implement IC designs with ARM technologies; the ARM Processor Foundry Program established a three-way official relationship between ARM, professional foundries and IC design companies, which would assist in implementing and accelerating the time-to-market of IC products incorporating ARM’s microprocessor IC designs. More recently, ARM also invested in developing process technologies by working with TSMC, the manufacturing service provider for many of ARM’s main business customers.

On the other hand, ARM worked only indirectly with professional foundry companies and had a much longer time gap between R&D investment and generation of sales revenue (see also 5.2.17 PMC-Sierra). According to the company’s annual reports, the design of an IP core would take 2 to 3 years of R&D before it was completed and publicly announced, after which, potential licensees—other IC design companies—would usually pay an up-front license fee for accessing the IP core. Licensees would then need to undertake another 3 to 4 years of R&D to successfully incorporate the IP core into their own IC products, upon which a royalty fee would be charged by ARM per unit of the final IC product. With some minor and incremental revisions, these microprocessor IC products tend to have longer commercial life cycles and larger production volume than other IC products. They have wider applications because of these microprocessor IC products are relatively standardized. In some cases, sales from a license may last more than a decade depending on specific applications and product variations.

Mainly operating as a supplier of IPs related to its microprocessor core designs, ARM’s version of the fabless business model slightly differs from that of other IC design companies studied in this research. ARM’s focus on IPs related to microprocessor core designs and technology licensing allowed many companies with IC design capability to introduce their microprocessor IC products, which were formerly supplied by a handful of IDMs (see also 5.2.15 MediaTek and 5.2.18 Qualcomm). ARM’s licensees were exempted from risking patent infringement litigation and duplicating R&D investments to internally develop a large part of a microprocessor IC product. Linden and Somaya (2003) point out the two historical developments in the semiconductor industry which effectively lowered the transaction costs and preconditioned a market for IP cores—the establishment of a silicon-based manufacturing technology as the dominant design in the 1980s, and the emergence of design software and communication network. These developments reduced the interdependency between design activity and manufacturing activity and between different parts of the design activity, facilitating the vertical disintegration and specialization of the semiconductor value chain.

In fact, the IP core licensing activity is not limited to microprocessor IC products. The further division of labor within the IC design industry allows companies to focus on designing the most value-adding part based on their technological expertise, while externally sourcing complementary technologies embedded in IP cores at reasonable prices. These reusable IP cores, which are designed by IP suppliers with related expertise and approved by other licensees, may expedite the time to market, reduce design costs and improve the performance of IC products (Brown & Linden, 2009). Moreover, through IP core licensing, related inventions that are complementary but proprietary to different companies can be transferred and recombined to create a novel multiple-invention IC product (Linden & Somaya, 2003).

Table 5.27 The geographical distribution of ARM’s knowledge creation

R&D Center	‘00	‘01	‘02	‘03	‘04	‘05	‘06	‘07	‘08	‘09	Patent	Since
Belgium (Leuven)				X	X	X	X	X	X		10 (0/0)	2004
France (Grenoble)							X	X	X	X	45 (2/6)	2002
France (Sophia Antipolis)	X	X	X	X	X	X	X	X	X	X		
Germany (Aachen)[1]						X	X	X	X	X	0 (0/0)	
Germany (Grasbrunn)[1]						X	X	X	X	X		
India (Bangalore)					24.8	68.5	50.2	94.7	88.5	63.5	4 (0/0)	2006
Norway (Trondheim)[2]							X	X	X	X	0 (0/0)	
Slovenia (Sentjernej)							X	X	X	X	0 (0/0)	
UK (Blackburn)		X	X	X	X	X	X	X	X	X	415 (37/3)	1992
UK (Cambridge)	X	X	93	93	93	93	93	93	90	90		
UK (Maidenhead,)	X	X	17.1	17.1	17.1	17.1	17.1	17.1	20	20		
UK (Sheffield)	X	X	X	X	X	X	X	10.2	X	X		
US (Austin, TX)	X	X	17	17	17	17	33.7	33.7	76	42	145 (5/2)	1997
US (Cary, NC)						X		X	X	X		
US (Irvine, CA)					X	X	X	X	X	X		
US (Olympia, WA)							X	X	X	X		
US (Plano, TX)						X	X	X				
US (San Diego, CA)					35.3	35.3	X	X	X	X		
US (Sunnyvale, CA)[3]					54.5	78	54.5	54.5	92	92		

Note: 1. Participation of German inventors was found in patenting records after 2008 as co-inventors. 2. Patents originating in Norway only appeared after 2008. 3. This entry includes nearby San Jose, California. 4. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.2.28 *Dialog Semiconductor and IC products for automobiles*

Dialog Semiconductor (FWB: DLG), one of the very few larger European IC design MNEs, developed and supplied power management and mixed-signal IC products that could optimize energy usage, process audio signals, and process analog and digital data for wireless, automotive and industrial applications. To avoid interference between different functions, electronics manufacturers used to mix individual analog-signal and digital-signal components to achieve the mixed-signal function in their electronics design. Mixed-signal IC products, which integrated various components, therefore provided a better solution for electronics manufacturers trying to achieve greater functionality, reduce product dimensions and lower power consumption.

Automobile and industrial equipment industries are and have different characteristics demands than consumer electronics manufacturers. In these markets, manufacturers are faced with longer business cycles and are more concerned with the safety and durability of IC products that control the electronic systems in cars or industrial equipment. For instance, IC products used in automobiles, the end product of the automotive industry, are expected to operate in extreme weather and terrain conditions and to remain fully functional in subfreezing as well as boiling temperatures. Moreover, because the end products are designed to be in service for decades, the testing and packaging activities for automobile IC products have been conducted with low tolerance of failure to meet unique specifications, such as shock tolerance, working temperature and durability. IC products for industrial equipment have their own specific requirements -- they have to be not just durable for their intended purpose, but must also comply with more restrictive and exclusive industrial and technological standards. Hence, in these industries, sufficient experience and long-term relationships are usually required for any IC company to be qualified and chosen by a specific business customer as a member of its supply chain. Moreover, both parties would face high switching costs.

Dialog Semiconductor, with a business focus on automotive electronics, originated from the European operation of International Microelectronic Products, which was later acquired by Daimler-Benz AG in 1989. Continuing to supply IC products for automotive electronic systems with funding from internal and external investors, including private equity funds and Ericsson, Dialog Semiconductor was spun-off in 1998 and incorporated in the United Kingdom with its principal headquarters in Kirchheim, near Stuttgart, Germany. The company also developed its customer base through its design centers in Austria and Japan and other offices in East Asia, which served the Chinese market. These efforts to internationalize the company created a global presence while providing localized support to business customers and their R&D activities. In particular, the company used uniform design software and information technology to facilitate knowledge sharing and coordination between individual design centers across multiple locations. Brown and Duguid (2001) suggest such a network of practice would foster communication and knowledge sharing between members.

Table 5.28 The geographical distribution of Dialog's knowledge creation

R&D Center	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	Patent	Since
Austria (Graz-Seiersberg)[2]	2.1	2.1	2.1	6.4	6.4	6.4	X	X	X	X	11 (4/0)	2002
Germany (Heidelberg)	3.3	3.3	5.2	5.2	5.2	5.2	X	X				
Germany (Kirchheim)[2]	39.8	47.0	45.7	62.2	62.7	62.0	X	X	X	X	104 (26/1)	1998
Germany (Munich)[2]	5.7	5.7	5.7	5.7	5.7	5.7	X	X	X	X		
Japan (Tokyo)[2]	73.8	73.8	4.2	4.2	4.2	4.2	X	X	X	X	1 (0/0)	2007
Sweden (Lund)	17.6	22.3	22.3								6 (1/0)	2002
UK (Edinburgh)[2]							X	X	X	X	17 (5/1)	2002
UK (Swindon)[2]	8.4	8.4	8.4	8.4	8.4	8.4	X	X	X	X		
US (Clinton, NJ)	7.1	7.1	7.1	7.1	7.1						10 (4/0)	2000

Note: 1. The floor space information was converted from square meters. 2. The company made limited reports on its R&D locations after 2007. However, according to company websites, these sites remained operational as of June 2014. 3. Patenting records include three numbers: Total patenting (Pioneering patenting/ Pioneering co-patenting). Source: This research.

5.3 Discussion and conclusion

The daily business of IC design companies is associated with competition and survival by constant and intensive international knowledge creation and multi-lateral knowledge transfer worldwide. Sales representatives and engineers, hired in international sale offices, join potential business customers to exchange ideas and create the specification for customized IC designs—together they develop the knowledge of specific customer demand. Researchers in corporate R&D centers develop new IC components and novel algorithms, renewing as well as cultivating the repertoire of technological knowledge. IC designers and engineers then link the knowledge of customer demand with firm-proprietary technologies, licensed technologies and design experience to work out the IC design, while collaborating with foundry companies, testing and packing companies and other service providers to ensure the quality and yields of IC products. Although job titles and organization of R&D labor forces vary, intensive knowledge creation and transfer are observed both internally and externally.

Moreover, the stories disclosed in the annual reports and news archives indicate these companies face a hyper-competitive business environment. Going through emergence, decline, restructuring and refocusing, all the while scouting for the inception of new demand for IC products, the successful few are characterized by close communication and collaboration between subsidiaries, the headquarters and business customers, and timely and cost-effective delivery of finished IC products.

The emergence of the IC design industry in the 1990s created a knowledge and design-intensive business model in the overall semiconductor industry, which was previously occupied by the vertically-integrated IDM companies. Fabless companies in the IC design industry sought to satisfy the unmet demand left by IDM companies due to scale diseconomies. Some created the innovative solution of PLD IC products, the flexibility of which was widely appreciated and adopted in different industries (see 5.2.2 Altera, 5.2.12 Lattice and 5.2.25 Xilinx). Others chose to work closely with end product producers, listened to their requirement, and created highly-customized ASIC and ASSP IC products for these business customers (see 5.2.13 LSI and 5.2.22 Silicon Labs).

Subsequently, when the personal computers and consumer electronics industries created enormous yet fast-changing demands for a large variety of IC products, a new group of IC design companies stepped into the markets in the 1990s with IC products consisting of novel combinations of technologies (see 5.2.3 Atheros and 5.2.8 CSR). Moreover, accompanied by the development of professional service providers, a few IC design companies were able to outcompete large IDM companies with high-performance IC products based on advanced manufacturing processes (see 5.2.4 ATI, 5.2.16 NVidia and 5.2.18 Qualcomm). Lastly, the fabless business model lowered the entry barrier to the semiconductor industry and furthered the division of labor, allowing the arrival of IC design companies in East Asia and Europe with the ability to serve business customers in the home region (see 5.2.19 Realtek, 5.2.15 MediaTek and 5.2.28 Dialog Semiconductor).

5.3.1 The business focuses of IC design companies

The following tables provide a summary of information related to the 28 IC design MNEs studied in this research. Table 5.29 summarizes the founding year and the headquarters identified from annual reports and historical news archives. In more than one case, these archival sources provided different yet more reliable reporting relative to databases entries. These less accurate database entries could be attributed to frequent relocation and reincorporation of these IC companies, as well as name changes during start-up and restructuration times. Interesting cases also came from those companies that moved their headquarters between different states and countries and those which operated dual-headquarters.

As suggested in this review, a dual-headquarters structure often stemmed from the discrepancy between the tax regime for corporate registration and the actual location where corporate decisions were made. As a result, database entries can sometimes be arbitrary in the absence of any reference to archival sources and a reading of lengthy texts. Instead, only in a few cases is there indeed a distribution of decision-making between the dual-headquarters as explained in annual reports. Moreover, the analysis of patenting records provides a nuanced illustration of the geographical distribution of knowledge-creating activities (see 5.2.17 PMC-Sierra and 5.2.28 Dialog Semiconductor).

Table 5.29 The 28 IC design MNEs

Company Name	Year founded	HQ / Home country[1]	Main markets and applications[2]	Main product lines	Defense application[3]
Agere	2000	Allentown (PA, US)	IC products for hard disk drives, mobile phones, high-speed communications systems and personal computers. (Acquired by LSI in 2007)	Storage/ Communication	N/A
Altera	1983	San Jose (CA, US)	Communications, industrial and automotive electronic devices, computer and storage, and various consumer applications.	FPGA/PLD	Yes
Atheros	1998	Santa Clara (CA, US)	IP products used in personal computers, networking equipment and consumer electronics devices, including Wi-Fi, Bluetooth, and GPS.	Communication	Yes
ATI	1985	Markham (CA)	Graphics and multimedia processors and technologies for desktop and notebook PCs and consumer electronic devices such as mobile phones, DTVs and game consoles.	Graphics	N/A
Avago	2005	Singapore (SG)	Industrial and automotive electronics, wired infrastructure, wireless communications, and consumer and computing peripherals.	Analog/mixed-signal/ Optoelectronic	Yes
Broadcom	1991	Irvine (CA, US)	Computing and networking equipment, digital entertainment and broadband access products and mobile devices.	Communication	N/A
Cirrus Logic	1981	Austin (TX, US)	High-precision analog and mixed-signal ICs for consumer, professional and automotive entertainment and industrial measurement applications.	Analog/mixed-signal	Yes
CSR	1998	Cambridge (UK)	Bluetooth IC for mobile phones, PC, automotive and other consumer electronics. More recently, Wi-Fi and GPS.	Communication	N/A
DSP Group	1987	Santa Clara (CA, US)	Short-range wireless communication technologies that enable home networking voice, audio, video and data	Communication	N/A
ESS	1984	Fremont (CA, US)	IC products for consumer electronics such as DVD, VCD, MP3 and other digital media players, digital camcorders, mobile phones and PC products.	Mixed-signal/ Graphics	N/A
Genesis Microchip	1987	Alviso (CA, US)	IC products that function as display controllers that receive and process video and images for viewing on flat-panel display devices, such as flat-panel televisions and computer monitors.	Mixed-signal/ Graphics	N/A
Lattice	1983	Hillsboro (OR, US)	Programmable logic products and related software packages for original equipment manufacturers in the communications, computing, consumer, industrial, automotive, medical and military end markets.	FPGA/PLD	Yes
LSI	1980	Milpitas (CA, US)	Customized and standard IC products for storage and networking applications. Enterprise storage system.	Storage/ Communication	N/A
Marvell	1995	Sunnyvale (CA, US)[4]	Communication infrastructure, enterprise and PC-client data communications and data storage systems.	Storage/ Communication	N/A
MediaTek	1997	Hsinchu (TW)	Wireless communication, optical storage, set-top box for television and IC products for other consumer electronics	Storage/ Communication/	N/A

NVidia	1993	Santa Clara (CA, US)	IC products designed to generate realistic, interactive graphics on consumer and professional computing devices.	Microprocessor Graphics	N/A
PMC-Sierra	1983	Santa Clara (CA, US); Burnaby (CA)[5]	Communications semiconductors, storage semiconductors and system-on-chips primarily for the communications service provider, storage, and enterprise markets.	Storage/ Communication	N/A
Qualcomm	1985	San Diego (CA, US)	Wireless devices, particularly mobile phones, data cards and infrastructure equipment. Satellite communications.	Communication/ Microprocessor	Yes
Realtek	1987	Hsinchu (TW)	Network and multimedia IC products used in personal computers, peripheral devices, and consumer electronics.	Mixed-signal/ Communication	N/A
SanDisk	1988	Sunnyvale (CA, US)	Flash memory devices used in consumer electronic devices, such as mobile phones, digital cameras, gaming devices and computers, or embedded in electronics systems in industrial and military markets.	Storage	Yes
Semtech	1960	Camarillo (CA, US)	IC products sold principally to customers in the computer, consumer electronics, and communications as well as industrial, military and aerospace markets.	Analog/Mixed-signal	Yes
Silicon Labs	1996	Austin (TX, US)	IC products in a broad range of applications in a variety of markets, including communications, consumer, industrial, automotive, medical and power management.	Analog/Mixed-signal	N/A
SMSC	1971	Hauppauge (NY, US)	IC products for a range of end products in consumer electronics and infotainment, mobile and desktop computer, computer network and industrial markets.	Analog/Mixed-signal	N/A
VIA	1987	Taipei (TW)	IC products used in personal computers and embedded systems, including processors, motherboard chipsets and peripherals.	Storage/ Communication	N/A
Xilinx	1984	San Jose (CA, US)	Wired and wireless communications, industrial, scientific and medical, aerospace and defense, audio, video and broadcast, consumer, automotive and data processing.	FPGA/PLD	Yes
Zoran	1981	Sunnyvale (CA, US)	IC products for digital entertainment and digital imaging, such as video players, movie and home theater systems, digital cameras, video editing, set-top boxes for television, and printers and scanners.	Mixed-signal/ Graphics	Yes
ARM	1990	Cambridge (UK)	Digital cellular phones, modems, and automotive functions. Potential use in many growing markets including smart cards and digital video.	Microprocessor	N/A
Dialog	1998	Kirchheim (DE)	Power management, audio and imaging technology, with mixed signal standard IC products as well as application specific IC products for wireless, automotive and industrial applications.	Analog/Mixed-signal	N/A

Note: 1. Principal executive offices in most of the period between 2000 and 2008. 2. Based on each company's own description of business and business segments as reported in annual reports. 3. Some companies indicated in annual reports that some products were used in the aerospace and defense applications. 4. Marvell moved its headquarters to nearby Santa Clara, California, in 2005. 5. PMC-Sierra operated with dual headquarters in Santa Clara, California, and Burnaby, British Columbia, Canada. Its annual reports, however, suggested the US site hosted its principal executive offices. Source: Company annual reports and this research.

Moreover, these archival sources also suggest that existing standard industrial classification (SIC) methods are inadequate and incongruous in the classification of IC design companies. For instance, while their business models differ, Intel, Texas Instruments, TSMC and MediaTek, representing the four different business models—IDM, hybrid, foundry and IC Design—all have the identical classifications, which are 3674: Semiconductors and Related Devices (US SIC 1987); 2611: Manufacture of electronic components (UK SIC 2007); and 334413: Semiconductor and Related Device Manufacturing (NAICS 2012). However, Qualcomm, which has been in the league of microprocessor IC suppliers along with Intel and MediaTek, was categorized as 3663: Radio and Television Broadcasting and Communications Equipment (US SIC 1987); 26309: Manufacture of communication equipment (UK SIC 2007); and, only more recently, 334413: Semiconductor and Related Device Manufacturing (NAICS 2012).

IBM is another notable example. The company has over the years revamped its business model and shifted business focus many times, its industrial classifications have changed several times, including 7373: Computer Integrated Systems Design (US SIC 1987); 6202: Computer consultancy activities (UK SIC 2007); and 541512: Computer Systems Design Services (NAICS 2012). However, as shown in this in-depth review, IBM related to the IC design industry as a service provider and a technology leader, at least until the end of the inter-crises period. In other words, the fast changing nature and new development of the semiconductor industries clearly require academic researchers to proceed with caution, especially those conducting data compilation based on SICs (Adams et al., 2013).

5.3.2 Main product categories

Alongside the description of business focus, the last two columns of Table 5.29 recorded the main product lines of each IC design company and whether its IC products had defense and aerospace applications. This information was based on each company’s own business description and product segmentation disclosed during the inter-crises period. Because an IC design company may change or expand its product lines over time and because the technologies behind these product lines can overlap, this classification should not be considered as exclusive and deterministic. Nonetheless, product lines and categories (see Table 5.30 in Appendix) imply different transaction properties of IC products which may impact different vertical integration and internationalization decisions—classical topics in internalization theory, which addresses the decision on the internalization of activities and the use of external service providers (see Table 5.31 in Appendix for the list of most frequently used service providers). In brief, although the IC design industry has been largely reliant on external service providers, the internalization of manufacturing and testing and packing activities may become the preferable choice—when an IC design company intends to maintain equity control over proprietary technologies and production quality and when the market demand is believed to be persistent in the foreseeable future (see 5.2.1 Agere, 5.2.2 Altera and 5.2.20 SanDisk).

On the other hand, the product lines of an IC design company also relate to the specific industries in which business customers were served and its IC products were incorporated into end products. In the case of consumer electronics industry, geographical proximity to business customers fosters the development and design-win of IC products (see 5.2.13 LSI and 5.2.26 Zoran). In the case of industrial and automobile industries, longer-term relationships and constant collaboration with business customers are associated with unique specifications and exclusive industrial and technological standards for IC products that are expected to have longer commercial life cycles (see 5.2.5 Avago and 5.2.28 Dialog Semiconductor). Regarding the defense and aerospace industries, with the technological goals of miniaturization and reliability, manufacturers in the sector created early demand for semiconductor devices and kept strict rules for protecting advanced technologies as well for as national security (see 5.2.21 Semtech). Moreover, further analysis of patenting records in the next chapter suggests that defense and aerospace manufacturers have continued to influence innovations in the IC design industry during the inter-crises period.

5.3.3 User dominated innovation

The early research on the semiconductor industry by von Hippel (1976) already emphasized the importance of customers to manufacturing process innovation. Although his notion of user dominated innovation, referring to IDM companies in the 1970s, seems less applicable to the highly specialized IC design companies, companies studied in this research have provided a strong indication of the customer influence and their specific demands on innovation. Working with digital camera and electronics manufacturers, SanDisk helped establish the technological standards and formats of various end products based on flash memory IC products (see 5.2.20 SanDisk). To deliver high-performance, mixed-signal IC products within shorter delivery times and at lower costs, Silicon Labs relied on senior engineers—who besides mixed-signal design expertise also had the market knowledge about various aspects of business customers and the technological knowledge about industrial standards and manufacturing processes (see 5.2.22 Silicon Labs). Lastly, the recent success of IC design companies in East Asia could be attributed to a large number of electronics manufacturers, which have been concentrated in the region and have accounted for the vast majority of worldwide sales of IC products.

5.3.4 Implications and limitations of the knowledge creation location information

This research intends to discover all active and identifiable sites that potentially create technology knowledge, and therefore a full-text search is conducted to register all research and development, design, technology service and engineering sites mentioned in company annual reports. However, an unexpected finding in this chapter is that not every R&D site is indeed associated with patenting records. The statistics suggest a discrepancy between the knowledge-creating locations claimed and reported in annual reports and those locations suggested by inventor residence information. Besides the fact that some sites were too young or too short-lived to have had patents, other potential explanations as well as limitations are discussed.

Firstly, knowledge creation in some locations may have played a supportive role in the MNE group and only made indirect contributions to its overall patenting. For instance, the patenting records of NVidia showed that none of its patents was originated in Hong Kong and Japan, according to first inventor residence information (see Table 5.16). Further examination of co-inventor residence information nevertheless reveals several patents with co-inventors in these locations. While these are arguably rare cases, future studies might consider the adoption of other assignment principles (see Bergek & Bruzelius, 2010) to shed more light on these supportive locations.

Secondly, as explained at the beginning of the chapter, even within the same industry, companies may have different definition and labeling of R&D sites. The variation in terminology may reflect business statements as well as the administrative heritage of the company. While further investigation on the semiotics is beyond the scope of this research, researchers may conduct qualitative research and field studies in the future.

Thirdly, a firm’s commitment to innovation may have implications on its corporate image. It cannot be excluded that less accurate claims were made in some cases to attract new customers, investors or government support. In addition, those sites in tax-friendly locations might also be less relevant to knowledge creation. Such cases are however beyond the scope of this research.

Lastly, the specific pieces of knowledge created in certain sites can be less patentable. For instance, a piece of knowledge can be created with practical use instead of novelty. Conversely, another piece might be categorized as basic science and published in academic journals or conferences. In these cases, the level of knowledge creation is likely under-represented by patenting records. Arguably, the sampling method of this thesis—which restricted the compilation of patenting records to single industry—had reduced the heterogeneity in patentability and patent intensity. However, patenting records indeed have limitations and not all knowledge creation can be reflected by patent metrics.

Due to these reasons and the difficulties in variable computation, these locations with no patent records will be excluded in the empirical analysis in Chapter 7.

Appendix to Chapter 5

Table 5.30 IC products and abbreviations mentioned in the Chapter

Category	Explanation
ASIC	Application-specific integrated circuit (ASIC) is designed according to specific customer demands, as opposed to general-purpose semiconductors such as memory devices and microprocessors. Because ASICs are highly customized and manufactured to detailed customer requirements and technical specifications, they are advantageous in terms of product performance and lower unit cost, although the design costs are also higher.
ASSP	Application-specific standard product (ASSP) is similar to ASIC as both are dedicated to a specific application. ASSP is however designed with more standardized functions and is not limited to a single customer.
FPGA	Field-programmable gate array (FPGA) is a type of programmable logic devices which can be programmed in the field to meet specific requirements of the customer using special software tools outside a factory. This flexibility allows PLDs to be sold as standard components to multiple users for different applications and the development cost of PLDs to be spread over a larger customer base.
Analog/ Mixed-signal	Analog IC products convert real-world phenomena, such as temperature, pressure, light, sound, speed and motion, into or back from digital signals which can be manipulated or stored. High-performance analog IC products can accurately process higher signal intensity with speed and high variation.
Opto-electronic	Optoelectronic devices are often deployed with analog and mixed-signal IC products and convert light into or back from analog signals.
PLD	Programmable logic device (PLD) is similar to FPGA but has a longer history. Although many logic functions can be implemented using either architecture, each has been considered more suitable for distinct types of logic applications. Also, FPGAs may contain fixed circuits such as memory, input/output interface and processors.

Table 5.31 Most frequently used service providers and their basic information

Service provider		Found	HQ	Notes
IC manufacturing (fabrication)				
CSM	Chartered Semiconductor Manufacturing	1998	Singapore	NASDAQ: CHRT
TSMC	Taiwan Semiconductor Manufacturing Company	1978	Taiwan	NYSE: TSM
SMIC	Semiconductor Manufacturing International Corporation	2000	Shanghai, China	NYSE: SMI
UMC	United Microelectronics Corporation	1980	Taiwan	NYSE: UMC
Testing and Packaging (Assembly)				
Amkor	Amkor Technology	1968	Chandler, Arizona	NASDAQ: AMKR
ASE	Advanced Semiconductor Engineering	1984	Taiwan	NYSE: ASX
ASAT	ASAT Holdings	1999	Hong Kong	
KYEC	King Yuan Electronics Corporation	1987	Taiwan	Public
SPIL	Siliconware Precision Industries	1984	Taiwan	NASDAQ: SPIL
STATS ChipPAC	ST Assembly Test Services & ChipPAC Incorporated	1994	Singapore	Public; merged in 2004
UTAC	UTAC Holdings (United Test and Assembly Center)	1997	Singapore	Public

Note: The list is restricted to professional service providers that were publicly traded in the inter-crises period between 2001 and 2008. Source: Company annual reports and this research.

6 INTERNATIONAL KNOWLEDGE SEEKING AND TRANSFER

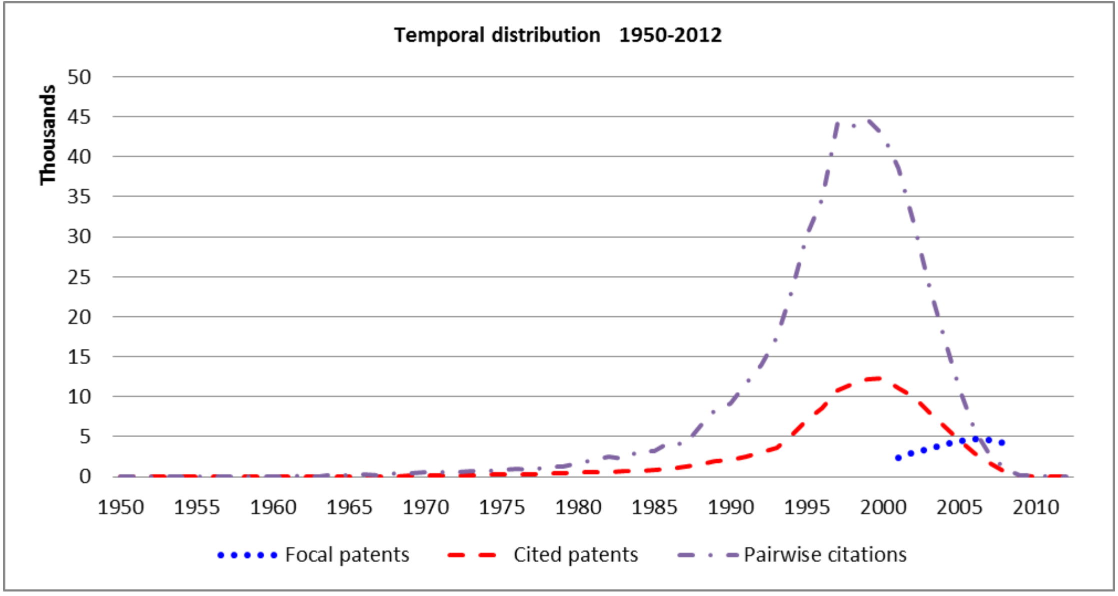
6.1 Introduction

This chapter analyzes the scope of international knowledge seeking and transfer of the IC design industry by identifying the knowledge sources and inflows into the 28 top IC design MNEs. This empirical observation of knowledge inflows is made possible by tracing and analyzing a large number of patent citations reported in their assigned patents, which account for a significant portion of the knowledge repertoire of the global IC design industry. Specifically, based on the reference information reported in each of the 30,964 *focal citing patents* assigned to the 28 IC design MNEs, 496,882 *pairwise citation records* were identified and attributed to 137,691 *backward cited patents*. A small percentage of focal patents (2.92%) do not contain any citation to utility patents, and yet they are retained in the analysis to maintain a consistent sample size.

Following essentially the same procedures for the citing patents (see Chapter 4), these backward cited patents were further verified and attributed to 70 countries of origin, 341 three-digit patent classes (USPC) and 39 industry categories (see Table 6.1 in Appendix). Figure 6.1 shows the frequency distribution of the focal citing patents, backward cited patents and pairwise citation records by the year of patent filing. The vast majority of citation records are associated with utility patents filed between 1980 and 2008, but the entire time window covers utility patents filed as early as the mid-19th century, including at least one patent by Alexander Graham Bell. Evidently, although the individuals and entities that created and patented specific pieces of knowledge may be deceased, the effects of their inventions will continue to exist and traverse in time-space.

Notably, the discussion and analysis in this chapter are mainly based on pairwise citation records—the linkages between focal citing patents and backward cited patents—for two reasons. Firstly, while patent documents report the inventors and inventive organizations of specific pieces of knowledge, pairwise citation records trace dynamic knowledge flows and establish the connections between knowledge pieces and between different inventors and inventive organizations. These traces and connections can be analyzed in order to understand in various aspects how different knowledge sources relate to the IC design industry. Secondly, the aggregated statistics of pairwise citations also provide indicators for the significance of these traces and connections. Therefore, besides the qualitative information about the identity and properties of these inventors and inventive organizations, the quantitative information about their relevance also becomes available.

Figure 6.1 Frequency distribution by the year of patent filing



Note: 1. Citations referring to patents filed before the 1970s account for a tiny percentage (0.52%) and even less (0.11%) for those filed before the 1960s, the first decade of the semiconductor industry. 2. Citation records referring to patents filed after 2008 are negligible (0.07%). Source: This research.

In the following sections, nearly half a million citation records are analyzed from three different aspects, each providing unique insights into the sources and intensities of technological knowledge inflows into the 28 IC design MNEs. Firstly, the geographical dimension of citation records is analyzed to locate the international knowledge sources of these IC design MNEs, revealing the geographical scope of their knowledge seeking and transfer. Secondly, citation records and associated patents are traced to their original assignees and source industries at the time of patent application. This information provides a panoramic view of the industrial dimension of knowledge sources and further investigation of the intensities of knowledge inflows from these sources. Thirdly, to delineate the effects of various factors in the temporal dimension of knowledge seeking and transfer, an econometric analysis is conducted for the observed year gaps between citing and cited patents. Relatively shorter year gaps imply intensive and time efficient knowledge flows, while longer year gaps may suggest otherwise. A summary and discussion of the findings conclude this chapter.

6.2 Geographical dimension of knowledge seeking and transfer

Table 6.1 summarizes the composition of pairwise citation records based on the property of backward cited patents, among 496,882 pairwise citation records, 306,764 (61.74%) are found associated with patent pairs of the same country origin, according to the residence information of first inventors. Interestingly, the percentage is higher among the subgroup of headquarters patents in the home country (68.14%) relative to subsidiaries' patents in host countries (23.92%). Instead, a significant portion of citation records reported in subsidiary patents (45.10%) are associated with patents invented in the home country of the MNE. This tendency to utilize local knowledge sources and home country sources appears weaker when geographical relevance is considered at the country-state-level, which further attributes knowledge sources and inflows in the US to each state.

Another important factor that connects individual pieces of knowledge is their technological relevance, which is found more pronounced than the industrial relevance. A higher proportion of citations were made to patents in the same 3-digit USPC (42.20%) than to same-industry patents (36.89%), including both the IC design and other sub-industries. Unlike the finding on geographical relevance, the effects of industrial and technological relevance are similar between headquarters and subsidiary patents. Based on the overall statistics, it is quite clear that the knowledge seeking and transfer by IC design MNEs are subject to national borders, and the concentration of knowledge flows are observed in both physical and technological space. The origin of patents has been summarized by countries and country-states. The countries are listed in Table 6.2. The denomination of country-state includes each American state as a separate location, while the denomination of country considers the entire US as one place. Considering the size of the country and its proportion in the dataset, further attribution of backward cited patents to individual American states is also appropriate because of the huge variation across American states.

Table 6.1 The composition of pairwise citation records

Relevance between the patent pairs	**Overall**		**Headquarters patents**		**Subsidiary patents**	
Geographical relevance						
Local: Same country origin	306,764	61.74%	289,548	68.14%	17,216	23.92%
Local: Same country-state origin	119,784	24.11%	111,174	26.16%	8,610	11.96%
Home: Home country origin[1]	322,009	64.81%	289,548	68.14%	32,461	45.10%
Home: Home country-state origin[1]	137,508	27.67%	122,150	28.75%	15,358	3.61%
Technological and industrial relevance						
Technological: Intra-firm citation	48,982	9.86%	42,786	10.07%	6,196	8.61%
Technological: Same patent class	209,675	42.20%	178,887	42.10%	30,788	42.77%
Industrial: Semiconductor industry	107,135[2]	21.56%	93,163	21.93%	13,972	19.41%
Industrial: Top IC design companies (28) [3]	76,188[2]	15.33%	65,617	15.44%	10,571	14.69%
Total citations	496,882	100%	424,903	85.51%	71,979	14.49%

Note: 1. Home origin is identified by the location of company headquarters. 2. Citations associated with top IC design companies or the 28 MNEs are separated. 3. The category includes 48,982 (9.86%) intra-firm citations made to 9,729 same company patents. 4. The percentage is separately computed for each category of citations and may not add up to one. 4. Country-state categories account for each America states separately. Source: This research.

6.2.1 Country origins of cited patents

Table 6.2 lists the fifteen most cited countries in each of the main regions and the rest of the world. The table is based on citation records instead of cited patent count, because the former is illustrative of the importance of each region as knowledge source area. While the citations made to North American patents are mostly split between Canada and the US, citations made to Asian and European patents are found relatively dispersed, particularly among European patents. European patents originating in eight European countries have received more than a thousand citations from the IC design MNEs, and in total thirty-five European countries have been identified as the countries of origin of backward cited patents. This may imply that knowledge creation in Europe is more dispersed across European countries than in other regions. However, the identification of European patents might be less accurate. Some European inventors can be hired in nearby countries while residing in another country, which would be reported as the country of residence in the actual patent document. In that case, a methodological limitation has to be accepted due to the definition of location, which can be regions, countries, states or cities.

Table 6.2 Fifteen most cited countries in the triad regions and the rest of the world

	Asia		**Europe**		**North America**		**Rest of the World**	
Citation counts	Japan (JP)	63,629	UK (UK)	9,981	US (US)	349,559	Australia (AU)	1,122
	South Korea (KR)	11,895	Germany (DE)	8,095	Canada (CA)	9,456	New Zealand (NZ)	121
	Taiwan (TW)	9,805	France (FR)	6,362	Mexico (MX)	20	South Africa (ZA)	56
	Israel (IL)	4,635	Finland (FI)	4,225	Cayman Islands (KY)	2	Brazil (BR)	50
	Singapore (SG)	1,155	Sweden (SE)	4,126	Bahamas (BS)	1	Egypt (EG)	14
	India (IN)	890	Netherlands (NL)	3,621	Costa Rica (CR)	1	Argentina (AR)	10
	China (CN)	530	Italy (IT)	1,999	Jamaica (JM)	1	Peru (PE)	3
	Hong King (HK)	380	Swiss (CH)	1,417			Venezuela (VE)	2
	Malaysia (MY)	299	Ireland (IE)	856			Columbia (CO)	1
	Philipines (PH)	51	Belgium (BE)	640			Marshall Islands (MH)	1
	Thailand (TH)	23	Russia (RU)	374			Nigeria (NG)	1
	UAE (AE)	7	Denmark (DK)	366				
	Pakistan (PK)	4	Austria (AT)	342				
	Saudi Arabia (SA)	3	Norway (NO)	231				
	Georgia (GE)	2	Spain (ES)	197				
	…	…	…	…				
Number of countries	17		35		7		11	
Citation count	93,310		43,151		359,040		1,381	
Concentration[2]	0.495		0.140		0.949		0.671	

Note: The index is computed by the formula for Herfindahl index. Source: This research.

In terms of Asia, although none of the studied IC design MNEs is headquartered in Japan or South Korea, citations made to patents invented in these countries actually account for a large majority (80.94%) of all citations made to Asian patents. Israel and Singapore, which host several important R&D sites, are right behind Taiwan, where three of the IC design MNEs are headquartered (see Chapter 5). Among emerging economies, patents primarily from several Southeast Asian countries have also been cited, but patents invented in China and India are more often found in citation records of the 28 IC design MNEs. The higher proportion of cited patents in these two emerging economies likely results from their significant roles in the electronics and IT industries. Finally, beyond the triad regions, Australia, Brazil, New Zealand and South Africa also stand out as international sources of technological knowledge for the IC design industry.

Along the temporal dimension, some interesting variation is found particularly in Asia, as shown in Figures 6.2 and 6.3. Figure 6.2 provides a breakdown of the regional citation records along the filing year of cited patents. According to the figure, while the majority of citations are associated with North American patents for all years, citations made to Asian patents are more often associated with recent Asian inventions. On the other hand, citations made to European patents include some of those filed in France, Germany and the UK before the Second World War and in the mid-20th century. This may reflect the recent technological development in East Asia relative to the established expertise of European countries. Notably, since all citing patents are filed between 2001 and 2008, these figures *do not* provide any indication of the longitudinal trend of knowledge seeking and transfer but represent the age and time background of regional knowledge utilized by the 28 IC design MNEs in the inter-crises period.

Figure 6.2 Geographical distribution of citations between regions, 1970-2008

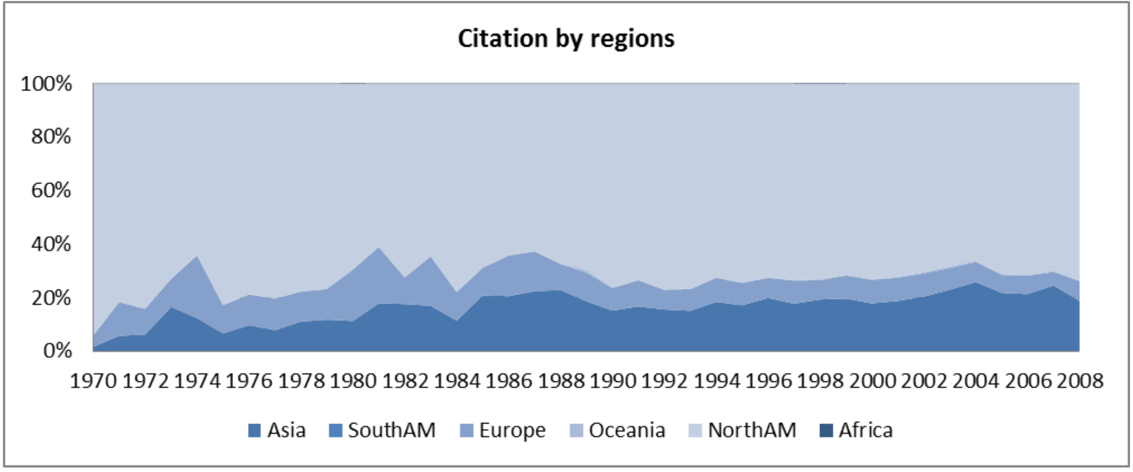


Figure 6.3 Geographical distribution of citations within Asia, 1970-2008

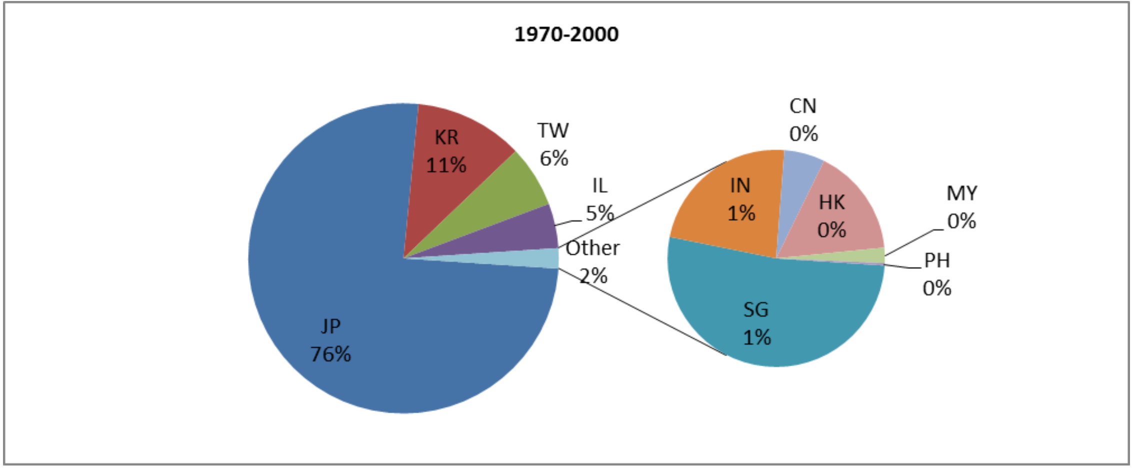
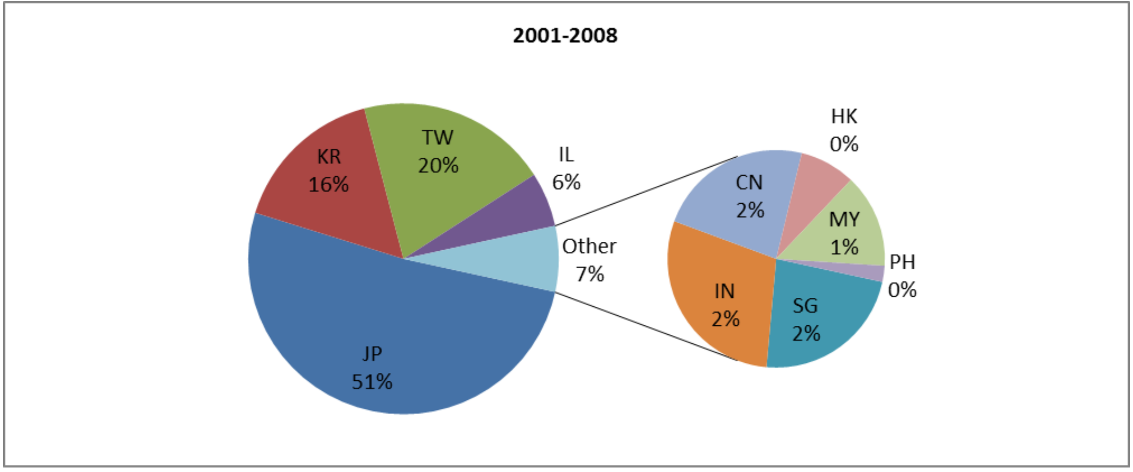


Figure 6.3 (Continued)



Note: These figures provide no indication of the longitudinal trend but relate to the time background of patents cited by the 28 IC design MNEs between 2001 and 2008. Source: This research. Source: This research.

Figure 6.3 splits the sample and shows the geographical composition of citations made to patents filed before and after 2001. Japanese inventions account for three-fourth of citations made to patents filed between 1970 and 2000, and Israel, Taiwan and South Korea together account for more than one-fifth. However, the composition of citations made to patents filed between 2001 and 2008, the same time period of the focal patents, is somewhat different in the sense that Taiwanese patents and emerging economy patents become more frequently cited. There can be several explanations for this observation. Firstly, even though none of these IC design MNEs are based in Japan, the repertoire of technological knowledge created by Japanese electronics, IT, semiconductor and other industries are still influential to the IC design industry. Secondly, that Japanese patents account for a substantial part of citations made to patents filed in earlier times may suggest delayed spillovers of these time-honored inventions to a relatively new industry. Thirdly, the composition of citations made to more recent patents suggests that a number of emerging economies, China, India and Malaysia in particular, have reshaped the technological landscape within Asia. Fourthly, the higher percentage of citations made to Taiwanese patents, despite the size of its economy, likely reflects the development of its domestic electronics, IT and semiconductor industries as well as localized flows of knowledge.

6.2.2 The changing role of location

The findings here largely reflect both the importance of knowledge-creating activities in MNE home countries, especially Taiwan and the US, the persistent technological edge of advanced economies and the tendency of knowledge flows to be locally bounded (Alcácer & Chung, 2007; Jaffe et al., 1993). However, these insights become less clear when several issues are considered. Firstly, while the knowledge-creating activities of the IC design industry appear to be less geographically bounded, their international knowledge seeking and transfer is subject to a multitude of factors, including at least the presence of related industries, the age of the technological knowledge sought as well as the home country. Secondly, another complication to the discussion of location comes from the recent popularity of the Internet and computer databases, which was not the case when most previous studies were conducted.

The readiness and accessibility of various online sources and patent databases, which also enabled this research, suggest that outside the close adjacency of corporate inventors, a significant portion of knowledge seeking may have occurred in virtual space.

Several IC designers consulted for this research claim that the design process usually begins with the search for existing solutions in patent and design module databases. This industrial practice may explain the high percentage of same-class citations in Table 6.1 and the effects of geographical and technological relevance on innovation diffusion. While the interpersonal exchange of ideas can be prevalent in close physical distances, beyond a certain range, other factors such as technological relevance, industry membership and organizational hierarchy may exceed geographical concentration as the determinant of knowledge flows (Cantwell & Piscitello, 2014; Owen-Smith & Powell, 2004; Tallman & Chacar, 2011).

Thirdly, it is critical to acknowledge that there is no single definition of location, and the specific choice of individual researchers can affect the insights and the implications of empirical findings. For instance, statistics at the country-state level, which further attribute cited patents to various states, provide a more refined indication of geographical relevance but reveal a much lower level of concentration than statistics computed at the country level (see Table 6.1). Besides the definition of location, the efforts to pinpoint the geographical source of technological knowledge can also be confounded by the mobility of inventors between adjacent geographical areas. The choice of a meaningful and fine-grained definition of location, therefore, becomes arbitrary. For instance, the Institute of Electrical and Electronics Engineers (IEEE), the world's largest association of technical professionals, including the users, participants and contributors to the semiconductor industry, divide the world into ten regions, six of which are in the US. Previous knowledge spillover studies have also adopted metropolitan statistical areas (MSA) rather than states and countries.

This research considers both the country and country-state level, but its empirical analysis mainly focuses on the country-state level. Although it may seem at odds with the concept of international business, the decision was made based on the understanding that a substantial part of knowledge sources and flows in the semiconductor industry is in the US. Table 6.1 reveals the stark difference between country- and country-state-level statistics (also see Table 6.4). Case studies in Chapter 5 also report the relocations of knowledge-creating subsidiaries between neighboring cities, which reflects the boundedness of business activities and knowledge flows within states. To consider larger countries, such as the US and China in other settings, as a whole and compare them with other smaller countries can result in blurred insights and over-simplistic conclusions.

6.3 Industrial dimension of knowledge seeking and transfer

Besides the geographical dimension of knowledge seeking and transfer, the assignee information in cited patents allows the identification of original patenting entities in various industry categories, providing another way to understand the knowledge sources utilized by IC design MNEs. The following analysis draws upon previous studies on localized knowledge flows, which analyze patenting records of firms in a specific industry to delineate the sources and direction of knowledge flows (e.g. Almeida, 1996; Almeida & Kogut, 1997).

Beyond an inherent perspective of industrial clusters and geographical proximity in these studies (Alcácer & Chung, 2007), these industrial relationships among customers, suppliers, competitors and non-competitors may also transcend locality when a particular ecosystem spans across geographical confinement and national borders. This suggestion reflects the development of global semiconductor industry in the late 20th century, including both the vertical disintegration and internationalization of the semiconductor supply chain and the emergence of a vast number of specialized subcontractors worldwide (Brown & Linden, 2009). On the other hand, this development also relates to the stronger tendency of IC design MNEs to collaborate with business customers. This section intends to analyze the assignee information reported in cited patents and provide empirical evidence for these observations.

6.3.1 Industry as a dynamic repertoire of technological knowledge

From a technical point of view, the industry as a constellation of firms and organizations worldwide creates a dynamic and non-exclusive repertoire of technological knowledge (Grant, 1996). This industrial repertoire of technological knowledge expands as complementary technologies are incorporated and recombined with core technologies by the members of this particular industry. Meanwhile, part of this industrial repertoire also evaporates, as existing technologies are rendered obsolete and nonessential by revolutionary industrial standards, disruptive innovations and new technological trajectories. Instead of adopting a predefined set of patent classes, considering the repertoire of technological knowledge by industry categories results in an evolving definition of technological fields following industrial changes and evolution. In fact, existing classifications of semiconductor technological fields and related patent classes are mainly based on semiconductor manufacturing activities, mostly related to IDMs and foundries, and their patenting records in the late 20th century, assuming a certain stability in the scope and interdependency of technologies (e.g. Ganco, 2013). The dynamic view of evolving technological fields is, therefore, more useful to understand the knowledge seeking and transfer of the IC design industry, which marks a significant departure from traditional semiconductor business models based on manufacturing technologies and internalized production.

The repertoire of technological knowledge created by IC design companies can also differ from those created by others in the overall semiconductor industry. The diverse and interchangeable business focus of IC design companies and customized product offerings can give rise to different knowledge search strategy (March, 1991), because any existing technologies can be appreciated and absorbed according to the demand of particular business customers. While IDMs and foundries pursue cutting-edge semiconductor technologies and basic science research, IC design companies tend to adopt a more application-specific and customer-orientated approach. Manufacturing process R&D, which is the focus of IDMs and foundries, is less relevant to IC design companies, which mainly rely on external service providers for manufacturing.

6.3.2 Identifying knowledge source industries

In order to pinpoint the knowledge source industries of the IC design industry, a manual identification procedure was devised to identify and categorize the assignees of cited patents into 39 different categories and sub-categories (see Table 6.7 in Appendix). The key steps and concerns are explained below. Firstly, these nearly half a million pairwise citations are found associated with 137,691 cited patents and more than twenty-five thousand assignee entries. While this research only considers inventive organizations instead of individuals, preliminary examination of these entries suggests that entities with too few patents cited are exceedingly difficult to trace and identify. This may imply either a marginal relevance to the IC design industry or limited presence as knowledge-creating organizations. Therefore, except for a number of advanced knowledge sources discussed later, a three-patent threshold was decided for inclusion, and fewer entries than three were discarded in the manual identification process.

Secondly, in most cases, assignees were identified by searching through several online news archives, including Google News Archive Search (http://news.google.com/archivesearch), The Free Library (http://www.thefreelibrary.com/) and technology news websites for more recent cases. Announcements of mergers and acquisitions and new product introductions, which usually contain brief descriptions of corporate history, operation status, product technologies, market focus, the address and contacts, were found particularly informative. Regarding confounding or missing information, additional sources were consulted, such as inventors and assignees' other patenting records, initial public offering (IPO) and startup records, annual reports of related companies, online personal biographies, company websites and company history reported in online archives. Moreover, the searching and unraveling of sector information of each inventive entity take into account the filing years of its cited patents—either the peak time of its knowledge-creating activity or the time period of knowledge creation most related to the IC design industry. This time information is critical to ensure the accuracy of sector information of assignees upon knowledge creation.

Thirdly, one category of knowledge sources known for their importance to the semiconductor industry is system companies—large and vertically integrated electronics and IT companies that integrate IC products into end products with system-level knowledge, such as HP, IBM, Philips, Siemens (Langlois & Steinmueller, 1999; Linden & Somaya, 2003). However, the definition of system companies varies in the empirical literature based on the semiconductor industry, including large electronics companies in Japan and Western Europe with internal IC design teams (Langlois & Steinmueller, 1999), vertically-integrated IDM companies (Dibiaggio & Nasiriyar, 2009), specialized IT companies (Langlois & Steinmueller, 1999; Linden & Somaya, 2003), and companies in industries that generally use IC products (Adams et al., 2013), among others. In particular, Adams et al. (2013) include six different categories by lines of businesses—industrial machinery, consumer electronics, computer equipment, telecommunications, automotive, instrumentation and aerospace and defense.

A general insight is that the exact definition of a system company may vary by the context and time background of specific research. For instance, any company which began with a specific business focus and specialized technology can become highly diversified and develop multiple technological fields after some time. Therefore, while building on these works, this research has adopted a refined categorization by identifying eleven sub-categories in the closely related IT industry, including one general *IT* category for large IT companies covering multiple sub-categories, which use IC products for different purposes and associate with the semiconductor industry in various ways. System companies in other non-adjacent industries are then categorized by main businesses and product markets. It is critical to acknowledge that this categorization is limited by both the knowledge of its author and the time background of this research in the early 21st century, although it intends to adopt the specific view of the global industrial landscape from the perspective of the IC design industry.

Fourthly, multi-business companies that cover multiple categories are categorized as *Diversified enterprises* to avoid arbitrariness and note their extensive involvement in diverse technological fields and product markets. This category also includes a number of assignee companies that had changed their business focus and were involved in different categories, such as Kyocera, LG, Tyco, mostly companies with a relatively long history. On the other hand, while the searching and unraveling of sector information have taken into account the filing year of cited patents, it was found that some long-standing companies would have crossed or switched between several categories while remaining as important knowledge sources for decades. These companies are also categorized as *Diversified enterprises*, even though they may have a clearly-defined business focus and technological expertise in specific time periods.

Fifthly, it was found that inventive entities in a number of industry categories, commonly considered as advanced knowledge sources, often have fewer patents cited and appear to be under-represented by the cited patent entries. These entities include governmental organizations, government-sponsored research institutes, universities, aerospace and defense companies and private laboratories (see Table 6.7 in Appendix). That their patents appear less frequently in the citation records might be due to the wider prospects of their individual inventions (Mazzoleni & Nelson, 1998). Given the potential impact and the different nature of their inventions, a decision was made to improve the coverage of these knowledge sources by allowing an exception to the previously mentioned three-patent threshold. The additional searches were based on keywords in assignee names, such as avionic, administration, institute, university, and laboratory among others (see Table 6.8 in Appendix).

Lastly and most importantly, based on the analysis of the semiconductor industry in Chapters 4 and 5, eight different sub-categories were devised for inventive entities in the overall semiconductor industry, including (1) *IC*: IDM and other IC design companies which develop and supply IC products to other industries, (2) *EDA*: companies which develop automated design software tools, (3) equipment suppliers which build various physical equipment and devices for semiconductor manufacturing, (4) professional foundry companies which provide manufacturing services, (5) IP core vendors which develop and license design modules to other companies, (6) MEMS developers which develop miniature micro-electro-mechanical systems based on semiconductor technologies, (7) packaging and testing companies which verify and finalize the manufacturing of IC products, and (8) the 28 top IC design MNEs in the sample.

6.3.3 Composition of knowledge source industries

The manual identification procedure attributed 124,837 (90.67%) cited patents to various inventive entities, including governmental organizations and related entities in 26 countries, universities and related entities in 27 countries and 2,265 private organizations in different countries. Location-bounded and controlled by governments, public organizations are considered as country-level entities and counted by the number of countries. These cited patents cover 278 3-digit USPCs and correspond to 456,561 (91.89%) citation records. Several conglomerates and business groups had additional affiliates separately categorized, based on available information. A small percentage of cited patents were not attributed to any specific source due to assignation to an individual inventor, the three-patent threshold and insufficient information. Moreover, with limited information about the ownership structure of private inventive organizations, the identification procedure did not consider recent mergers and acquisitions and partial ownership by other companies. This limitation should have minimal impact on the validity of categorization since the level of analysis here is industry and the industrial background of these inventive entities matters more than their ownership.

Figure 6.4 Industry categories of cited assignees

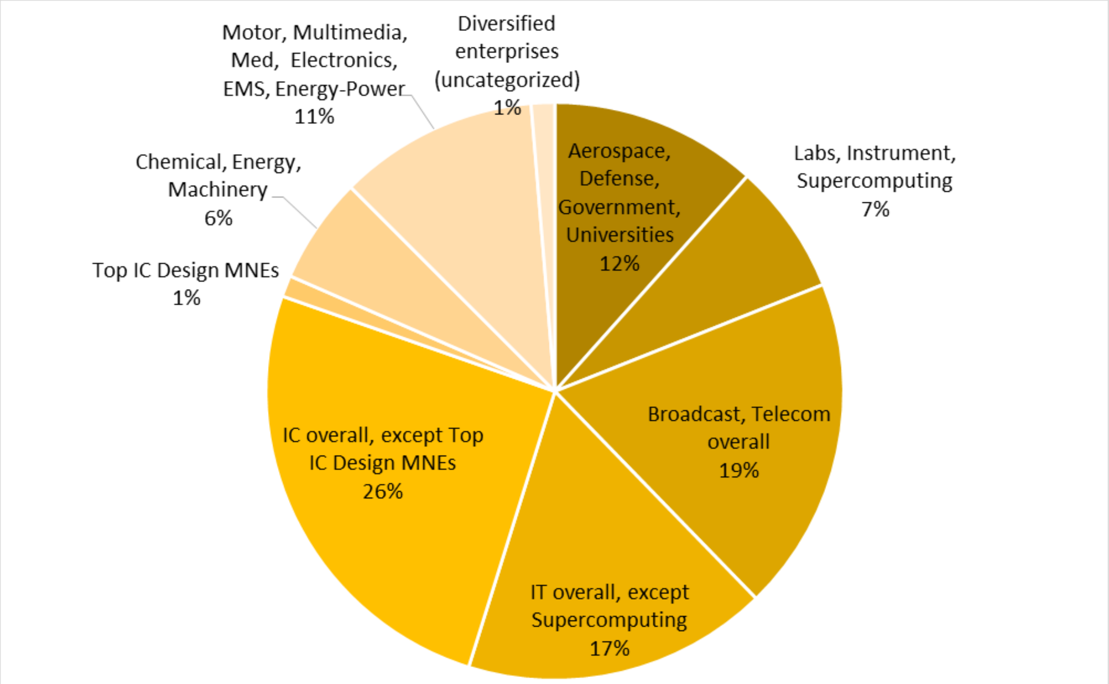
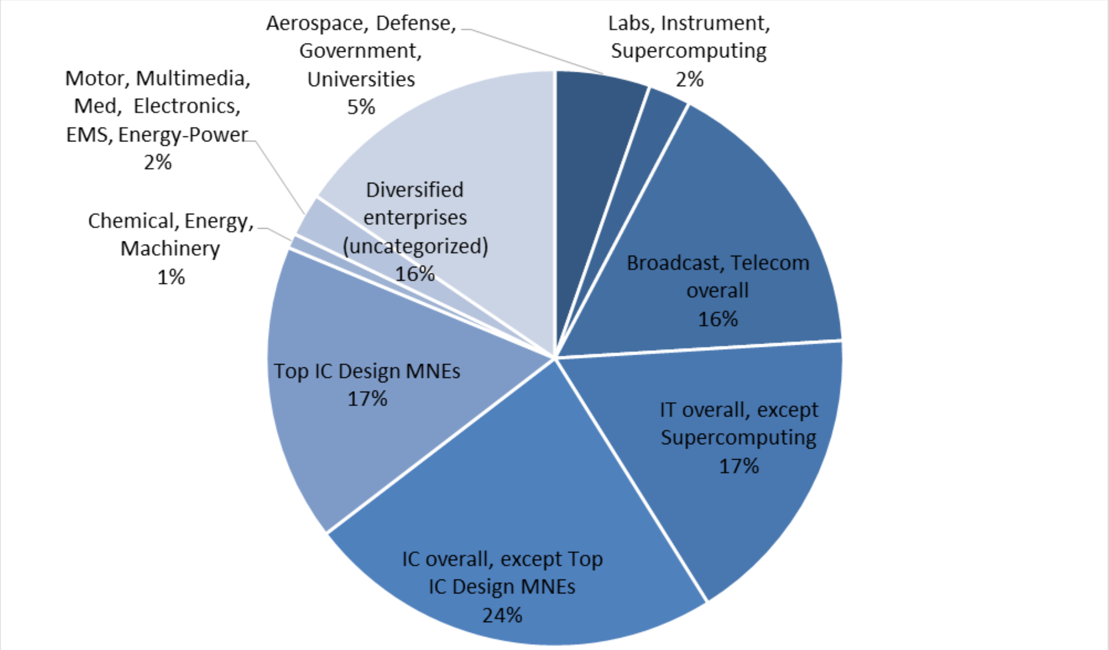


Figure 6.5 Industry categories of citation records



Source: This research.

Figure 6.4 summarized the composition of assignees in 39 industry categories, which are further aggregated by general properties, and Figure 6.5 then shows the composition of patent citations. One salient observation that immediately stands out is the small group of *Diversified enterprises* accounts for a significant portion of citation records, which reflects the larger scale and wider business and technological scopes of most companies in this category.

A less surprising discrepancy is found in *Top IC Design MNEs*, which is a direct observation of the intensity of knowledge flows resulting from the 28 IC design MNEs seeking and transferring knowledge between and within themselves. Meanwhile, despite their scale, assignees in *Chemical, Energy*, and *Machinery* categories are only associated with a small portion of citations. Notwithstanding the size of companies in these industries, their business focuses and knowledge repertoire are less relevant to the IC design industry, when compared with other industry categories, such as *Broadcast, Telecom,* and various sub-categories of *IT* and *IC*. In brief, the utilization of a specific group of knowledge sources seems related to the size and relevance of its knowledge repertoire as well as inter- and intra-organization relationships.

Discrepancies in the opposite direction are found among governmental organizations and related inventive entities, a group of specialized laboratories, and developers and suppliers of science instruments and supercomputing. Knowledge inflows from these sources seem to be less intensive given a lower average citation per assignee (see Table 6.2). The magnitude of discrepancy would be even larger if the assignees in the public sectors, at least three hundred of them, were counted separately. These discrepancies may be due to the wider technological scope of inventive entities in these categories, which implies that their knowledge repertoire may be more diverse, and only part of it relates to the IC design industry. However, companies in the categories of *Medical, Motor, Multimedia devices, Electronics, EMS and Power management*, which generally use IC products, are also associated with a disproportionately small share of citations. The alternative explanation is that the patenting behavior and patent intensity of various categories also differs. Statically, the average numbers of citations per cited patent are within one standard deviation of the general mean, except for the small and nascent sub-category of *IC-MEMS* (see Table 6.3).

This visible discrepancy between the number of assignee entities, the number of cited patents and citation counts has a critical implication—it implies that the choice of any single empirical indicator for the importance of specific knowledge sources can be arbitrary in the absence of caution and justification. Although the presence of backward citations to a specific knowledge source industry implies its relevance to the knowledge-seeking organization, the connections between firms and industries are much less straightforward than assumed in previous studies. Moreover, patent class information reveals that every industry category could have somewhat overlapping technological fields, which were cited by IC design MNEs (see Table 6.9 in Appendix). Therefore, industry categories, whether mainly the supplier or customers of semiconductor technologies, can become knowledge sources of IC design companies because of their commonality in technological expertise. In other words, companies in other industry categories can be supplying or using technologies of IC design companies at the same time. Also, between different industries, technological fields can be overlapping, which invalidates patent class information as an effective way to separate the technological scope of different industries. Hence, underneath the industrial landscape, intertwined networks of technological relevance would form a technological landscape with very different outlook.

Table 6.3 Industry categories and average number of citations received

Industry categories[1]	**Cited patents**	**Citations**	**Avg. citations per assignee**	**Avg. citations per patent**	**Patent filing year (mode)**
Aerospace	2,646	8,840	60.136	3.341	1999
Broadcast	669	2,092	27.893	3.127	2000
Chemical	408	1,426	32.409	3.495	2001
Diversified enterprises	23,172	70,712	2281.032	3.052	1999
Defense	997	3,527	52.642	3.538	1997
Electronics	1,588	5,278	61.372	3.324	2000
EMS	157	262	32.750	1.669	2001
Energy: Electrical	159	648	34.105	4.075	1997
Energy: Fossil fuel	151	392	26.133	2.596	1995
Energy: Management	76	194	11.412	2.553	2002
Government	1,450	5,390	207.308	3.717	1998
IC[2]	23,330	93,027	210.946	3.987	2000
IC: EDA	673	2,122	60.629	3.153	2001
IC: Equipment	1,080	2,608	50.154	2.415	2000

IC: Foundry	934	2,025		289.286	2.168	1999
IC: IP	544	2,296		82.000	4.221	2002
IC: MEMS	193	3,245		249.615	16.813	2005
IC: PAT	619	1,812		72.480	2.927	2001
IC: Top design[3]	14,157	76,188		2721.000	5.382	2002
Instrument	723	2,056		31.631	2.844	2001
IT[4]	13,990	41,624		2973.143	2.975	1997
IT: Data	544	1,353		41.000	2.487	2000
IT: Devices	1,042	3,625		60.417	3.479	1995
IT: GPS	310	1,297		99.769	4.184	1997
IT: Graphics	3,414	13,242		232.316	3.879	1998
IT: IP	253	671		27.958	2.652	1995
IT: RFID	29	82		11.714	2.828	1999
IT: Service	1,120	4,353		59.630	3.887	1996
IT: Software	2,162	6,193		76.457	2.864	2000
IT: Storage	1,212	5,595		139.875	4.616	1999
IT: Supercomputing	1,970	6,197		344.278	3.146	1997
Laboratories	730	2,558		28.422	3.504	1997
Machinery	541	1,306		21.065	2.414	1997
Medical	289	829		19.738	2.869	2001
Motor	783	1,880		43.721	2.401	1999
Multimedia devices	1,069	2,599		38.791	2.431	2000
Telecom	3,549	12,048		223.111	3.395	1997
Telecom: Equipment	16,481	60,333		193.375	3.661	1999
Universities	1,623	6,636		245.778	4.089	2000
Total	**124,837**	**456,561**	**Average**	**194.613**	**3.657**	

Note: 1. See Table 6.1 in the appendix for the definition of each industry category. 2. IC categories include both IDM and IC design companies that directly supply IC products to other industries. 3. The Top IC design category includes 48,982 (64.29%) intra-firm citations made to 9,729 (68.72%) same company patents. 4. IT categories include large IT companies mostly, which may encompass some of the business activities of relatively specialized IT companies in the sub-categories. Source: This research.

6.3.4 Comparing between industry categories

Historically, many of the large, diversified and vertically integrated companies in the *IT* and *Diversified enterprises* categories were the pioneers in developing and manufacturing various types of semiconductor devices. Their scale and scope allowed them to finance ventures into the business and commercialized semiconductor technologies decades before the emergence of professional foundry companies. Even within the modern day highly specialized semiconductor industry, many of these system companies still retain internal IC design capability, while cooperating with external IC design and foundry companies. Their capability to conduct IC design activities internally and to co-design with specialized IC companies is a source of competitive advantages in end product markets, because developing and incorporating highly customized IC products is the essential approach to end product differentiation.

On the other hand, the aerospace and defense industries and various government related organizations also played a major role in the early development of the semiconductor industry. They are often the sources of cutting-edge technologies, and the aerospace and defense industries, in particular, created the initial demand for semiconductor devices. For instance, while seeking and absorbing knowledge created in this sector, many IC design MNEs in the sample have also supplied mission-critical IC products for the aerospace and defense industries (see Table 5.1). Although the shares of sales revenue contributed by this specific sector tend to be small, it is likely that technological knowledge created and patented by the aerospace and defense industries have assisted the development of IC products for civil use, which then contribute to the majority of product sales. This observation does not necessarily concern the case of dual-use technology (Molas-Gallart, 1997), since many modern applications of IC products, such as the Internet and GPS, emerged only recently. It is also possible that corporate inventors in IC design companies recovered some decades-old technologies and indirectly revived their commercial value for novel applications and business opportunities, which implies that the age of a specific piece of technology can sometimes be less indicative of its value.

Laboratories, which include private R&D labs and industry consortiums, are another widely mentioned source of technological knowledge. One observation, which emerged during the manual identification process, is the qualitative difference in these entities across countries. Private laboratories specialized in a range of science and technological fields, and contract

R&D service providers are more common in Western countries. On the other hand, industry consortiums consisting of competing firms and sometimes universities are popular in Japan. Using the average number of citations per patent as an indicator of technological prominence (see Table 6.3), the *Laboratories* category is comparable to advanced knowledge sources and is higher than other application-oriented categories—*Chemical, Energy: Fossil fuel* and *Management, EMS, Machinery, Medical, Motor* and *Multimedia devices*—which generally use IC products but only indirectly relate to the industry (see Table 6.9 in Appendix).

In terms of more related industry categories, companies in the *IT* and *IC* categories and sub-categories are indeed more frequently cited, and likewise for *Telecom* and *Telecom: Equipment*. In particular, the sub-categories of *IT: GPS, Graphics, Service* and *Storage*, which are closely related to various modern applications of IC products, are frequently found with IC design MNEs in the sample. Conversely, within the semiconductor industry, companies in the sub-categories of *IC: Equipment, Foundry* and *PAT*, which generally relate to semiconductor manufacturing, are less cited. While no direct conclusion should be based on these descriptive statistics, which can be confounded by other factors, both technological and business relevance seem to increase the likelihood of specific industry categories as the knowledge sources of the IC design industry.

Lastly, statistics in the *IC: Top design* category are indicative of intra-firm and intra-industry knowledge seeking and transfer, revealing the traces of knowledge flows from intra-firm units as well as competing IC design MNEs. These citation records are incorporated in the subsequent analysis of the temporal dimension of knowledge seeking and transfer, and further investigation and discussion on intra-firm knowledge flows are covered in Chapter 7.

6.3.5 Limitations of manual categorization process

Besides limited ownership information, the manual categorization procedure is subject to a number of data limitations. Assignee names of foreign assignees, universities and prolific patenting entities often contain multiple and sometimes foreign spellings. The problem was to some extent addressed by additional search and identification with firm-specific keywords and foreign spellings (see Table 6.2 in Appendix). Also, information was found to be more available for recent assignees, particularly those remaining operative after the 1990s. Citations made to patents filed before the 1990s account for a minor portion of the entire sample (see Figure 6.1). Lastly, several private research laboratories were found hardly distinguishable from non-practicing entities (NPE), which were not directly engaged in creating or applying technological knowledge but mainly in acquiring and licensing patents and asserting legal rights (see Feldman & Lemley, 2015). Several NPEs claimed as their roles the promotion of licensing and commercialization of academic research. In a limited number of such cases, the identification and categorization could be arbitrary with limited information.

In previous patent studies, researchers have compiled the assignee information by matching and linking companies in the NBER patent database to financial databases, such as Compustat among others. This database matching approach effectively and consistently identifies patent assignees and industry categories based on Standard Industrial Classification (SIC) code. For a number of reasons, however, the database matching approach is not applicable to this research and therefore information had to be collected firsthand.

Firstly, the list of assignees retrieved from these 137,691 cited utility patents contains a large number of short-lived start-ups, private companies and companies headquartered outside North America and Western Europe. Database entries about these companies are often missing or inaccurate. Secondly, many assignees in several categories, such as *IT* and sub-categories and *Multimedia devices*, were found constantly changing business focuses, especially during the startup and restructuring phase. This raises the concern that SIC codes may be less meaningful as an indicator for these emerging and fast-changing industries. Thirdly, many of the public research institutes, governmental organizations, universities, laboratories and research consortiums, which prove to be valuable knowledge sources of the IC design industry, are minimally covered in financial and other commercially-available databases. Lastly and most importantly, as the discussion in Chapter 5 points out, SIC codes do not distinguish between semiconductor companies with different business models and business focuses. These companies are manually categorized by their roles in the semiconductor business ecosystem surrounding the IC design companies.

6.4 Temporal dimension of knowledge seeking and transfer

The subsequent analysis considers the time dimension of the knowledge flows from external and internal knowledge sources. The concept of time efficiency is closely related to the intensity of knowledge flow. With other factors controlled at the same level, intensive flows of knowledge should also occur sooner between the source and recipient. Conversely, less intensive knowledge flows should be sporadic and sluggish. This analysis is conducted at the level of citations, which avoids the heterogeneity issue of citation counts (see 6.3.4 for a discussion).

The consideration of knowledge transfer time—the timespan between knowledge creation by the source and absorption of this specific piece of knowledge by the recipient—is rather explicit in management and strategy literature. Intra-firm knowledge transfer literature suggests that knowledge transfer is often laborious, time-consuming and fraught with difficulty, and delays can be costly as well as unsatisfactory (Pedersen, Petersen, & Sharma, 2003; Zander & Kogut, 1995). Managerial efforts and engineering activities that expedite knowledge transfer within the MNE are costly and often involve complicated control mechanisms (Björkman et al., 2004; Teece, 1977). Time efficiency of knowledge flow and innovation diffusion is also a key element in studying the impact of geographical concentration and social networks on the occurrence and intensity of knowledge flows (e.g. Almeida & Kogut, 1999; Owen-Smith & Powell, 2004). Burt (1992, 1997) suggests that the information benefits of social networks include access and early timing, which assist individuals in acting on information. Powell et al. (1996) explain that a network as a locus of information provides timely access to knowledge and resources. However, in contrast with abundant studies on the impact of knowledge management and social networks on knowledge flows, there is a curious paucity of empirical investigation into the temporal dimension of knowledge flows.

However, an explicit consideration of the temporal dimension is found in patent data studies by the presumption of knowledge depreciation, that patented inventions generally lose value over time and thus knowledge-based assets should depreciate annually along with other physical assets (Frost & Zhou, 2005; Phene & Almeida, 2008). Although this presumption is commonly adopted in approximating the present value of corporate patent stocks, it is actually at odds with examples in the history of science suggesting that the value of inventions often remain unknown until years later (see Walters, 2005). Also, it is highly unlikely that the process of innovation diffusion is identical for every piece of knowledge and all its potential applications. The diffusion of patented inventions would start from the moment of publication and only at certain point get picked up by inventors seeking inspiration from various sources and through various channels. In that sense, the citations made to a specific piece of patented invention become a chronicle of inspired knowledge creation and recreation in different time-space, revealing as well as reviving the value of the earlier invention.

6.4.1 Observed temporal patterns

Citation lag, the time difference in the application or publication of cited and citing patents, provides a numerical indicator of the time length between the creation of a piece of technological knowledge and its subsequent transfer and diffusion. As shown in Table 6.4, different temporal patterns are observed among citations, which IC design MNEs made to inventions of different geographical, industrial and technological backgrounds. Among citations made to local inventions originating from same country-state location, the average year gaps are 4.296 since the publication of cited patents and 6.951 since filing. Meanwhile, citations made to inventions originated from the MNE home country-state where the MNE is headquartered show average year gaps of 4.418 and 7.085, which are shorter than the average year gaps of 5.660 and 8.320 among citations made to inventions from MNE home countries. The decision to use country or country-state as the level of analysis—considering the US as a single geographical unit or further attributing US inventions to individual American states—results in a substantial discrepancy in empirical observations. The discrepancy between the country-state-level and country-level statistics suggests that the former is likely the most suitable level of analysis for geographical concentration.

Table 6.4 Observed year gaps between the filing of cited and citing patents

Relevance between the patent pairs	**Publication to Filing (P-F)**$^{1, 2}$	**Filing to Filing (F-F)**^{2}
Geographical relevance		
Local: Same country origin	5.675	8.325
Local: Same country-state origin	4.296	6.951
Home: Home country origin	5.660	8.320
Home: Home country-state origin	4.418	7.085
Technological and industrial relevance		
Technological: Intra-firm citation	2.845	5.572
Technological: Same patent class	4.917	7.610
Industrial: Semiconductor industry[3]	4.795	7.317
Industrial: Top IC design[4]	3.053	5.779
Overall average	5.588	8.261

Note: 1. The average year gap between the publication year of cited patent and the filing year of citing patent. 2. The average year gap between the filing years of cited patent and citing patent. Correlation between data series of two measurements is close to unity. 3. Unlike Table 6.1, the statistics here exclude both *Top IC design* and intra-firm citations, which tend to have shorter year gaps. 4. Intra-firm citations are excluded. 5. All categories are significant at 99% level with unequal. variances. Source: This research.

Among the sizable shares of semiconductor industry citations and same class citations (see Table 6.1), average year gaps of 4.795 and 7.317 are observed among citations made to other semiconductor companies and 4.917 and 7.610 among citations to same class patents (see notes of Table 6.4). However, the shortest average year gaps of 2.845 and 5.572 are found among intra-firm citations, and 3.053 and 5.779 among intra-industry citations. Hall et al. (2001) have similar findings of shorter filing year gaps among self-citations—citations made to same assignee's previous inventions—relative to citations made to unrelated assignees. They attribute this finding to the relative time efficiency of intra-firm and intra-industry knowledge transfer. While descriptive statistics from the citation records of top IC design MNEs also indicate such intra-firm and intra-industry time efficiency, the smallest year gaps are found among intra-firm citations, which may suggest the relative efficiency of MNE intra-firm knowledge transfer (Kogut & Zander, 1993; Pearce, 1999a) given the industrial and technological background of a specific piece of patented knowledge.

6.4.2 Highly heterogeneous knowledge flows and the MNE

The time differences shown in Table 6.4 are largely in line with what one would have expected in classical innovation diffusion studies, which consider the spatial or sociological factors of diffusion and assume that information takes different lengths of time reaching potential users with different connectedness and varying degrees of networks centrality (Attewell, 1992; Powell et al., 1996). However, Table 6.5 greatly complicates this picture with the varying year gaps observed in different industry categories. For instance, shorter year gaps are observed among citations in the *IC* category and sub-categories, and yet the year gaps vary widely across different sub-categories of *IT*, an industry closely related to IC design MNEs. In addition, between the service provider and customer, the *EMS* category shows shorter year gaps than the *Electronics* category it serves, and likewise for the *Telecom* and *Telecom*: *Equipment* categories. Moreover, the larger year gaps observed among citations made to several advanced knowledge source categories, including *Aerospace, Instrument, Government* and *Universities*, are likely due to the nature of their inventions at the forefront of science. Longer year gaps are also observed in industry categories less related to *IC design*, such as *Chemical*, *Energy: Electrical* and *Fossil fuel* and *Machinery*. However, relevance measured by patent class concurrency and correlation failed to explain the long year gap in *Diversified enterprises* and the opposite in *EMS* (see Table 6.9 in Appendix). Although the validity of these measures is subject to further discussion, these statistics indeed suggest that the process of knowledge diffusion is multidimensional and relates to a multitude of factors.

Table 6.5 Year gaps by industry categories

	Overall sample		Technological: same patent class		Geographical: same country		Geographical: same country-state	
Industry categories	**Year gaps**		**Year gaps**		**Year gaps**		**Year gaps**	
	P-F^{1,2}	F-F^{2}	P-F^{1,2}	F-F^{2}	P-F^{1,2}	F-F^{2}	P-F^{1,2}	F-F^{2}
1. Aerospace	9.308	11.803	8.694	11.284	9.184	11.666	9.235	11.535
2. Broadcast	5.474	8.646	5.356	8.344	5.391	8.551	4.306	7.619
3. Chemical	9.178	11.573	6.937	9.286	9.975	12.272	7.296	9.493
4. Defense	6.455	9.081	5.722	8.317	7.905	10.503	3.843	6.396
5. Diversified enterprises	11.454	14.060	11.300	14.000	10.950	13.599	8.202	10.563
6. Electronics	6.293	8.817	5.674	8.125	9.786	12.342	13.297	15.840
7. EMS	1.821	3.996	2.303	4.262	2.382	4.455	1.909	3.879
8. Energy: Electrical	12.722	15.201	12.768	15.182	13.754	16.197	8.964	11.143
9. Energy: Fossil fuel	14.263	16.566	14.533	16.860	15.305	17.387	11.540	13.414
10. Energy: Management	4.423	6.598	3.525	5.932	4.521	6.764	1.200	3.560
11. Government	9.788	12.200	9.395	11.860	12.659	14.965	17.431	19.948
12. IC	5.067	7.583	4.567	7.070	5.475	7.962	4.669	7.162
13. IC: EDA	2.954	5.711	2.455	5.255	3.137	5.886	2.880	5.686
14. IC: Equipment	4.903	7.376	4.598	7.116	4.722	7.203	4.174	6.836
15. IC: Foundry	3.450	5.314	3.251	5.073	3.023	5.264	2.776	5.034
16. IC: IP	2.725	5.514	3.166	5.550	2.627	5.292	2.967	5.571
17. IC: MEMS	1.354	4.317	1.458	4.108	1.196	4.182	0.767	3.757
18. IC: PAT	3.098	5.323	2.514	4.788	3.965	6.152	3.681	5.783
19. IC: Top design^{3}	3.053	5.779	2.772	5.535	3.169	5.858	3.351	5.930
20. Instrument	9.313	11.685	9.650	11.988	9.797	12.203	4.849	7.576
21. IT	6.622	9.212	6.042	8.662	6.685	9.282	6.686	9.229
22. IT: Data	4.545	7.422	4.668	7.538	4.547	7.382	5.914	8.599
23. IT: Devices	6.932	9.621	6.161	9.030	7.244	9.899	6.191	8.891
24. IT: GPS	5.950	8.259	6.244	8.578	5.965	8.295	5.948	8.274
25. IT: Graphics	5.163	7.849	4.685	7.370	5.519	8.247	4.458	6.962
26. IT: IP	4.271	7.425	4.042	7.054	2.550	5.562	2.196	5.587
27. IT: RFID	3.317	5.329	2.974	4.711	3.549	5.493	3.944	5.361
28. IT: Service	6.782	9.609	5.565	8.507	6.828	9.619	7.003	9.801
29. IT: Software	3.596	6.952	4.565	7.823	3.893	7.232	3.407	6.524
30. IT: Storage	5.274	7.702	4.696	7.204	5.398	7.837	5.670	7.973
31. IT: Supercomputing	5.327	8.084	4.957	7.713	5.361	8.085	4.837	7.455
32. Laboratories	6.539	9.306	6.328	9.082	7.925	10.537	6.403	9.147
33. Machinery	11.065	13.484	10.453	12.894	10.041	12.572	11.574	13.607
34. Medical	8.440	10.825	8.513	10.894	7.845	10.141	5.402	7.275
35. Motor	8.040	10.299	7.826	10.218	9.065	11.347	1.471	5.176
36. Multimedia devices	6.450	9.318	5.863	8.800	5.391	8.660	3.803	7.105
37. Telecom	8.782	11.542	7.801	10.693	9.266	11.909	6.336	9.315
38. Telecom: Equipment	4.594	7.577	4.204	7.294	4.895	7.757	3.336	6.519
39. Universities	6.983	9.615	6.906	9.570	7.351	9.908	8.050	10.461
Sample average	**5.588**	**8.261**	**4.917**	**7.610**	**5.675**	**8.325**	**4.296**	**6.951**

Note: 1. The average year gap between the publication year of cited patent and the filing year of citing patent. 2. The average year gap between the filing years of cited patent and citing patent. Correlation between data series of two measurements is close to unity. 3. Unlike Table 6.3, the statistics here exclude intra-firm citations. Source: This research.

Besides the year gaps observed in the overall sample, the impact of geographical conglomeration also varies by industry, as shown in the third and fourth column of Table 6.5. Citation year gaps observed in *Defense*, *Diversified enterprises*, sub-categories of *Energy*, *IC: MEMS, Instrument*, *Motor*, *Medical, and Multimedia devices* are notably shorter given the same country-state, but the year gaps in *Government*, *IT: RFID* and *Universities* are the exact opposite. Neither do the statistics of same class citations, listed in the second column of Table 6.5, show consistently shorter year gaps in every industry category. The classical model of innovation diffusion and the knowledge depreciation presumption are simply not capable of explaining this great diversity in citation lags. In addition to geographical, industrial and technological factors, the communication channels, management and social interactions within the MNE also moderate international knowledge flows (Carlile, 2004; Noorderhaven & Harzing, 2009). While coordinating business activities internationally, the MNE may seek and transfer knowledge across national borders, essentially connecting geographically bounded knowledge flows to its internal international knowledge flows.

Citation records, which trace international and inter-industry, inter- and intra-firm knowledge flows, may reveal the variation in temporal patterns. However, it is notable that patent filing only happens after both knowledge seeking and transfer and time-consuming R&D—the processes that create the specific piece of knowledge. While the question remains why corporate inventors draw upon specific patents from certain time periods and knowledge sources of various geographical, industrial and technological relevance or remoteness, the application of citing patents has implications beyond the confirmed diffusion of cited patents. Firstly, citation is an explicit recognition of the contribution of cited pieces to the inspired invention, while diffusion may only describe the awareness of it. Secondly, regardless of the age, background and context of cited pieces, the application of an inspired invention is direct evidence of the value of cited pieces, which justifies the expenditures for R&D, IP management and potential licensing payment. Thirdly, generation of an inspired invention represents not only learning, but also re-creating the cited pieces of knowledge (Attewell, 1992). In that sense, the cited pieces are not only recognized and assimilated but also applied and recombined (Cohen & Levinthal, 1990).

6.5 Econometric analysis of time difference

To further analyze the temporal patterns of knowledge flows, an econometric analysis is conducted to empirically investigate how geographical relevance, industry, technological relevance and MNE organization affect the time difference between citing and cited patents. A series of dummy explanatory variables, *Local country-state, Citing home country-state, Intra-firm citation, Same 3-digit USPC,* are included for coefficient estimation, indicating the properties of each citation in various dimensions. Meanwhile, *knowledge transfer time*—the dependent variable measured by the year gaps between the publication of a cited patent and the application of a citing patent—presents some empirical issues that need to be addressed in the model specification and estimation strategy. Because the year gaps are essentially pairwise observations, clustering at each node—both citing and cited patents— they should be considered in the estimation of multi-way cluster-robust standard errors (Cameron, Gelbach, & Miller, 2011).

6.5.1 Model specification and estimation

All citing patent are filed between 2001 and 2008 and assigned to one of the 28 IC design MNEs. Because of shared experience, common ownership and coordinated management of knowledge-creating activities, as well as other common influences of the organization, a batch of patents invented, filed and assigned to a specific organization are likely to share some common features. Similarly, other common features can be inferred from the geographical, industrial and technological dimensions. These group-level common shocks should be controlled by the inclusion of specific fixed-effects; in this case, random-effects are less appropriate due to the likely violation of the strict exogeneity assumption that explanatory variables are independent of all random components and that all random components are mutually independent (Verbeek, 2005).

Firstly, *citing firm fixed-effects* are included in the model for each IC design MNE, which has sought and created knowledge and accounted for part of the citing patents. Detailed case studies in Chapter 5 suggest that each of the 28 IC design MNEs has reached different degrees of R&D internationalization and different coverage of product lines, geography and customer bases, which may result in specific temporal patterns of knowledge flows. The inclusion of firm dummies estimates such firm-specific effects and reduces omitted variable bias which renders OLS estimates biased and inconsistent (Baltagi, 2005).

Secondly, *cited industry fixed-effects* of the 39 industry categories are included—since each cited assignee is associated with a knowledge source industry, incorporating cited industry dummies avoids thousands of dummies for cited organizations. Given the finite size of the analytical sample, adding a large number of dummy variables causes multicollinearity problems and considerable loss of degrees of freedom (Baltagi, 2005). However, because the filing of cited patents spreads across several decades, the model also includes the *median age* of each cited assignee's batch of patents at the time when the citing patent is filed. The variable controls for the active time period of each organization and the median is chosen over the mean as it better indicates the peak filing time of the specific assignee's cited batch.

Thirdly, additional fixed effects are included to account for the heterogeneity in citing patents, including *3-digit USPC*, *Filing yea*r and *Country origin*. Inventions in a specific technological field, as indicated by the patent class, may involve particular patterns of knowledge seeking and transfer as well as knowledge creation, which differ from those in other fields and result in unique time frames. In terms of the country origin and patent classes, although it seems intuitive to incorporate fixed-effects at a more refined level, such as country-state and 6-digit patent class, Cameron, Gelbach and Miller (2011) recommend the most aggregated level of the nested clusters. Moreover, specification tests reveal strong multicollinearity associated with the dummies for California and Texas, where some IC design MNEs were headquartered. In addition, *SUB patent*, also a dummy variable, is included to indicate whether the citing patent is derived from subsidiary knowledge-creating activities, according to the residence information of first inventor at the country-state level.

Finally, while these fixed-effects are including to model the multi-way clustering in the dependent variable—observed year gaps, the clustering in explanatory variables, also requires attention, which otherwise leads to severely underestimated standard errors and problematic statistic inferences (Cameron et al., 2011). In this case, the clustering and serial correlation in the explanatory variable follows specifically from the use of least-squares dummy-variables (LSDV) estimator (Kézdi, 2004). The LSDV specification in this analysis models the clustering in four dimensions—geography, technology, industry and organization, and the computation of multi-way cluster-robust standard errors generates essentially much larger estimates and allows more conservative t-tests.

Test results of the year gaps in 456,358 pairwise citations are shown in Table 6.6, after excluding citations made to patents assigned to unidentified assignees or filed before the emergence of the semiconductor industry in the 1960s (see Figures 6.6 in Appendix for the scatter plot of potential outliers). Specified in parentheses are multi-way cluster-robust standard errors adjusted by citing firms, cited industry categories, country-origin and 3-digit USPC of citing patents. Four-way cluster-robust standard errors were estimated for Models 1-3 and Model 5, which further excludes cited patents filed before the 1990s (see Figure 6.8 in Appendix). Model 4 incorporated a fifth cluster—filing year of citing patents. Robustness tests are included in Table 6.10 in Appendix, which provides the coefficient estimates of different model specifications. In brief, results remain largely the same when the filing year gap is the dependent variable and when intra-firm citations are excluded. A five-way random-effects model has the same effect directions but deviates substantially from LSDV estimates.

Table 6.6 LSDV regressions on observed filing year gaps between the citing and cited patents

	Model 1	Model 2	Model 3	Model 4	Model 5
Geographical relevance					
Local country-state		-0.7 (0.336)**	-0.655 (0.266)**	-0.655 (0.252)***	-0.485 (0.237)**
Citing home country-state		0.552 (0.476)	0.378 (0.403)	0.378 (0.383)	0.386 (0.332)
Technological relevance					
Intra-firm citation		1.006 (0.43)**	1.152 (0.473)**	1.152 (0.491)**	0.522 (0.416)
Same 3-digit USPC		-0.818 (0.11)***	-0.816 (0.107)***	-0.816 (0.109)***	-0.582 (0.082)***
Organizational factors					
SUB cites HQ			0.63 (0.579)	0.63 (0.576)	0.648 (0.495)
HQ cites SUB			-2.203 (0.514)***	-2.203 (0.5)***	-1.579 (0.452)***
SUB cites other SUB			-2.145 (0.433)***	-2.145 (0.409)***	-1.644 (0.388)***
Citing firm fixed-effects			28 (baseline: Qualcomm)		
ARM	-0.414 (0.589)	-0.146 (0.499)	-0.13 (0.491)	-0.13 (0.477)	-0.015 (0.375)
ATI Technologies	-0.388 (0.52)	-0.131 (0.436)	-0.119 (0.43)	-0.119 (0.486)	0.181 (0.366)
Agere	-0.542 (0.352)	-0.317 (0.336)	-0.314 (0.335)	-0.314 (0.357)	-0.01 (0.222)
Altera	1.116 (0.346)***	1.228 (0.322)***	1.222 (0.323)***	1.222 (0.335)***	1.055 (0.275)***
Atheros	0.243 (0.352)	0.347 (0.339)	0.353 (0.339)	0.353 (0.398)	0.557 (0.295)*
Avago	0.311 (0.431)	0.564 (0.458)	0.583 (0.458)	0.583 (0.447)	0.583 (0.33)*
Broadcom	0.532 (0.35)	0.647 (0.329)**	0.648 (0.327)**	0.648 (0.343)*	0.76 (0.244)***
CSR	0.66 (0.598)	1.075 (0.597)*	1.042 (0.599)*	1.042 (0.645)	0.779 (0.542)
Cirrus Logic	-0.057 (0.46)	-0.027 (0.44)	-0.023 (0.43)	-0.023 (0.44)	0.18 (0.323)
DSP Group	-0.612 (0.494)	-0.412 (0.481)	-0.383 (0.481)	-0.383 (0.653)	-0.139 (0.239)
Dialog	0.521 (0.874)	0.652 (0.809)	0.636 (0.804)	0.636 (0.878)	0.475 (0.477)
ESS Technology	0.021 (0.645)	0.178 (0.613)	0.196 (0.624)	0.196 (0.671)	0.205 (0.422)
Genesis Microchip	0.462 (0.554)	0.536 (0.55)	0.542 (0.548)	0.542 (0.613)	0.732 (0.482)
LSI	-0.864 (0.376)**	-0.697 (0.36)*	-0.658 (0.345)*	-0.658 (0.361)*	-0.337 (0.241)
Lattice	-0.24 (0.352)	0.262 (0.432)	0.288 (0.43)	0.288 (0.437)	0.37 (0.256)
Marvell	1.026 (0.43)**	1.126 (0.413)***	1.126 (0.412)***	1.126 (0.399)***	0.868 (0.228)***
MediaTek	-0.617 (0.566)	-0.316 (0.575)	-0.348 (0.576)	-0.348 (0.581)	-0.143 (0.493)
NVidia	-1.023 (0.435)**	-0.881 (0.404)**	-0.867 (0.402)**	-0.867 (0.431)**	-0.477 (0.287)*
PMC-Sierra	0.938 (0.967)	1.134 (0.922)	1.185 (0.918)	1.185 (0.931)	0.895 (0.673)
Realtek	-0.504 (0.552)	-0.166 (0.566)	-0.196 (0.57)	-0.196 (0.593)	-0.053 (0.45)
SMSC	-0.281 (0.398)	-0.013 (0.396)	-0.014 (0.396)	-0.014 (0.418)	0.054 (0.203)
SanDisk	1.448 (0.457)***	1.472 (0.407)***	1.458 (0.402)***	1.458 (0.442)***	1.144 (0.301)***
Semtech	-0.677 (0.573)	-0.429 (0.556)	-0.388 (0.543)	-0.388 (0.578)	-0.26 (0.487)
Silicon Labs	2.068 (0.64)***	2.046 (0.629)***	2.027 (0.628)***	2.027 (0.609)***	1.427 (0.396)***
VIA	-0.805 (0.557)	-0.422 (0.563)	-0.448 (0.571)	-0.448 (0.553)	-0.226 (0.422)
Xilinx	-0.216 (0.349)	-0.229 (0.34)	-0.197 (0.332)	-0.197 (0.332)	0.026 (0.235)
Zoran	-0.503 (0.535)	-0.3 (0.545)	-0.288 (0.545)	-0.288 (0.589)	0.092 (0.415)
Cited industry fixed-effects			39 (baseline: Top IC design)		
Aerospace	-0.355 (0.309)	0.17 (0.23)	0.142 (0.225)	0.142 (0.22)	-0.344 (0.251)
Broadcast	-2.15 (0.37)***	-1.672 (0.284)***	-1.695 (0.272)***	-1.695 (0.256)***	-1.028 (0.252)***
Chemical	-0.862 (0.74)	-0.458 (0.755)	-0.522 (0.752)	-0.522 (0.765)	-1.598 (0.451)***
Conglomerate	-0.82 (0.351)**	-0.246 (0.247)	-0.308 (0.239)	-0.308 (0.247)	-0.716 (0.258)***
Defense	-0.901 (0.41)**	-0.349 (0.37)	-0.403 (0.359)	-0.403 (0.405)	-1.62 (0.335)***
Electronics	-1.003 (0.467)**	-0.33 (0.453)	-0.374 (0.451)	-0.374 (0.48)	-0.624 (0.384)
EMS	-1.389 (0.403)***	-0.855 (0.311)***	-0.914 (0.3)***	-0.914 (0.32)***	-0.824 (0.263)***
Energy: Electrical	-0.763 (0.383)**	-0.299 (0.339)	-0.351 (0.332)	-0.351 (0.416)	-0.763 (0.429)*

Energy: Petro	0.259 (1.333)	0.819 (1.164)	0.788 (1.163)	0.788 (1.045)	-1.036 (0.494)**
Energy: Management	-1.574 (0.451)***	-1.071 (0.385)***	-1.109 (0.379)***	-1.109 (0.461)**	-0.289 (0.292)
Government	-0.755 (0.649)	-0.204 (0.589)	-0.26 (0.585)	-0.26 (0.633)	-1.897 (0.431)***
IC	-0.791 (0.342)**	-0.24 (0.327)	-0.266 (0.32)	-0.266 (0.307)	-0.027 (0.329)
IC: EDA	-1.446 (0.337)***	-0.851 (0.357)**	-0.865 (0.354)**	-0.865 (0.349)**	-0.475 (0.277)*
IC: Equipment	-0.682 (0.476)	-0.166 (0.379)	-0.186 (0.374)	-0.186 (0.366)	-0.572 (0.249)**
IC: Fab	-2.623 (0.4)***	-2.002 (0.361)***	-2.063 (0.363)***	-2.063 (0.342)***	-1.049 (0.305)***
IC: IP	-1.213 (0.285)***	-0.682 (0.272)**	-0.698 (0.277)**	-0.698 (0.284)**	-0.382 (0.259)
IC: MEMS	-2.535 (0.665)***	-1.821 (0.61)***	-1.783 (0.612)***	-1.783 (0.59)***	-1.91 (0.364)***
IC: PAT	-1.756 (0.547)***	-1.18 (0.412)***	-1.223 (0.409)***	-1.223 (0.4)***	-0.653 (0.292)**
Instrument	-0.303 (0.36)	0.256 (0.282)	0.197 (0.275)	0.197 (0.26)	-0.027 (0.26)
IT	-1.381 (0.303)***	-0.829 (0.231)***	-0.864 (0.235)***	-0.864 (0.242)***	-0.267 (0.232)
IT: Data	-1.525 (0.454)***	-0.946 (0.334)***	-0.94 (0.336)***	-0.94 (0.349)***	-0.331 (0.293)
IT: Devices	-0.553 (0.313)*	0.101 (0.282)	0.104 (0.27)	0.104 (0.319)	1.062 (0.295)***
IT: GPS	-1.706 (0.6)***	-1.142 (0.528)**	-1.179 (0.525)**	-1.179 (0.512)**	-1.042 (0.395)***
IT: Graphics	-2.674 (0.345)***	-2.161 (0.262)***	-2.205 (0.259)***	-2.205 (0.263)***	-1.546 (0.272)***
IT: IP	-1.224 (0.438)***	-0.436 (0.471)	-0.495 (0.451)	-0.495 (0.451)	-0.224 (0.417)
IT: RFID	-0.893 (0.424)**	-0.333 (0.346)	-0.384 (0.339)	-0.384 (0.335)	0.036 (0.275)
IT: Service	-1.303 (0.389)***	-0.71 (0.306)**	-0.75 (0.307)**	-0.75 (0.315)**	-0.83 (0.234)***
IT: Software	-1 (0.282)***	-0.382 (0.268)	-0.375 (0.268)	-0.375 (0.265)	0.101 (0.237)
IT: Storage	-1.071 (0.358)***	-0.497 (0.279)*	-0.482 (0.287)*	-0.482 (0.283)*	-0.063 (0.268)
IT: Supercomputing	-0.736 (0.432)*	-0.231 (0.397)	-0.289 (0.387)	-0.289 (0.441)	-1.035 (0.42)**
Laboratories	-2.14 (0.459)***	-1.605 (0.387)***	-1.653 (0.379)***	-1.653 (0.389)***	-0.819 (0.292)***
Machinery	-0.549 (0.419)	-0.103 (0.373)	-0.165 (0.36)	-0.165 (0.427)	-0.672 (0.413)
Med	-1.116 (0.433)**	-0.667 (0.388)*	-0.719 (0.375)*	-0.719 (0.43)*	-0.549 (0.4)
Motor	-0.351 (0.621)	0.167 (0.496)	0.108 (0.493)	0.108 (0.504)	-0.129 (0.418)
Multimedia	-0.545 (0.515)	0.046 (0.415)	0.011 (0.408)	0.011 (0.395)	-0.802 (0.254)***
Telecom	-0.418 (0.582)	0.169 (0.518)	0.102 (0.515)	0.102 (0.466)	-0.724 (0.336)**
Telecom: Equipment	-1.272 (0.314)***	-0.675 (0.209)***	-0.726 (0.213)***	-0.726 (0.225)***	-0.157 (0.185)
Universities	-0.686 (0.361)*	-0.149 (0.305)	-0.188 (0.302)	-0.188 (0.306)	-0.31 (0.32)
Other control variables and fixed-effects					
Median year (cited firm)	0.941 (0.022)***	0.942 (0.02)***	0.942 (0.019)***	0.942 (0.023)***	0.655 (0.035)***
SUB patent (citing patent)	-0.017 (0.158)	-0.111 (0.172)	-0.151 (0.185)	-0.151 (0.185)	-0.118 (0.143)
3-digit USPC (citing patent)	152 (baseline: USPC 1; Class 378 dropped for multicollinearity)				
Country-origin (citing patent)	aseline: Australia (AU))				
Filing year (citing patent)	8 (baseline: 2001)				
Sample (cited patents)	since 1960				since 1990
Sample size (citations)	456,358				415,197
R-Square	0.339	0.345	0.346	0.346	0.273

Note: 1. Subsidiary is noted as SUB and the headquarters as HQ, based on the country-state of the first inventor. 2. Constant terms are omitted from the table. 3. Class 422 is dropped in Model 5 due to no observation. 4. Model 4 computes a fifth cluster of the filing year of citing patents. 5. Model 5 employs a more restrictive sample and focuses on cited patents filed since the 1990s. 6. Standard errors in parentheses are adjusted for multi-way clustering (see Cameron et al., 2011). 7. *** p-value < 0.01; ** p-value < 0.05; * p-value <0.1.

6.5.2 Test results of main explanatory variables

With a series of fixed-effects controlled, a moderately significant result is found for shorter year gaps among local country-state citations, while no significant time difference is found among citations made to home country-state. The finding of shorter time gaps among localized and semiconductor-related knowledge flows, as shown by the significant findings from the *IC* category and sub-categories, is in line with earlier studies by Jaffe et al. (1993) and Almeida and Kogut (1999), even though they have employed different research designs and focused mostly on the US in the 1980s. Meanwhile, the analysis does not find evidence for a strong tendency among MNE inventors to cite patents recently originated in the local area of the headquarters, including a weakly significant finding on the interaction terms between *SUB patent* and *Citing home country-state* (see Model 6 in Table 6.10). It appears that geographically proximate knowledge sources have a stronger influence on knowledge seeking and transfer than home country knowledge sources do. The finding remains the same when intra-firm citations are excluded (see Model 8 in Table 6.10 in Appendix).

The non-significant finding on citations to home-country originated patents defies the simple descriptive statistics provided in Table 6.4 and becomes surprising with the significantly longer year gaps among intra-firm citations. Except in Model 5, which restricts the sample to citations made to patents filed since the 1990s, coefficient estimates of *Intra-firm citation* are found positive and significant at the 95% level, suggesting that MNE inventors have in general cited older in-house inventions, controlling for other effects. One might argue that the time difference between filing years seems more appropriate in the case of intra-firm citations, assuming that awareness and access to new in-house innovations should be timely and relatively direct within the firm. In fact, since the correlation between the two measurements is close to unity, test results based on filing year gaps are largely the same (see Model 7 in Table 6.10).

There are two plausible explanations for the unexpected finding—one relates to path-dependency in knowledge-creation and the other concerns the heterogeneity in international knowledge-creating activities. Firstly, innovations based on existing firm-specific knowledge are likely incremental and reflect path-dependency in new product and technology development (Neffke & Henning, 2012; Teece, Rumelt, Dosi, & Winter, 1994). While exploiting and extending the firm-specific knowledge repertoire, corporate inventors are naturally more familiar with knowledge previously created and accumulated within the firm. Since geography, industry and technology effects are all controlled, the significantly larger time difference suggests that inventors may have searched in depth existing expertise within the firm (Hansen, 1999; Morris et al., 2014), and in the meanwhile maintained certain corporate coherence in knowledge-creation at the MNE-level (Papanastassiou & Pearce, 2009; Teece et al., 1994).

Secondly, recent studies in MNE knowledge transfer have argued that flows of knowledge are both diverse and multi-lateral (Gupta & Govindarajan, 2000; Papanastassiou & Pearce, 2009). Models 3-5, therefore, include the test results of dummy variables indicating the directionality of intra-firm citations. Indeed, a fascinating picture emerges in the sense that coefficient estimates for different directionalities are in different directions. The year gaps among headquarters-to-subsidiary and inter-subsidiaries citations are significantly shorter, suggesting different velocities of knowledge flows in different directions. On the other hand, that knowledge-creating activities in the headquarters tend to be pioneering and influential (Argyres & Silverman, 2004) may imply the abiding applicability and enduring value of headquarters knowledge. The shorter year gaps among inter-subsidiary citations, which are notably rare in the sample, correspond with the findings of Phene, Madhok and Liu (2005), who analyze filing dates and find inter-subsidiary knowledge transfer is significantly faster.

6.5.3 Test results of firm and cited industry fix-effects

Several interesting findings also came from *citing firm fixed-effects*. With other effects controlled in the model, test results are firm-specific and indicative of the unique temporal pattern of knowledge seeking and transfer in each IC design MNE. Relative to the baseline IC design company, *Qualcomm*, the industrial leader and largest contributor of citing patents in the sample, year gaps among citation records of *LSI* and *NVidia* are found significantly shorter, while those of *Altera*, *Broadcom*, *Marvell*, *SanDisk* and *Silicon Labs* are significantly longer. Coefficient estimates seem to contain performance implications in the sense that market leaders are found citing more recent inventions (Jiang, Tan, & Thursby, 2011). *NVidia* and *Xilinx* have significantly shorter citation lags than their major competitors, *ATI Technologies* and *Altera*, in graphics processors and field-programmable IC products, respectively. Meanwhile, *Qualcomm* is slightly ahead of its main competitor in communication IC products, *Broadcom*, but no better than *MediaTek*, a fast-growing entrant based on emerging country markets and competitive pricing (see Chapter 5).

Regarding test results for *cited industry fixed-effects*, significantly shorter year gaps are found among citations made to companies in the sub-categories in the semiconductor industry, including *IC: EDA*, *Fab* and *PAT*, which generally assist, implement and provide services to IC design companies. In addition to these supply-side sub-categories, the *IC: IP* and *MEMS* sub-categories, which include companies developing and supplying reusable IC design modules and nascent micro-electro-mechanical systems technology, are associated with smaller time differences. Shorter time gaps are also observed from assignees categorized as *EMS* and *Energy: Management*. Incorporating IC products in their end products, electronics manufacturing service providers and power management devices suppliers are often important business customers of IC design companies. In addition, test results of *Broadcast*, *IT: GPS* and *Graphics* and *Telecom: equipment* seem related to modern applications of IC products in multimedia devices and personal mobile devices.

More significant findings are found in a number of industry categories that mainly operate in the business market and support other industries. Relative to the baseline, shorter year gaps are found in *Laboratories*, which include private organizations and consortiums focused on applied R&D, and *IT: Service*, which provides customized services to other business. Test results of *IT*, *Data* and *Storage* lose significance in Model 5, which employs a restricted sample of cited patents filed since the fast-growing phase of the IC design industry in the 1990s. These categories include a number of incumbents of historical importance in the IT industry, such as Bull Informatique, National Cash Register, HP, and IBM among others. Despite their technological legacy, these companies mostly work with business customers and are largely absent from the recent development in the consumer electronics market which has created tremendous demand for IC products.

6.6 Discussion and conclusion

This chapter analyzes the patent citation records of the 28 IC design MNEs in order to empirically investigate their knowledge sources and inflows from geographical, industrial and temporal dimensions. In the geographical aspect, the analysis confirmed the rising role of NIEs and China, relative to Japan in Asia, and France, Germany and the UK in Europe, which are long-established as the sources of cutting-edge technologies outside North America. Moreover, adding to existing studies on the location decision in the semiconductor industry, this research also investigates the members in the semiconductor ecosystem and various public and private knowledge sources of the IC design industry. Despite a general shift of semiconductor manufacturing to Southeast Asia, many of these inventive entities are embedded and bound locally, which limits the range and efficiency of innovation diffusion.

Moreover, test results also provide insights into the internal multilateral transfer of knowledge. Surprisingly, within the firm, knowledge flows of different directionalities attain different velocities, vertically or horizontally. The difference in velocities may relate to the nature of subsidiary knowledge creation, which differs from the knowledge creation in the headquarters.

However, it can also imply that the headquarters is fully aware of the new knowledge created at the subsidiary level and retrieves it with time efficiency. This explanation contravenes the claim of several recent studies that the headquarters can act inadvertently with limited knowledge (Ciabuschi et al., 2011). It is, however, in line with internalization theory, which suggests MNEs transfer information more efficiently than external markets (Buckley & Casson, 1976; Casson, 2000). In brief, these empirical findings reveal a highly dynamic picture of knowledge flows hitherto largely unknown and require further investigation in future studies.

6.6.1 Knowledge flows and the semiconductor business ecosystem

This research provides a first-hand look into the knowledge flows across industries by identifying thousands of assignees from citation records. Instead of relying on secondary sources for a pre-defined categorization of knowledge source (e.g. Ganco, 2013), this information enables a fact-based investigation of knowledge source industries of the IC design industry. On one hand, the knowledge seeking and transfer by IC design MNEs are indeed diverse and comprehensive, reaching inventive organizations of various nature and scale in worldwide locations. On the other hand, the intensity and efficiency of knowledge flows are related to the relevance between the IC design industry and specific knowledge source industries. Test results suggest that relevance in various dimensions all have significant effects on the amount and year gaps of pairwise citations across industries. Although the chapter also emphasizes the empirical issues of measuring and comparing knowledge flows, multidimensional relevance and importance of knowledge sources, this panoramic view of the global semiconductor business ecosystem provides rich information as well as opportunities for future studies.

6.6.2 A contingent view of the value of inventions

Besides the relevance of pieces of knowledge, another factor of knowledge flow is essentially the value of the specific pieces. Although IC design MNEs frequently cite other companies in the semiconductor and other related industries, the analysis has also identified citations to advanced knowledge sources in the aerospace and defense industries and other public and private research institutes, whose research projects at the forefront of science are often assumed as more valuable. In fact, the relevance and value of specific pieces of knowledge are likely intertwined—irrelevant knowledge would also be considered subjectively as less valuable. Since citations can be regarded as the ultimate endorsement of the value of specific pieces of knowledge, longer citation lags may imply that some technologies only become useful and relevant after some time, when business entrepreneurs and corporate inventors find new applications for these age-old technological breakthroughs. Established firms may enter new industries with novel applications of their existing technologies and capabilities, which have lost the technological edge in the current industry but remain competitive in other industries and applications. From a historical perspective, the relevance and value of technologies vary by context and change over time.

This conclusion suggests a contingent view of the value of inventions and rejects the simplistic presumption of constant knowledge depreciation. While previous patent data research often assumes that patents constantly devalue over time, this research finds that old patents can also be cited because of the relevance of knowledge and the background of transfer. This finding, therefore, casts doubts on the current practice of the universal citation window and constant depreciation rate. Future studies may examine the temporal distribution of citations made to specific knowledge pieces and inventive entities, which evolve and accumulate over decades and provide the historical records for the changing applications and evaluation of technologies, as well as the evolving relationship between the inventive entities and the recipients. One may argue that some decades-old inventions could have been long forgotten but later recreated by others, but it is indeed this long delay until the recreation and reconstruction of pieces of knowledge that reflects the difficulty and incompleteness of technical knowledge transfer (Attewell, 1992; Szulanski, 2000). Citation to older patents might actually be an indicator of originality, as one of the IC designers consulted for this research has said, "go back to root and start a new path."

Appendix to Chapter 6

Table 6.7 List of industry categories

Industry categories	Business, product, service and technological focus	Cited Assignees
Aerospace[1]	Organizations related to space exploration, aircraft manufacturers, suppliers of avionics, space and flight electronics and devices, suppliers of aviation-related products and services, and commercial satellite communication products and services providers.	147
Broadcast	Mass media companies, suppliers of product and services related TV and radio broadcasting toward the general public, developers and suppliers of technologies for marketing and advertising, and product and services related to media content production and distribution.	75
Chemical	Chemical companies, suppliers of specialized chemicals (some of which are related to semiconductor manufacturing), industrial gas suppliers, special materials companies, food and agriculture products.	44
Diversified enterprises	Diversified business enterprises which control multiple businesses and cover several categories in the list.	31
Defense[2]	Developers and suppliers of specialized defense products and technologies, including other companies supplying various products for defense applications.	67
Electronics[3]	Manufacturers of home electronics and appliances, lighting and LED devices, small electronics components, printed circuit boards, and thermal devices.	86
EMS	Original equipment manufacturers providing design, manufacturing and product repair services.	8
Energy: Electrical	Companies in the businesses of electricity generation and grids, utility metering, water supply, and suppliers of other utility related products and services, including photovoltaic devices for solar energy.	19
Energy: Fossil fuel	Companies in the businesses of exploration and refinery of petroleum, natural gas and other fossil fuels, suppliers of related products and services, and mining companies.	15
Energy: Management	Suppliers of power supply devices and power converters, batteries, and other power storage and management devices.	17
Government[4]	Governmental organizations, commissions, research laboratories and scientific research institutions, inter-governmental bodies, ministries and national armed forces.	26
IC	IDM companies, DRAM manufacturers, other semiconductor companies, and other IC design companies not included in the sample.	441
IC: EDA	Developers and suppliers of electronic design automation software and related technologies.	35
IC: Equipment	Developers and suppliers of semiconductor manufacturing equipment and related devices.	52
IC: Foundry	Professional foundry companies.	7
IC: IP	Semiconductor IP core vendors, and patent assertion and licensing companies.	28
IC: MEMS	Developers and suppliers of products and technologies related to micro-electro-mechanical systems.	13
IC: PAT	Semiconductor packaging and testing companies, including specialized developers and suppliers of related technologies.	25
IC: Top design	The 28 top IC design companies in the sample.	28

Instrument[5]	Specialized manufacturers of timepieces, scientific instruments, optoelectronics components, high-precision components and processing tools with multiple industrial applications.	65
IT[3]	Large information technology and system companies, some of which also operate internal semiconductor business.	14
IT: Data	Datacenter operators, and developers and suppliers of data management tools and enterprise data storage systems.	33
IT: Devices	Manufacturers of minicomputers, personal and laptop computers, standalone devices, and other smaller, end-user oriented devices and hardware components.	60
IT: GPS[6]	Manufacturers of personal navigation devices based on the global positioning system and related technologies.	13
IT: Graphics[7]	Manufacturers of computer graphics processing hardware, display devices, imaging devices, and photocopiers, and developers of related technologies and software.	57
IT: IP	Patent assertion and licensing companies and other non-practicing entities (NPE).	24
IT: RFID	Developers and suppliers of radio-frequency identification tags and related technologies.	7
IT: Service	Companies in the businesses of enterprise services, information system planning, hardware and software installation and management, data security and encryption, security systems, logistics and tracking, and financial services.	73
IT: Software	Developers and distributors of software packages for business enterprises, database systems, software tools for multimedia content, and other commercial software packages, including suppliers of geographical information systems and map data.	81
IT: Storage	Manufacturers of data storage hardware and devices based on various technologies.	40
IT: Super-computing	Developers and suppliers of supercomputers, mainframe computers and high-speed parallel processing systems.	18
Laboratories	Private organizations in the business of basic and applied research, contract R&D service, and other general purpose R&D and technology licensing, including industrial consortiums and foundations.	90
Machinery	Developers and suppliers of industrial equipment, automation and robotics, manufacturers of light and heavy machinery and power tools, and companies in the businesses of transportation, building and construction and industry printing.	62
Medical[8]	Pharmaceutical and biotechnology companies, medical device manufacturers, public and private medical institutions, and other organizations related to healthcare and pharmacy management.	42
Motor	Automobile manufacturers and suppliers of automotive electronics and other components for automobiles.	43
Multimedia devices	Personal entertainment devices, audio and video devices, end-user-oriented multimedia devices, and devices related to haptics and human-machine interface.	67
Telecom	Long-distance communication and data transmission service providers, including larger companies which internally develop and manufacture telecommunication equipment.	54
Telecom: Equipment	Developers and suppliers of equipment, tools, cables, network management software and other hardware devices for long-distance communication systems and infrastructure, including companies supplying enterprise telephone and telecommunication system.	312

Universities[9]	Universities, colleges and polytechnics, including related foundations and boards of trustees and regents.	27
Total		**2,346**

Note: 1. The Aerospace category includes defense contractors and government agencies that participate in the aerospace industry. 2. The Defense category includes developer and suppliers of a wide range of mission-critical products and rugged systems built or customized for defense purpose. 3. Several large electronics and IT companies also operate internal semiconductor business. 4. Various governmental organizations of 26 countries were identified. 5. The Instrument category includes companies whose products have important applications in the telecommunication industry and semiconductor manufacturing. 6. Companies using different positioning technologies other than the GPS satellites were categorized as Telecom: Equipment. Suppliers of geographical information systems and map data were categorized as IT: Software. 7. The IT: Graphics category includes a number of companies in the optical industry, which supply scientific instruments and semiconductor manufacturing equipment as a minor part of their business scope. 8. The Medical category includes a number of companies in the business of medical electronics and hearing aids. 9. Large variations in assignee names, including foundation and boards of regents, licensing bodies, labs, departments, and centers among others.
Source: This research.

Table 6.8 Search keywords for advanced knowledge sources

Aerospace	**Government**	**Laboratories**		**Universities**	
Aerial	Administration	Centr-	Lab-	Board	Regent
Aero	Agency	Development	Pesquisa	College	School
Avionic	Authority	Forschung	Recherche	Ecole	Schule
-craft	Council	Forskning	Research	Escola	Scu-
Dynamic	Department	Instelling	Ricerc-	Etude	Skol-
Flight	Government	Institut	Science	Facul-	Szkola
Plane	Majesty	Institute	Senter-	Foundation	Uczelnia
Propulsion	Minis-	Investiga-	Tutkimus	Gym-	Univ-
Sate-	Regent	Istitut	Zentr-	Kolai	Univers-
Space	Secretary	Kenkyu	-trum	-koulu-	Yliopisto
-nautic		Keskusta		Library	

Table 6.9 Frequently cited patent classes

Industry categories	**Top 10 cited USPC**										**Concurrent[1]**	**Correlation[2]**
Aerospace	375	370	455	342	359	714	341	330	333	331	4	0.580
Broadcast	348	375	725	370	345	455	386	704	713	712	3	0.359
Chemical	257	428	349	362	359	385	174	345	310	8	1	0.069
Diversified enterprises	365	375	370	455	348	257	714	327	345	341	7	0.799
Defense	375	370	455	341	359	714	365	348	330	331	5	0.651
Electronics	315	333	361	439	362	375	345	310	359	348	2	0.212
EMS	439	361	362	323	363	165	370	455	710	1	2	0.048
Energy: Electrical	365	330	257	363	710	370	361	307	340	324	2	0.527
Energy: Fossil fuel	363	711	342	324	136	367	345	359	330	340	1	0.184
Energy: Management	363	323	438	327	320	336	700	710	174	713	2	0.048
Government	359	370	257	375	714	326	438	455	343	327	7	0.571

IC	365	375	257	327	359	326	438	345	711	710	6	0.798
IC: EDA	716	703	714	326	712	713	375	710	717	323	4	0.262
IC: Equipment	438	714	375	324	327	365	370	451	455	341	7	0.457
IC: Foundry	438	257	365	361	327	216	326	430	716	324	5	0.247
IC: IP	365	327	712	375	716	713	711	710	714	326	6	0.718
IC: MEMS	359	345	438	365	333	356	216	385	310	257	3	0.057
IC: PAT	257	438	361	174	29	228	324	333	714	716	2	0.129
IC: Top design	326	365	370	375	455	345	716	714	327	438	10	1.000
Instrument	341	375	327	331	356	359	324	370	330	702	3	0.429
IT	370	714	710	711	345	365	375	257	713	327	6	0.713
IT: Data	714	711	370	710	709	361	360	1	713	375	3	0.375
IT: Devices	345	710	713	370	711	375	714	361	712	715	4	0.399
IT: GPS	342	701	375	455	707	370	345	315	340	702	4	0.061
IT: Graphics	359	345	382	348	358	257	349	710	438	711	2	0.184
IT: IP	712	359	375	370	711	342	369	715	331	713	2	0.369
IT: RFID	333	340	375	455	29	329	330				2	0.053
IT: Service	370	455	235	375	710	709	713	714	340	705	4	0.509
IT: Software	345	713	709	714	370	375	382	715	717	455	5	0.418
IT: Storage	360	711	714	710	365	375	341	713	327	361	4	0.265
IT: Supercomputing	345	711	710	712	714	709	370	327	713	708	4	0.435
Laboratories	348	375	370	438	359	382	257	345	455	430	5	0.506
Machinery	363	710	375	380	382	700	702	318	327	340	2	0.267
Medical	359	600	345	365	330	607	379	320	341	370	3	0.412
Motor	455	257	340	361	701	370	381	307	375	438	3	0.354
Multimedia devices	345	369	375	381	341	704	348	463	455	386	3	0.279
Telecom	370	455	375	714	379	704	330	709	341	725	4	0.570
Telecom: Equipment	370	455	375	709	714	359	330	379	327	257	5	0.559
Universities	359	375	370	714	257	326	712	455	365	349	6	0.630
Average											**3.923**	**0.397**

Note: 1. Concurrent measurement suggests the number of patent classes a specific industry category share with the *IC: Top design* in the Top 10 list. 2. These 39 industry categories cover 278 3-digits USPCs, and each category has a unique vector of citation counts across 278 patent classes. The Correlation measurement is, therefore, the correlation coefficient between the citation count vector of a specific industry category and the vector of *IC: Top design*. 3. The correlation coefficient between two measurements is 0.795. Source: This research.

Figure 6.6 Scatter plot of observed year gaps from unrestricted sample

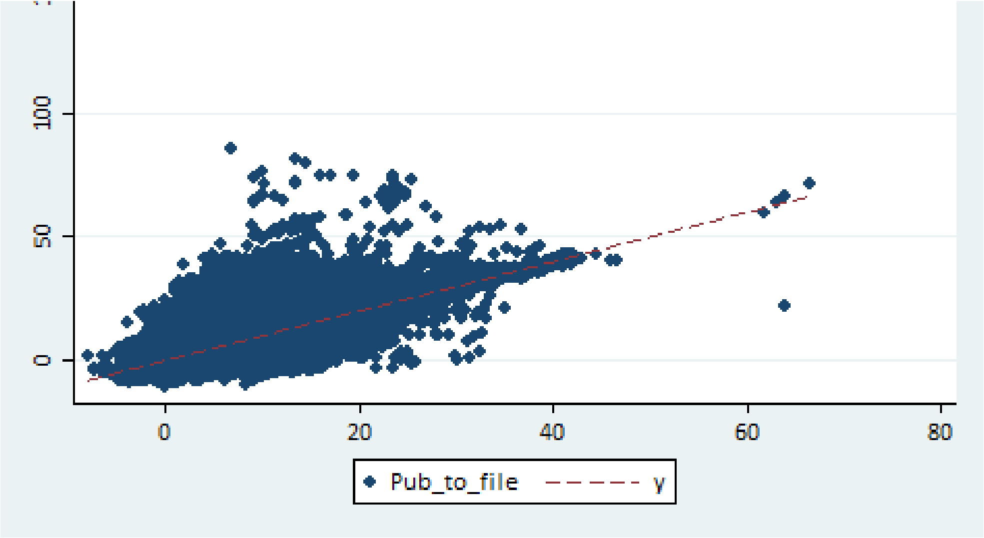


Figure 6.7 Scatter plot of observed year gaps from restricted sample of cited patents filed since the 1960s

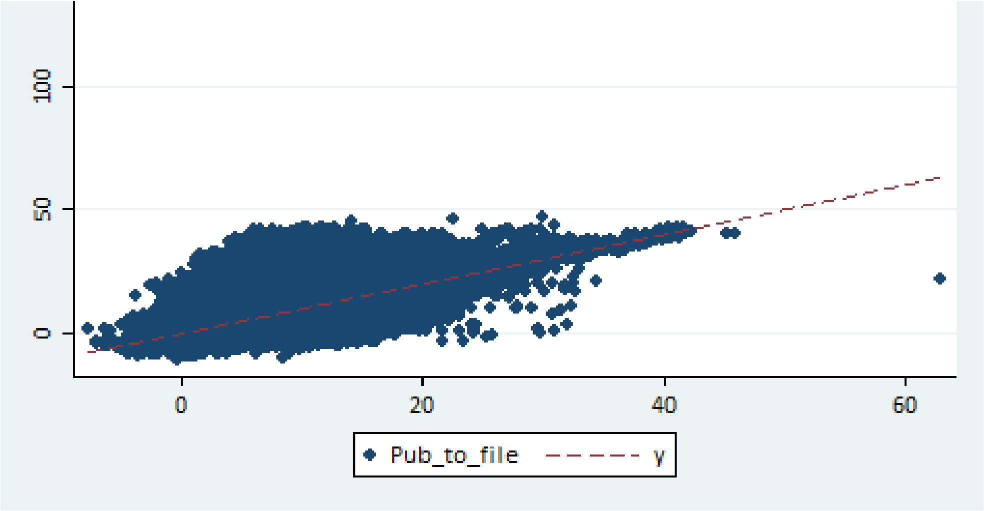


Figure 6.8 Scatter plot of observed year gaps from restricted sample of cited patents filed since the 1990s

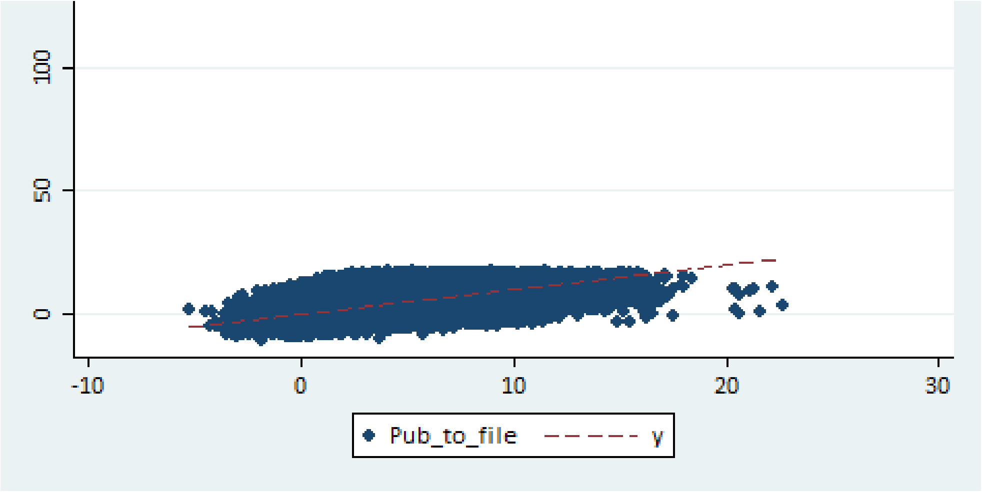


Table 6.10 Additional tests

	Model 3	Model 6	Model 7	Model 8	Model 9
Model notes:	Full model	Interaction terms	Filing year gap as DV	Intra-firm citations excluded	Five-way random effects
Geographical relevance					
Local country-state	-0.655	-1.059	-0.633	-0.309	-0.474
	(0.266)**	(0.422)**	(0.251)**	(0.144)**	(0.023)***
Citing home country-state	0.378	0.845	0.358	0.004	0.378
	(0.403)	(0.555)	(0.362)	(0.267)	(0.033)***
Interaction: SUB patent & Citing home country-state		-0.76			
		(0.424)*			
Technological relevance					
Intra-firm citation	1.152	1.128	1.16		-0.011 (0.133)
	(0.473)**	(0.472)**	(0.442)***		
Same 3-digit USPC	-0.816	-0.813	-0.733	-0.762	-0.622
	(0.107)***	(0.106)***	(0.114)***	(0.098)***	(0.015)***
Organizational factors					
SUB cites HQ	0.63	0.819	0.42		0.919
	(0.579)	(0.591)	(0.556)		(0.397)**
HQ cites SUB	-2.203	-2.178	-2.152		-1.345
	(0.514)***	(0.511)***	(0.508)***		(0.056)***
SUB cites other SUB	-2.145	-2.237	-1.874		-0.998
	(0.433)***	(0.399)***	(0.417)***		(0.049)***
Other control variables and fixed-effects					
Median year (cited firm)	0.942	0.942	0.903	0.951	0.863
	(0.019)***	(0.019)***	(0.02)***	(0.017)***	(0.004)***
SUB patent (citing patent)	-0.151	-0.034	-0.122	0.036	-0.155
	(0.185)	(0.184)	(0.168)	(0.161)	(0.019)***
Citing firm effects	Included as FE				Included as RE
Cited industry effects	Included as FE				Included as RE
3-digit USPC (citing pat)	Included as FE				Included as RE
Country-origin (citing pat)	Included as FE				Included as RE
Filing year (citing pat)	Included as FE				Included as RE
Sample size (citations)	456,358			407,376	456,358
R-Square	0.346	0.346	0.344	0.353	

Note: 1. Subsidiaries are noted as SUB and the headquarters as HQ, based on the country-state of the first inventor. 2. Constant terms are omitted from the table. 3. For Models 3 and 6-8, standard errors in parentheses are adjusted for multi-way clustering. 4. The estimation of multiway RE model in Model 9 is found more efficient but inconsistent. 5. *** p-value < 0.01; ** p-value < 0.05; * p-value <0.1.
Source: This research.

7 THE HETERARCHICAL MNE AND MULTILATERAL KNOWLEDGE TRANSFER

7.1 Introduction

In the previous chapter, a comprehensive investigation of knowledge flows in the IC design industry reveals the highly dynamic and knowledge-intensive nature of the industry. Analysis of citation records of the 28 IC design MNEs identifies knowledge inflows from various external sources and shows that intra-firm knowledge flows may attain different velocities vertically or horizontally. Among various sources and directionalities, the observed variation in knowledge transfer efficiency implies that knowledge flows, both inter- and intra-firm, are neither homogeneous nor frictionless. More importantly, across industry, geographical and technological boundaries, the diversity of knowledge sources and the rich nature of knowledge inflows distinguish IC design companies from other semiconductor companies with a manufacturing focus.

This chapter continues to the empirical analysis of multilateral knowledge flows surrounding knowledge-creating subsidiaries, according to subsidiary patenting and intra-firm citation records. Specifically, two different processes of multilateral knowledge transfer are investigated—firstly, knowledge inflows deposit transferred knowledge in subsidiaries and affect subsidiary knowledge creation, and, secondly, knowledge outflows from subsidiaries contribute to the knowledge creation by the headquarters. The focus of this chapter is on the effects of the heterarchical structure on subsidiary knowledge creation and on MNE knowledge transfer and integration. Although multilateral knowledge transfer may include the transfer to other subsidiaries, only subsidiary-to-headquarters transfer is considered in this chapter, because of the relative importance of the headquarters in MNE knowledge development.

The following section first reviews the cross-level interdependency perspective proposed in Chapter 2. The purpose of this review is to develop the conceptual framework further (see Figure 2.2) and suggest a testable empirical framework with hypothesized relationships between subsidiary knowledge creation, the heterarchical structure and subsidiary-to-headquarters knowledge transfer. Subsequently, empirical measurements and research designs are devised based on the patenting and citation records of the 28 IC design MNEs between 2001 and 2008. Moreover, location information retrieved from annual reports augment the dataset of mainly patent metrics with qualitative information (see 5.3.4). Lastly, a series of regression analyses are conducted on a compiled dataset of subsidiary knowledge creation in 438 country locations. Findings and implications are discussed before the concluding section.

7.2 Multilateral knowledge transfer and subsidiary knowledge creation

The process of multilateral knowledge transfer involves knowledge creation by subsidiaries in various host country environments and knowledge transfer and integration by the MNE headquarters. Multilateral transfer of knowledge essentially connects these levels based on cross-level interdependencies. Conventional headquarters-to-subsidiary knowledge transfer remains critical in supporting the dissemination and application of firm-proprietary knowledge at the subsidiary level, but the concept of multilateral knowledge transfer intends to facilitate subsidiary knowledge creation and subsequently incorporate subsidiary knowledge into the knowledge repertoire of the MNE group (Frost & Zhou, 2005; Håkanson & Nobel, 2001; McCann & Mudambi, 2005; Schulz, 2003).

In the absence of multilateral knowledge transfer, subsidiary knowledge creation may only cause redundant investments, isolated subsidiaries, problematic headquarters-subsidiary relationships and unnecessary increases in organization cost. From the perspective of the MNE, multilateral knowledge transfer, therefore, enables recombination of internal and external knowledge-based assets at the boundary of the MNE (Kogut & Zander, 1992, 1993;

Rugman & Verbeke, 1992). Knowledge-based assets sought and created by subsidiaries utilizing both internal firm-specific and foreign country-specific advantages are thus globally recombined, shared and subsequently leveraged by the headquarters as new competitive advantages of the MNE.

7.3 Cross-level interdependencies and subsidiary knowledge creation

The external conditions for subsidiary knowledge creation, especially the location factor of technologically advanced nations, regions and clusters have been the topic of regional studies and international R&D literature (Cantwell & Piscitello, 2002; Verspagen & Schoenmakers, 2004). Subsidiaries depend on local networks to access knowledge sources in the host country and to build own competencies (Andersson & Forsgren, 1996; Andersson et al., 2002; Frost et al., 2002). These studies debate the implications of the subsidiary-host interdependency between subsidiaries with local external knowledge sources. However, their suggestions are rather unequivocal in that subsidiaries should connect with external knowledge sources and seek inflows of knowledge from external networks. The absorption and recombination of external knowledge are thus the key elements of subsidiary knowledge creation.

Hypothesis 1 *Knowledge inflows from local external knowledge sources are positively associated with subsidiary knowledge creation*

On the other hand, subsidiary knowledge creation also relies on the support of the headquarters and knowledge inflows from internal knowledge sources. Different from the flows of goods and capital, internal knowledge flows are based on internal communication systems and the constructive social and organizational context of the MNE (Björkman et al., 2004; Noorderhaven & Harzing, 2009; Rugman & Verbeke, 2003). Between the headquarters and internal subunits, the intra-firm transfer and infusion of proprietary knowledge are indispensable to the establishment and continuing relevance of subsidiary knowledge creation. Similar to the consideration of subsidiary-host interdependency, the interdependencies with internal knowledge sources should provide the critical support for subsidiary knowledge creation.

Hypothesis 2 *Knowledge inflows from corporate internal knowledge sources are positively associated with subsidiary knowledge creation*

7.4 The heterarchical structure

Despite the efforts of the headquarters to connect and integrate foreign subsidiaries, the perspectives of subsidiaries and the headquarters may gradually diverge. This divergence may intensify when subsidiaries increasingly embed in local networks and become interdependent with local knowledge sources. Subsidiaries may prioritize the product customization tasks for local customers, engage in local communication channels and tie research efforts to a specific product market (Andersson & Forsgren, 1996; Argyres & Silverman, 2004). Subsidiaries may also develop complex and idiosyncratic interaction processes with external parties, which may cause difficulty in communicating with the headquarters and other subunits (Björkman et al., 2004). The knowledge accumulation at subsidiary level in specific institutional, organizational and corporate management contexts gradually differentiate the subsidiary knowledge base from the headquarter knowledge bases (Verbeke & Yuan, 2005).

This deviation, which results from growing subsidiary-host interdependencies, is nevertheless justifiable. Divergent perspectives and some differentiation from the headquarters knowledge base may help subsidiaries seek tacit and idiosyncratic knowledge-based assets in a foreign environment (Björkman et al., 2004; Rosenkopf & Almeida, 2003). The search for new knowledge relies on existing knowledge bases and established organizational practices. However, innovative ideas from external knowledge sources might be too distant from the existing firm knowledge base to be appreciated and absorbed immediately (Cohen & Levinthal, 1990). Insisting on a dominant view and perfectly-aligned perspective within MNEs can frustrate the knowledge-seeking and creation efforts to expand the firm-specific knowledge repertoire, which requires venturing beyond familiar technological and geographical contexts (Levinthal & March, 1993; Rosenkopf & Almeida, 2003).

7.4.1 Subsidiary knowledge seeking and accumulation

Lane and Lubatkin (1998) suggest that absorptive capacity is relative and dyadic between the knowledge source and the recipient and is based on the similarity of their knowledge bases. Such relative absorptive capacity can affect the actual benefits of knowledge inflows between interdependent dyads. Although MNEs may have developed specific firm-level absorptive capacity through knowledge absorption and creation mainly at the home base, subsidiaries may develop relative absorptive capacity with local knowledge sources when seeking knowledge locally. This localized absorptive capacity requires differentiated and specialized knowledge bases to acquire and assimilate external knowledge with improved perception, scope and speed. Björkman, Barner-Rasmussen and Li (2004) suggest extensive long-term cooperation with customers and suppliers enhances absorptive capacity, problem-solving capacity and the ability to create new knowledge within specific contexts.

The difference between knowledge bases of subsidiaries and the headquarters may reflect their unique exposure and growing interdependencies with different knowledge sources. Specialization and differentiation at the subsidiary level assist subsidiary knowledge creation by improving the appreciation and acquisition of outside ideas and knowledge and the recombination with those infused by internal knowledge inflows. On one hand, the success of subsidiary knowledge creation requires the development of relative absorptive capacity for specific external sources through specialized knowledge seeking efforts. On the other hand, the trajectory of subsidiary knowledge seeking and creation would necessarily differ from that of the headquarters; otherwise, the efforts and resource commitments on either side would become redundant.

From the viewpoint of headquarters, what differentiation and specialization at the subsidiary level actually imply is the emergence of a heterarchical structure. Heterarchical MNEs encourage subsidiaries to differ and specialize and form a differentiated network, from which additional value can be derived for the broader MNE organization (Frost et al., 2002; Kretschmer & Puranam, 2008; Mudambi, 2008). In order for subsidiary knowledge seeking and accumulation to occur, the heterarchical structure recognizes and encourages, in other words, mandates differentiation and specialization. Awarding knowledge-creating mandate means giving specific subsidiaries a special role in MNE global knowledge creation, and subsidiaries awarded the mandate are expected to contribute to the proprietary knowledge repertoire of MNEs.

Hypothesis 3a *Heterarchical knowledge seeking at the subsidiary level is positively associated with subsidiary knowledge creation*

Hypothesis 3b *Heterarchical knowledge accumulation at the subsidiary level is positively associated with subsidiary knowledge creation*

The heterarchical structure and knowledge-creating mandates grant subsidiaries the autonomy to engage in differentiated and specialized knowledge seeking and accumulation. Knowledge-creating mandates allow subsidiaries to initiate their own technological trajectories (Birkinshaw, 1997; Blomkvist et al., 2010), obtain bargaining power (Mudambi & Navarra, 2004), gain more attention (Bouquet & Birkinshaw, 2008), and to certain extent, influence R&D decision-making (Andersson et al., 2007). From an intersecting position of knowledge inflows from external and internal networks, subsidiaries access external and internal knowledge sources, absorb inflows of knowledge, build competencies, and ultimately perform a contributory role in the MNE and generate outflows of knowledge. Throughout the process, multilateral knowledge transfer not only assists subsidiaries in absorbing and recombining knowledge potentially available from external and internal knowledge sources, but also in integrating these creative outputs into the knowledge repertoire of the MNE.

Hypothesis 4 *Subsidiary knowledge creation is positively associated with multilateral knowledge transfer to the headquarters*

7.4.2 The cognitive gap between subsidiaries and the headquarters

Differentiation and specialization at the subsidiary level are the preconditions for subsidiary knowledge creation, but there are side effects. As the extent of divergence grows, it is likely that the subsidiary knowledge base would deviate excessively from the headquarters knowledge base. On one hand, the diverging views and knowledge bases of subsidiaries and the headquarters hamper corporate communication channels (Rugman & Verbeke, 2003; Verbeke & Yuan, 2005). On the other hand, knowledge created by subsidiaries in diverse host countries and idiosyncratic processes can be myopic and limited to specific local demands, and thus becomes inapplicable or underappreciated by the headquarters and other subsidiaries (Argyres & Silverman, 2004; Björkman et al., 2004). Cognitively, the headquarters, with asymmetric information about the innovation processes and network relationships at the subsidiary level, might intervene inadvertently or commit insufficient resources to multilateral knowledge transfer (Ciabuschi et al., 2011; Dellestrand & Kappen, 2012; Di Minin & Bianchi, 2011). Gradually, excessive deviation from the corporate internal network causes isolation and negligence and hinders internal knowledge transfer (Monteiro et al., 2008).

Therefore, although the hierarchical MNE is rich in creative potential, its management is faced with organizational challenges and a high requirement for internal communication channels (Egelhoff, 1991; Papanastassiou & Pearce, 2009; Rugman & Verbeke, 2003). As a result, a cognitive gap can emerge between subsidiaries and the headquarters and hinder the multilateral transfer of knowledge and the contributory role of subsidiaries.

Hypothesis 5a *Differentiated knowledge seeking between subsidiaries and the headquarters is negatively associated with multilateral knowledge transfer*

Hypothesis 5b *Differentiated knowledge accumulation between subsidiaries and the headquarters is negatively associated with multilateral knowledge transfer*

7.4.3 Cross-level interdependencies and MNE knowledge integration

The R&D internationalization literature generally supports the creative potential of subsidiary knowledge creation. However, the difficulties to integrate subsidiary knowledge are reflected in empirical findings, which more often reveal the strong tendency for MNEs to centralize R&D in the home country (Cohen, Di Minin, Motoyama, & Palmberg, 2009; Di Minin & Bianchi, 2011; Frost, 2001; Patel & Pavitt, 1991; Sanna-Randaccio & Veugelers, 2007; Wolf et al., 2012). This strong reliance on the home country environment renders the exploitation of multinationality far-fetched and the potentially contributory role of subsidiaries irrelevant to MNE knowledge creation. In such cases, MNEs might neglect external knowledge sources (Tan & Meyer, 2011), underrate knowledge created outside the home base and refrain from multilateral knowledge transfer (Di Minin & Bianchi, 2011). As a result, cross-level interdependencies collapse, and subsidiary knowledge creation and the heterarchical structure only add costs.

Innovation research suggests that highly useful innovations tend to emerge from the interaction between specialization and diversity, and, more importantly, the integrative mechanism connecting the two (Yayavaram & Ahuja, 2008). It falls on the shoulders of the headquarters to explore and leverage the diverse knowledge bases in differentiated and specialized subsidiaries. The headquarters needs to break divisional boundaries, leverage interdivisional knowledge and maximize the creative potential of MNEs (Miller et al., 2007).

7.4.4 Knowledge integration mechanism

To improve interdivisional knowledge integration, several strategies have been proposed in the IB literature, including decentralized IP management (Di Minin & Bianchi, 2011), expatriation (Gaur, Delios, & Singh, 2007; Hocking, Brown, & Harzing, 2007), interpersonal networks (Hansen et al., 2005; Morris et al., 2014), incentives design (Björkman et al., 2004; Gupta & Govindarajan, 2000), and intra-MNE R&D collaboration (Bergek & Bruzelius, 2010; Frost & Zhou, 2005). Firstly, decentralized IP management improves the awareness, protection and commercial exploitation of the knowledge-based assets created in peripheral locations, which are often difficult to identify, understand and appropriate (Di Minin & Bianchi, 2011). Secondly, the transfer of informal practices often relies on expatriates, who transfer knowledge from the headquarters or become agents to elicit subsidiary knowledge; moreover, this interpersonal transfer of knowledge offers increased informality, tacitness and richness of contextual meaning (Gaur et al., 2007; Hocking et al., 2007). Thirdly, inter-subsidiary and inter-team social networks affect the scope and distance of intra-firm knowledge seeking and transfer (Hansen et al., 2005). Lastly, the use of intra-firm R&D collaborations, which often involves the strategies above, is particularly relevant to subsidiary knowledge creation.

Intra-firm R&D collaborations may involve expatriation (Brown et al., 2005; von Zedtwitz, 2003), the establishment of an intra-firm network of inventors (Nerkar & Paruchuri, 2005; Paruchuri, 2014), the development of relative absorptive capacity between subunits (Frost & Zhou, 2005), and the coordination between centralized IP management and subsidiary knowledge creation (Di Minin & Bianchi, 2011). Various interactions and non-R&D activities may occur between co-inventors during international R&D collaboration (Bergek & Bruzelius, 2010). Frost and Zhou (2005) argue, beyond joint technological activities, R&D collaboration facilitates knowledge transfer and integration within the heterarchical MNE by establishing interpersonal relationships, common values, collective goals and trust. R&D collaboration may incur the convergence of differentiated knowledge bases and help to establish common values and collective goals within a decentralized MNE (Frost & Zhou, 2005; Minbaeva, Pedersen, Bjorkman, Fey, & Park, 2003).

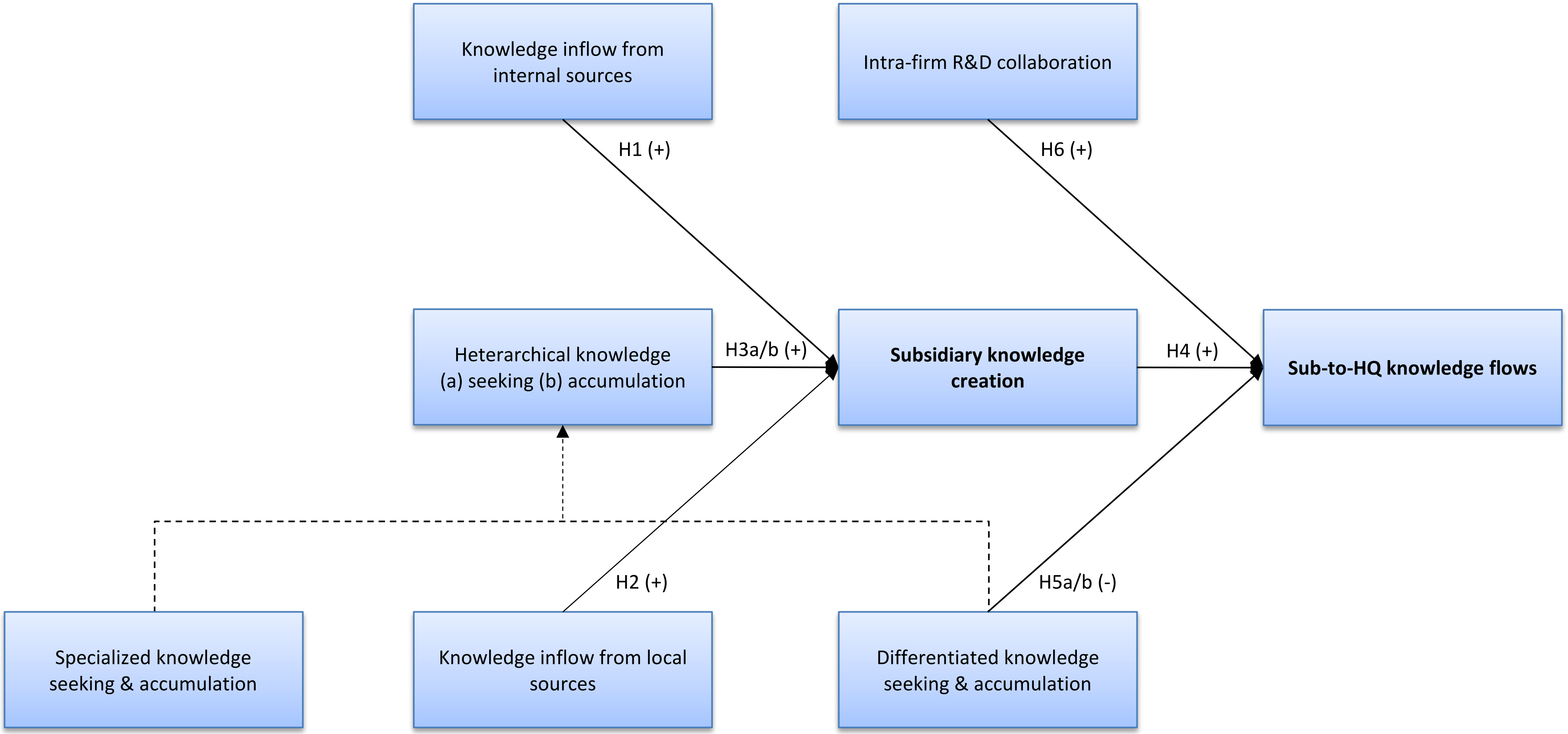
This thesis argues that R&D collaboration between subsidiaries and the headquarters has important implications on cross-level interdependencies. R&D collaboration is a lateral integrative mechanism that bridges the cognitive gap and re-establishes interdependencies between subsidiaries and the headquarters. More importantly, R&D collaboration tends to be a temporary arrangement and therefore avoids merge of the subsidiary and the headquarters knowledge bases. The differentiation and specialization of subsidiary knowledge base remain intact. Figure 7.1 summarizes the hypotheses for testing.

Hypothesis 6 *R&D collaboration between subsidiaries and the headquarters is positively associated with multilateral knowledge transfer*

7.5 Data and methods

The primary data source employed in the following analysis is USPTO patent data. The patent dataset is compiled from the patenting and citation records of 28 IC design MNEs between 2001 and 2008. The semiconductor industry in general makes intensive use of patents, while IC design companies benefit particularly from a strong patent regime and use comprehensively the IP protection it provides (Hall & Ziedonis, 2001). IC design companies focus on the creation and revision of IC designs and related IPs and its transfer into digital format to external service providers for product manufacturing, testing and packaging (Brown & Linden, 2009). Companies are advised to start patenting at an early stage of development, search for related patents owned by other firms and engineers, establish committees to regularly review internal research projects and patentable inventions, and establish close relationships with IP lawyers with good backgrounds in companies' technological fields (Hurtarte et al., 2007).

Figure 7.1 Empirical framework



Notes: 1. Dotted lines specify interaction terms. 2. Control variables are not included.

Inventor residence information is used to identify patent location of origin and R&D collaborations, and assignee information is used to identify the owner (Cantwell & Janne, 1999; Frost, 2001; Frost & Zhou, 2005). Filtered by application year and first assignee, a database search for patents assigned to these 28 IC design MNEs between 2001 and 2008 identifies 30,964 patents, of which 10,363 originated outside the MNE home country and state. Following previous empirical studies that have analyzed a substantial amount of US inventions, location of origin is identified at the state level for patents originating in the US (Almeida & Kogut, 1999; Jaffe et al., 1993). These non-home-base patents revealed 459 subsidiary locations at the level of country and state. Further breaking down patents originating in the US to individual states also implies a more strict definition of localized knowledge flows to intra-state citations (see Chapter 6 for a discussion).

In terms of the technological aspect, these patents covered 153 3-digit patent classes, which are used to determine the technological fields of MNEs (Yayavaram & Ahuja, 2008) (Note 1). The calculation of variables is based on both patent class information and location of origin. Moreover, these patents report 496,882 backward citations attributed to 137,691 cited utility patents in 341 patent classes, which are the basis to measure knowledge inflows, knowledge seeking and multilateral knowledge transfer.

Another data source specifically used for the identification of knowledge-creating subsidiaries is company annual reporting. Because IC design companies generate most of their profits from creating and exploiting IP, most publicly traded companies actively disclose their R&D sites, which may include R&D centers, design centers, engineering and product development activities, and field engineering and technology support offices among others. Information as such is useful to both investors and customers, who collaborate on product design with IC design companies and nearby subsidiaries. In addition, one of the 28 IC design MNEs, Agere, reported limited information about its subsidiary in the US. Excluding the state-level data of

Agere reduces the total sample size to 438, among which 187 are claimed in company annual reports as locations for knowledge creation.

7.5.1 Variables and measures

Knowledge creation and subsidiary-to-headquarters knowledge transfer. *Mandated subsidiary knowledge creation* is measured by the number of years a location is reported in company annual reports as hosting knowledge-creating activities between 2001 and 2008. It represents a visible recognition of knowledge-creating and contributory subsidiaries in specific locations (Bouquet & Birkinshaw, 2008; Frost et al., 2002). *SUB-to-HQ knowledge transfer* is a dummy variable that equals one when the headquarters makes intra-firm citations to patents originated in subsidiaries, indicating the transfer and integration of subsidiary knowledge into the headquarters (Frost & Zhou, 2005). Although the measurement of multilateral knowledge transfer may also be a count measure of the number of backward citations made by the headquarters to individual subsidiaries, the count variable is found over-dispersed and zero-inflated (Note 2). Following Frost and Zhou (2005), a dichotomized measure and binary variable regressions are employed in the second analysis.

Knowledge inflows from external and internal sources. Knowledge inflows to subsidiaries in a specific location are measured with backward citation information between 2001 and 2008. Citation records were categorized by local *external sources* and corporate *internal sources*, according to the assignee and inventor residence information of cited patents. Moreover, among a large variety of external sources, citations made to *advanced knowledge sources* and *other IC design MNE* are further identified and tested (see Chapter 6 for more details). On the other hand, internal sources are distinguished between the headquarters and other subsidiaries, noted by *HQ* and *Other SUBs*. Lastly, citation counts indicating knowledge inflows are rescaled by dividing by its total number of backward citations.

Heterarchical knowledge seeking and accumulation. *Specialized knowledge seeking* is a Herfindahl-type concentration index of subsidiary citation records in 341 3-digit cited patent classes. The variable equals the sum of squared ratios of citation count in each patent class to the total number of subsidiary citations between 2001 and 2008 (Garcia-Vega, 2006; also see Chapter 3). *Differentiated knowledge seeking* is derived as a dyadic measure from the citation profiles of subsidiaries and the headquarters. The variable equals one minus the correlation coefficient of the vector of subsidiary citation counts in 341 cited patent classes and that of the headquarters. Essentially, it measures the dissimilarity in knowledge-seeking behaviors of each subsidiary-headquarters pairs (Nooteboom, 2009; Nooteboom, Van Haverbeke, Duysters, Gilsing, & van den Oord, 2007). Finally, *heterarchical knowledge seeking* is the interaction between specialization and differentiation, which measures the extent to which subsidiary knowledge seeking is concentrated in technological fields less explored by the headquarters. *Specialized* and *differentiated knowledge accumulation* and *heterarchical knowledge accumulation* are calculated with essentially the same formulae from patenting records in 153 patent classes.

Intra-firm R&D collaboration. While the residence information of first inventors is usually prioritized in the attribution of patented inventions (Cantwell & Piscitello, 2002; Frost, 2001), co-inventions with inventors from multiple locations may reflect international activities, especially intra-MNE interactions (Bergek & Bruzelius, 2010). This research follows previous studies and measures and measures intra-firm R&D collaborations by co-inventions, or joint-patents, of inventors from both subsidiaries and the headquarters (see 2005). Moreover, this research further distinguishes between joint-patents led by first inventors in subsidiaries and those by first inventors in the headquarters. Dinstinguishing between these two types of intra-MNE collaborations leads to two measurements, *SUB-led* and *HQ-led R&D collaboration*. Following from the cross-level interdependency perspective, collaborations led by the headquarters suggest the headquarters-host-subsidiary interdependency; those led by subsidiaries suggest the subsidiary-host-headquarters interdependency. Both variables are resscaled accordingly. The former is divided by the total number of subsidiary patents and the latter by the total number of patents assigned to the MNE home base.

Control variables. *Knowledge exploitation* is the percentage of same class citations, which is the number of citations made to patents in the same three-digit patent classes divided by the total number of citations. This variable controls for the orientation of subsidiaries to conduct incremental knowledge creation within familiar technological fields (Frost, 2001). *SUB knowledge creation scale* is the total number of subsidiary patents, representing the scale of subsidiary R&D. *SUB knowledge creation time* is the year length between patent application for the first time and the latest time, suggesting the active time length of subsidiary knowledge creation. *MNE R&D centralization* equals the sum of squared ratios of the patent count for each location to the total number of patents assigned to the MNE between 2001 and 2008. The variable controls for the geographical concentration of MNE knowledge creation. *MNE absorptive capacity* is the average R&D intensity of MNE, and *MNE scale* is the average number of employees between 2001 and 2008. These variables control for the abilities, structure and scale of specific MNEs for global knowledge creation and integration. Furthermore, MNE and location fixed effects are included to control for other unobserved heterogeneities (see Note 3).

Entrepreneurial subsidiary knowledge creation. Preliminary testing with *mandated subsidiary knowledge creation* shows somewhat mixed results. Hence, an alternative patent data based measurement for subsidiary knowledge creation is also adopted. While the aforementioned archival measure is based on the explicit recognition and reporting of subsidiary knowledge-creating activities, *entrepreneurial subsidiary knowledge creation* is a count measure of subsidiary patenting in new technological fields. Blomkvist, Kappen and Zander (2010) suggest that subsidiary entry into new technological fields, in which the entire MNE had never patented previously, is related to subsidiary external embeddedness, combinative capabilities and utilization of the intra-MNE network for knowledge creation.

The variable is calculated by the number of pioneering patents by subsidiaries in 3-digit patent classes new to the entire MNE between 2001 and 2008. This measurement assumes that subsidiaries were able to fund R&D projects and file patents only with the support from the headquarters, and the relatively small scale of most IC design MNEs and subsidiaries suggests that the alternative is unlikely to be true.

7.5.2 Model specification

The analytic sample contains 438 locations, of which 187 show mandated knowledge creation and 147 appear entrepreneurial. Because both measures of knowledge creation are non-normal count variables, count data models are employed for the first regression analysis. The distribution properties of dependent variables are the main concerns in model specification. Count data models have been the standard approach in patent data based studies, because of the skewed and often over-dispersed distribution of patent and patent citation counts.

The traditional approach of conducting log-linear regression ignores the discrete nature and heteroskedasticity of count data and requires the adjustment of zero outcomes by adding a constant which actually introduces bias (Winkelmann, 2008). Poisson regression avoids these problems, but coefficient estimates are relatively inefficient when data is over-dispersed; in such cases, negative-binomial regression which models data dispersion is preferred (Cameron & Trivedi, 1998). Specifically, Models 1-4 based on mandated knowledge creation are estimated with negative-binomial regression, and Models 5-8 based on entrepreneurial knowledge creation with Poisson regression.

Moreover, exposure variables are included to control for the maximum count of each measurement. *MNE report frequency* is included in Models 1-4 to adjust for the number of years in which knowledge creation locations are disclosed in annual reports. For Models 5-8 based on entrepreneurial knowledge creation, *subsidiary knowledge creation scale*, or the largest possible number of pioneering patents, is included as the exposure variable.

7.6 Results and finding

Descriptive statistics are provided in Table 7.1. Firstly, correlation coefficients between *SUB knowledge creation scale* and several other variables are moderately high, which may cause the model estimation to suffer multicollinearity. It is, however, a critical control variable for subsidiary-level heterogeneity. With the variance inflation factor (VIF=5.04) at an acceptable level, the variable still is included as a control in Models 5-8. Robustness tests show mild changes in effect sizes and significance levels, but the results are similar. Secondly, it is surprising that the correlation between *mandated* and *entrepreneurial knowledge creation* is at a very low level, which questions the convergent validity of these two measurements of subsidiary knowledge creation. Implications of this disparity are discussed later. Thirdly, the low correlation between the two measures and *SUB-to-HQ knowledge transfer*—the outcome variables of the two empirical models—suggest their divergent validity. Lastly, both measurements of knowledge creation show over-dispersion as indicated by the inequality between mean and variance statistics. However, the dispersion parameter was significant only in models based on *mandated knowledge creation*, for which negative-binomial regression is appropriate.

Table 7.1 Descriptive statistics and correlation matrix

Variable	Mean	S.D.	Min	Max	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Mandated knowledge creation	2.45	3.89	0.00	33.00																	
2. Entrepreneurial knowledge creation	1.30	7.65	0.00	137.00	0.09																
3. SUB-to-HQ knowledge transfer	0.34	0.47	0.00	1.00	0.22	-0.03															
4. Local sources	0.05	0.09	0.00	0.80	0.15	0.18	0.09														
5. Internal sources	0.06	0.09	0.00	0.55	0.00	-0.03	0.32	-0.02													
6. Special. knowledge seeking	0.32	0.24	0.00	1.00	-0.29	-0.13	-0.28	-0.11	-0.04												
7. Diff. knowledge seeking	0.58	0.27	0.02	1.02	-0.19	0.01	-0.42	-0.03	-0.41	0.20											
8. Special. knowledge accumulation	0.53	0.34	0.06	1.00	-0.43	-0.18	-0.37	-0.18	-0.03	0.65	0.27										
9. Diff. knowledge accumulation	0.61	0.30	0.02	1.04	-0.18	-0.04	-0.41	-0.03	-0.37	0.11	0.74	0.25									
10. SUB knowledge creation time	4.91	4.68	0.00	32.00	0.37	0.02	0.43	0.24	0.16	-0.41	-0.29	-0.53	-0.26								
11. Knowledge exploitation	0.45	0.23	0.00	1.00	0.04	-0.04	0.02	0.06	-0.01	0.32	-0.07	0.01	-0.09	0.07							
12. MNE R&D centralization	0.47	0.17	0.19	0.85	-0.04	-0.12	0.18	-0.03	0.05	-0.05	-0.13	0.05	-0.16	-0.14	-0.07						
13. MNE absorptive capacity (log)	-1.53	0.39	-2.25	0.65	0.12	-0.09	-0.06	-0.04	-0.11	0.02	-0.06	-0.07	-0.05	0.11	-0.02	-0.08					
14. MNE scale (log)	7.83	0.91	5.59	9.19	-0.14	0.01	0.21	-0.07	0.13	-0.09	-0.11	-0.14	-0.19	0.10	-0.04	-0.03	-0.14				
15. MNE report frequency	7.48	1.21	3.00	8.00	0.10	-0.30	0.22	-0.17	0.18	-0.02	-0.10	0.00	-0.13	0.16	0.04	0.22	0.19	-0.02			
16. HQ-SUB R&D collaboration	0.37	0.89	0.00	11.00	-0.09	-0.06	0.09	-0.10	0.11	0.15	-0.07	0.15	-0.09	0.01	-0.08	0.11	-0.01	0.08	0.11		
17. SUB-HQ R&D collaboration	0.24	0.33	0.00	1.00	-0.12	-0.09	0.18	-0.07	0.16	0.07	-0.11	0.16	-0.15	-0.04	0.01	0.16	-0.05	0.13	0.22	0.33	
18. SUB knowledge creation scale (log)	1.83	1.53	0.00	6.20	0.51	0.26	0.52	0.27	0.16	-0.56	-0.42	-0.81	-0.40	0.60	0.07	-0.02	0.05	0.18	0.04	-0.12	-0.10

Note: 1. N=438; 2. Mean VIF=1.90; 3. Max VIF=5.04.

Table 7.2 Count data regressions on subsidiary knowledge creation

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Subsidiary knowledge creation	Mandated knowledge creation				Entrepreneurial knowledge creation			
Local sources (H1)	-1.089 (1.258)	-0.759 (1.226)	-0.929 (1.248)		1.62 (1.031)	1.31 (0.951)	1.385 (1.005)	
Advanced knowledge sources				-37.632 (19.912)*				21.805 (8.267)***
Other IC design MNEs				-8.348 (3.431)**				-0.71 (2.611)
Internal sources (H2)	2.685 (1.154)**	2.359 (0.959)**	2.865 (1.046)***		-1.727 (1.748)	-1.696 (1.657)	-1.318 (1.839)	
HQ				2.728 (1.353)**				-2.256 (2.562)
Other SUBs				3.238 (1.585)**				2.24 (4.03)
Heterarchical structure (H3)								
Special. knowledge seeking	-2.029 (1.188)*		-0.59 (1.164)	-0.796 (1.204)	-8.684 (2.751)***		-4.228 (2.869)	-4.184 (2.746)
Diff. knowledge seeking	-0.091 (0.515)		0.134 (0.602)	0.01 (0.598)	-0.723 (0.624)		-1.564 (0.802)*	-1.64 (0.807)**
Heter. knowledge seeking[1]	2.505 (1.492)*		1.765 (1.528)	2.06 (1.57)	9.566 (3.005)***		4.571 (3.316)	4.723 (3.234)
Special. knowledge accumulation		-2.706 (0.753)***	-2.639 (0.793)***	-2.478 (0.778)***		-7.82 (1.881)***	-6.873 (2.243)***	-6.637 (2.228)***
Diff. knowledge accumulation		-0.735 (0.46)	-0.856 (0.555)	-0.903 (0.556)		-0.429 (0.593)	0.386 (0.727)	0.657 (0.769)
Heter. knowledge accumulation[1]		1.9 (0.896)**	1.42 (0.969)	1.268 (0.947)		8.375 (2.041)***	7.421 (2.372)***	7.012 (2.369)***
Control variables								
Knowledge exploitation	-0.101 (0.368)	-0.092 (0.363)	-0.243 (0.355)	-0.173 (0.36)	-0.394 (0.54)	-0.201 (0.454)	-0.405 (0.504)	-0.506 (0.503)
SUB knowledge creation time	0.041 (0.021)*	0.028 (0.021)	0.038 (0.022)*	0.039 (0.022)*	0.004 (0.021)	0.019 (0.019)	0.023 (0.019)	0.032 (0.019)*
SUB knowledge creation scale (log)	0.574 (0.072)***	0.373 (0.079)***	0.371 (0.08)***	0.392 (0.079)***	Exposure variable (original value, coefficient fixed at 1)			
MNE R&D centralization	6.313 (2.272)***	5.862 (2.299)**	6.732 (2.218)***	6.371 (2.174)***	-1.365 (2.15)	-1.23 (2.066)	-1.598 (2.093)	-0.425 (2.208)
MNE absorptive capacity (log)	-0.732 (0.969)	-0.861 (0.995)	-0.684 (0.942)	-1.02 (0.94)	-1.121 (0.833)	-1.172 (0.756)	-1.568 (0.824)*	-1.733 (0.814)**
MNE scale (log)	-2.625 (0.552)***	-2.609 (0.56)***	-2.623 (0.541)***	-2.569 (0.54)***	-1.311 (0.804)	-1.294 (0.785)*	-1.564 (0.834)*	-1.821 (0.846)**
MNE report frequency	Exposure variable (coefficient fixed at 1)							
MNE fixed-effects	Included				Included			
Location fixed-effects	Included				Included			
Dispersion parameter	0.549 (0.119)***	0.541 (0.112)***	0.502 (0.114)***	0.468 (0.107)***				
Log pseudo-likelihood	-630.451	-624.622	-622.212	-618.659	-301.879	-289.905	-287.604	-285.455
Pseudo R^2	0.231	0.238	0.241	0.246	0.670	0.683	0.686	0.688
AIC	1480.901	1469.244	1470.424	1467.319	815.759	791.811	793.208	792.910

Note: 1. *Heterarchical knowledge seeking (accumulation)* is the interaction term of *specialized knowledge seeking (accumulation)* and *differentiated knowledge seeking (accumulation)*; 2. N=438; 3. Models 1-4 are based on negative-binomial regressions and Models 5-8 on Poisson regression; 4. Robust standard errors are in parenthesis; 5. *** p-value < 0.01; ** p-value < 0.05; * p-value <0.1; 6. The baseline model for the entrepreneurial mandate with control variables, exposure variable and fixed-effects has a Pseudo R^2 of 0.596.

7.6.1 Hypothesis testing for subsidiary knowledge creation

Table 7.2 provides the test results of Models 1-4 based on *mandated knowledge creation*, and Models 5-8 based on *entrepreneurial knowledge creation*. Test results vary between models based on the two measurements. Although there is no direct support for hypothesis 1 on the importance of local external knowledge sources for subsidiary knowledge creation, significant effects are found in knowledge inflows from specific categories of external knowledge sources as shown by Models 7 and 8. In terms of *mandated knowledge creation*, knowledge inflows from advanced knowledge sources and other IC design MNEs have negative impacts on the frequency that a specific location is identified in annual reports. This interesting finding may imply a certain level of isolation between the knowledge bases of mandated locations and main competitors and specific knowledge sources. Regarding *entrepreneurial knowledge creation*, knowledge inflows from advanced knowledge sources show strong positive effects on the number of pioneering patents observed in specific locations. This finding is in line with previous studies in R&D internationalization but casts doubt on knowledge evolutionary literature, which generally advocates the importance of knowledge-creating mandate.

The coefficient estimates of *internal sources* are positive and significant in Models 1-3 based on *mandated knowledge creation*, providing clear support for hypothesis 2 on knowledge inflows from other members in the MNE corporate network. Separate effects of inflows from the headquarters and other subsidiaries are both significant in Model 4 with different effect sizes. This finding generally confirms previous studies on the relation between subsidiaries and internal networks. However, coefficient estimates in Models 5-7 based on *entrepreneurial mandate*, particularly the effect associated with the headquarters, suggest a different finding. In other words, although support from the headquarters is necessary for subsidiary R&D, knowledge inflows from the headquarters are found to be irrelevant to subsidiary patenting in new technological fields.

Regarding hypotheses on the heterarchical structure, coefficient estimates on *heterarchical knowledge seeking* are generally positive and weakly significant throughout different model specifications using different measurements of subsidiary knowledge creation. This result provides weak support for hypothesis 3a on the importance of heterarchical knowledge-seeking on knowledge creation at the subsidiary level. On the other hand, hypothesis 3b, which concerns the impact of *heterarchical knowledge accumulation*, has moderate support in Models 1-4 and strong support in Models 6-8 based on different measurement of subsidiary knowledge creation.

Moreover, the negative and significant findings on *specialized knowledge accumulation* in various model specifications suggest that over-specialization may not assist subsidiaries in gaining visible recognition or generating pioneering inventions. Regarding the two differentiation measures, a weakly negative effect of *differentiated knowledge seeking* is found in models based on *entrepreneurial knowledge creation*. This might imply a mild alignment between the knowledge seeking orientations of entrepreneurial subsidiaries and the headquarters, but further examination of the estimated marginal effect of *differentiated knowledge seeking*, which takes into account the interaction term, shows an even weaker association. Instead, the estimated marginal effect of *differentiated knowledge accumulation* is negative and highly significant.

Lastly, the positive and significant coefficient estimates of *SUB knowledge creation time* and *SUB knowledge creation scale* confirm with patenting records the validity of *mandated knowledge creation* as an archival measurement. Besides these subsidiary-level control variables, the coefficient estimates of two MNE-level control variables stand out. *MNE R&D centralization* shows positive and highly significant effects on *mandate knowledge creation*, while *MNE scale* is negative and significant. This finding suggests that these MNEs may have used mandating as a mechanism to integrate and coordinate subsidiary knowledge creation.

However, a larger firm scale, which increases information processing costs, seems to discourage mandating.

Table 7.3 Probit regressions on SUB-to-HQ knowledge transfer

	Model 9	Model 10	Model 11	Model 12
	Sub-to-HQ knowledge transfer			
	(SUB is cited by all HQ patents)		(SUB is cited by HQ solo patents)	
SUB knowledge creation (H4)				
Mandated knowledge creation (rescaled)	0.624 (0.209)***	1.268 (0.278)***	0.634 (0.213)***	1.767 (0.351)***
Entrepreneurial know. creation (rescaled)	-0.388 (0.671)	0.669 (0.584)	-0.17 (0.667)	0.958 (0.652)
SUB-HQ cognitive gap (H5)				
Differentiated knowledge seeking	-1.893 (0.458)***	-2.631 (0.585)***	-1.7 (0.457)***	-2.404 (0.648)***
Differentiated knowledge accumulation	-0.706 (0.412)*	-0.21 (0.496)	-0.686 (0.413)*	-0.27 (0.529)
Intra-firm R&D collaboration (H6)				
HQ-SUB R&D collaboration	-0.048 (0.098)	-0.114 (0.103)	-0.008 (0.097)	-0.055 (0.1)
SUB-HQ R&D collaboration	0.754 (0.275)***	0.623 (0.298)**	0.537 (0.277)*	0.377 (0.315)
Control variables				
MNE R&D centralization	2.047 (0.523)***		2.124 (0.523)***	
MNE absorptive capacity (log)	-0.358 (0.217)*		-0.374 (0.219)*	
MNE scale (log)	0.446 (0.1)***		0.431 (0.099)***	
MNE fixed-effects		Included		Included
Location fixed-effects	Included	Included	Included	Included
Log pseudo-likelihood	-162.554	-128.728	-155.735	-111.085
Pseudo R^2	0.420	0.541	0.419	0.586
AIC	491.107	377.457	385.469	314.170
Correctly classified	81.28%	84.25%	81.74%	87.90%

Note: 1. N=438; 2. Robust standard errors are in parenthesis; 3. *** p-value < 0.01; ** p-value < 0.05; * p-value <0.1.

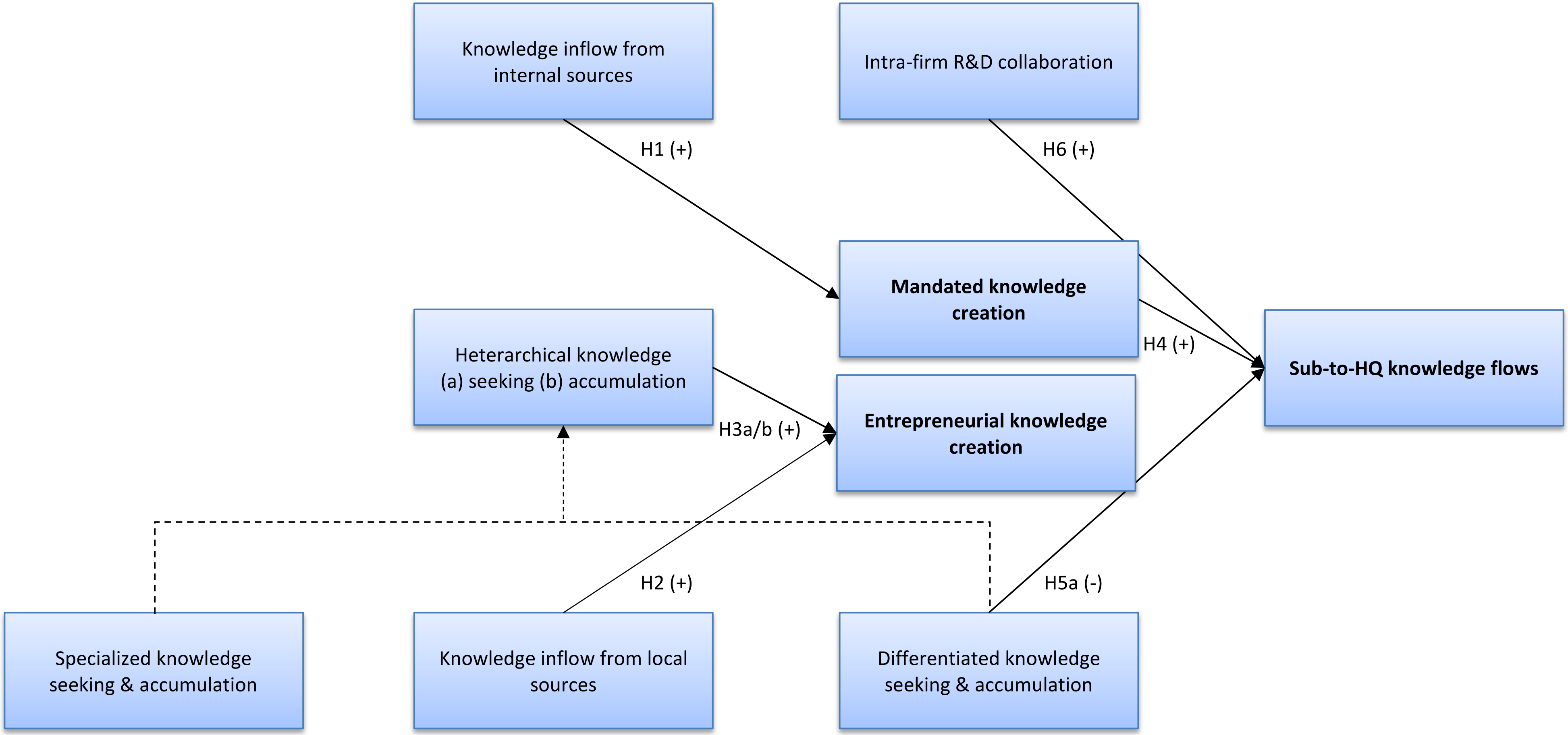
Hypothesis 4 argues that subsidiary knowledge creation relates positively to multilateral knowledge transfer from subsidiaries to the headquarters, which integrates subsidiary knowledge into the knowledge repertoire of MNE. Interestingly, positive and significant results are found only with *mandated knowledge creation*, regardless of the measurements of *SUB-to-HQ knowledge transfer* and model specifications. On the contrary, *entrepreneurial mandate*, which is an indicator of pioneering knowledge creation, is found unrelated to the knowledge transfer.

Hypothesis 5a, which suggests a negative impact of the cognitive gap between subsidiaries and the headquarters on dyadic knowledge transfer, is supported by the highly significant coefficient estimates of *differentiated knowledge seeking* throughout different model specifications. However, hypothesis 5b, which suggests a negative effect of divergent knowledge bases on multilateral transfer, is not supported by the insignificant coefficient estimates of *differentiated knowledge accumulation*. While Yang, Mudambi and Meyer (2008) also find no support for the independent effect of knowledge base difference, the finding of this research highlights how differentiated orientation of subsidiary knowledge seeking may negatively impact the knowledge transfer and integration of MNE.

Lastly, hypothesis 6, which suggests the positive association between intra-firm R&D collaboration and multilateral knowledge transfer, is moderately supported by the significant effect of *SUB-HQ R&D collaboration* in Models 9-11. Collaborations led by subsidiaries significantly increase the likelihood that subsidiary patents are cited by patents assigned to the headquarters. However, the results are less clear in Models 11 and 12 based on patents solely by headquarter inventors. On the other hand, the coefficient estimates of HQ-SUB R&D collaboration are generally insignificant.

Notably, the empirical analysis by Frost and Zhou (2005) does not distinguish between joint-patents led by subsidiaries or by the headquarters, and headquarters' patents with subsidiary co-inventors are included. The somewhat mixed findings in this research suggest that the choice of patent metrics may affect test results and conclusions of other similar studies. In terms of theory implications, the different scenarios of intra-firm R&D collaborations, led by subsidiaries or the headquarters, can have different effects on intra-firm knowledge transfer and require future studies. Figure 7.2 summarizes the test results of all hypotheses.

Figure 7.2 Summary of test results



Notes: 1. Dotted lines specify interaction terms. 2. Control variables are not included.

7.7 Discussion

The IB literature has long discussed the importance of balancing between local external and intra-firm connections (Andersson & Forsgren, 1996). Andersson and Forsgren (1996) analyze subsidiary business relationships and argue that external embeddedness may counteract hierarchical control from the headquarters. Frost (1998) discusses the balance between internal and external sources of innovation, and Pearce (1999b) emphasizes the capability of subsidiaries to understand and implement their positions in both MNE and local technological communities. In other words, the discussion on embeddedness in the IB field essentially concerns interdependencies and knowledge flows between subsidiaries and external and internal knowledge sources. Subsidiaries may develop their own knowledge bases and perspectives through interactions with external knowledge sources, but in the meanwhile, an intra-firm cognitive gap may grow and gradually hinder intra-firm communication, increasing the difficulty of balancing between external and internal embeddedness.

7.7.1 The hierarchical structure and cognitive gap

Although this thesis on multilateral knowledge transfer mainly considers the viewpoint of subsidiaries, other studies have highlighted the divergent perspectives and information asymmetry between subsidiaries and the headquarters (Argyres & Silverman, 2004; Asakawa, 2001; Björkman et al., 2004; Verbeke & Yuan, 2005). From the viewpoint of the MNE, subsidiary evolution and knowledge creation brings the challenge to manage and coordinate a network of differentiated and externally embedded subsidiaries (Björkman et al., 2004; Rugman & Verbeke, 2003). Researchers have had concerns about the cognitive gap between subsidiaries and the headquarters. The headquarters can act inadvertently with limited knowledge (Ciabuschi et al., 2011), become suspicious of subsidiary entrepreneurship and impose hierarchical control (Ambos et al., 2010). Executives in the headquarters have limited and unbalanced attention to subsidiaries (Bouquet & Birkinshaw, 2008), and therefore accepting subsidiary initiatives often requires reformulating corporate objectives and excluding other initiatives (Verbeke & Greidanus, 2009).

The heterarchical structure is, therefore, crucial because it encourages deliberate learning and unique perspectives at the subsidiary level. The structure allows subsidiaries to appreciate and draw upon ideas neglected by the headquarters. While companies in knowledge-intensive industries can be vulnerable to unspotted external technological discontinuities (Di Minin & Bianchi, 2011), a heterarchical structure may lower the risk of neglecting knowledge and ideas available from external knowledge sources.

Meanwhile, other researchers have pointed out that knowledge creation at the headquarters level is aimed at wider applicability and longer-term impacts and less bounded by specific views and time constraints (Argyres & Silverman, 2004). In other words, headquarters knowledge seeking and accumulation is based on a global perspective relative to the local perspective of subsidiaries (Argyres & Silverman, 2004; Verbeke & Yuan, 2005). Subsidiary perspective can be either valuable or problematic, depending on whether entrepreneurial knowledge creation generates unique and valuable knowledge-based assets or managerial challenges to the MNE organization. In the case of IC design MNE, it also implies meaningless and R&D expenditures at the subsidiary level, such as the payroll of R&D staff, office space, EDA software license fees, travel budgets, IP legal fees, the additional costs to train foreign employees and the risk of knowledge dissipation. Through multilateral knowledge transfer, heterarchy may justify additional investments in subsidiary knowledge creation and MNE internal communication.

7.7.2 Incidental interdependencies

Multilateral knowledge transfer can be the critical integrative mechanism to incorporate and leverage different perspectives co-existing in a heterarchical MNE. Paradoxically, it can also buttress subsidiary perspective, because extensive internal knowledge flows can ultimately bring together separate knowledge bases and re-align divergent views. Subsidiaries may become incapable of spotting emerging external technologies and foreign market demand and fail to inform the headquarters of these changes (Buckley Carter 2004). As a result, subsidiaries become less receptive to external creativity and no longer entrepreneurial. The underlying issue here is, therefore, again, how to balance these concerns?

Based on the patenting records of IC design MNEs, the empirical findings of this chapter suggest that intra-firm R&D collaborations between subsidiaries and the headquarters can be a feasible strategy to balance between external and internal interdependencies and knowledge flows. These intra-firm R&D collaborations between the headquarters and knowledge-creating subsidiaries can generate moderate coupling (Yayavaram & Ahuja, 2008) between geographically-dispersed knowledge-based assets.

Considering that most R&D and patenting requires support from the headquarters, the flexible use of intra-firm R&D collaborations also implies that the headquarters retains the decision-making power to add temporarily internal connections, partially reconfigure R&D and implement internal entrepreneurship, and otherwise leave individual subsidiaries to specialize. In a sense, these collaborations establish *incidental interdependencies* between members of the MNE corporate network. Such incidental interdependencies do not alter the evolution of individual subsidiaries, impair their interdependencies with external knowledge sources nor affect external embeddedness in the host country environment. These temporary collaborations may preserve internal diversity and cause a little increase in overall information costs because subsidiaries are distracted only occasionally when the headquarters find it worthwhile to do so.

7.7.3 Asymmetric intra-firm R&D collaboration

Moreover, a unique finding of this chapter emerges from the different impacts of two models of R&D collaborations that are led by subsidiaries and the headquarters. Previous studies suggest that intra-firm collaborative technological activities revealed through patenting records facilitate knowledge sharing, collaboration experience, knowledge networks, technological trajectory and social capital (Bergek & Bruzelius, 2010; Frost & Zhou, 2005; Nerkar & Paruchuri, 2005). However, as the test results suggest, different scenarios of collaboration can have different goals and implications. For instance, R&D collaborations led by the headquarters may be aimed at conventional knowledge transfer and hierarchical control over subsidiary knowledge creation. On the other hand, the finding that subsidiary-led collaborations are positively associated with subsidiary-to-headquarters knowledge transfer may suggest the potential for subsidiary knowledge creation to contribute to the MNE knowledge repertoire.

7.8 Conclusion and limitation

This chapter contributes to the ongoing discussion on MNE knowledge creation and integration. From subsidiary knowledge creation to transfer and integration into knowledge creation at the headquarters level, the dynamics and managerial implications of multilateral knowledge transfer are empirically examined with the patenting and citation records of 28 IC design MNEs. Although the R&D internationalization and the subsidiary evolution literature generally agree on the importance of external knowledge sources and the heterarchical structure, empirical findings in this chapter suggest that both lines of discussion have presented a partial view of the phenomenon. One on hand, the attempts to leverage external creativity and diversity, as advocated in the international R&D research, can be counteracted by internal organizational challenges of MNEs, as accentuated in the subsidiary evolution literature. On the other hand, the real effect of explicitly recognizing and mandating subsidiary knowledge creation, as recommended in the subsidiary evolution literature, can be viewed as reinforcing the existing knowledge repertoire of the MNE, instead of the invention of explorative and path-breaking intellectual works, as envisioned in the international R&D literature.

In the particular case of pioneering patenting, test results reveal that entrepreneurial subsidiaries rely less on the MNE home base but tend to acquire knowledge from advanced external knowledge sources. Their knowledge is, however, less utilized by the headquarters. In fact, these entrepreneurial subsidiaries are generally less engaged in corporate internal networks and knowledge flows. On the contrary, mandated subsidiaries with an explicitly acknowledged knowledge-creating role are often deeply embedded in the corporate network and integrated into internal flows of knowledge. Recognition and mandate versus entrepreneurship and serendipity—these reflect the different attitudes of the two lines of thinking. While subsidiary evolution research reflects the managerial issues of internal resources and relationships, international R&D proponents maintain the call for attention to the opportunities from external resources creativities. While both views are integral to the IB literature, it is indeed the combination of both, and the simultaneous consideration of the different perspectives of subsidiaries and headquarters, that merit the pursuit of multinationality.

Lastly, one important limitation is the potential simultaneousity between knowledge bases within the MNE. Given the relatively short time window and smaller size of most IC design MNEs, the analysis of inter-firm knowledge flows excludes the coevolution of external and internal knowledge bases. In other words, the nature of knowledge bases outside the firm boundary could be considered as exogenous at least in the short term. However, the same assumption may not apply in the analysis of intra-firm knowledge flows, because a subsidiary knowledge base is essentially a subset of the MNE knowledge repertoire. While, the intra-firm flows of knowledge can change the nature and relationship between knowledge bases within the firm, the empirical analysis in this chapter control for this potential simultaneousity by including a list of control variables at both the MNE and subsidiary level.

Appendix to Chapter 7

Notes

1. Instead of empirically restricting the study to a shorter list of patent classes (Ganco, 2013; Rosenkopf & Almeida, 2003; Yayavaram & Ahuja, 2008), all patent classes covered by cited and created patents are incorporated in the analysis. This all-embracing approach ensures the coverage of diverse technological activities of IC design companies, as a result of their flexible and customized product designs. Several companies were also involved in manufacturing process R&D.
2. Multilateral transfer from subsidiaries to headquarters is only observed in around one-third of the sample, and the frequency distribution of citation counts is dispersed between zero and hundreds.
3. Ideally, the model should control for the cultural and institutional distances between subsidiaries and the headquarters, which may cause misinterpretation of critical information and difficulties in assimilating knowledge (Dellestrand & Kappen, 2012; Gaur & Lu, 2007). However, the dataset is constructed at the state level for location in the US, and there are no equivalent state-level variables for these country-level factors.
4. The use of terminology in knowledge seeking and knowledge accumulation reflects the concepts of flow and stock, respectively.

8 DISCUSSION AND IMPLICATION

"Design is a technical profession with a marketing function."

—Knut Yran, Norwegian designer
(quoted in Design since 1945 by Peter Dormer, 1993)

8.1 Introduction

Relative to semiconductor companies with internal manufacturing facilities, IC design companies took a different route and adopted the fabless model, which relinquishes the ownership of fabrication plants and becomes agiler and more responsive to the demand of customers worldwide. These companies work closely with their clients and provide customized product offering according to specific demands. Their international R&D centers also access foreign sources of technological expertise with geographical proximity. This explains both how and why IC design MNEs have internationalized and decentralized knowledge creation to a greater extent than companies with internal manufacturing and assembly facilities have done. These facilities and physical assets demand hefty capital investments in locations with advanced infrastructure, and as a result the operations are agglomerated and bounded locally to benefit from internal coordination of manufacturing.

In Chapter 6, the analysis of patenting and citation records reveals the R&D internationalization of these IC design MNEs. Empirical evidence suggests that external knowledge inflows into the IC design industry are subject to geographical, technological and industrial factors. In Chapter 7, the analysis of subsidiary knowledge creation confirms some of the arguments proposed previously. The interdependencies and knowledge flows between subsidiaries, the headquarters and the host country environment influence multilateral knowledge transfer. These findings from the IC design industry in the early 21st century confirm the known challenge for MNEs to balance between external networks in specific host countries and MNE internal corporate networks across countries. In other words, despite the geographical and technological flexibilities of the asset-lite fabless business models, these 28 IC design MNEs have demonstrated a pattern of multilateral knowledge transfer one would have anticipated in most other industries.

This chapter briefly discusses the findings of this thesis and responds to the research questions proposed in Chapter 2. The following section summarizes the four research questions and empirical findings of this thesis. Theory implications for the IB literature and policy implications are discussed in the third and fourth section.

8.2 Findings of this thesis

Findings from the IC design industry raise some of the most fundamental issues in the IB field, specifically the coordination of geographically-dispersed knowledge-creating activities. MNEs may achieve greater efficiency in global knowledge creation, seeking and accumulation through the coordination of geographically-separated and individually-specialized subunits (Grant, 1996; Pearce, 1999b; Srikanth & Puranam, 2014). However, increasing the degree of intra-firm specialization and differentiation at the subsidiary level makes intra-firm collaboration more rewarding and yet more challenging (Kretschmer & Puranam, 2008). MNEs need to evaluate whether the potential benefits are indeed worth the additional managerial and organizational costs. Existing studies on the semiconductor industry, often in the context of firm vertical boundary studies, are much less concerned with these issues (e.g. Leiblein et al., 2002; Macher & Mowery, 2004; Monteverde, 1995).

This thesis synthesizes the international R&D literature and subsidiary evolution literature and proposes the cross-level interdependency perspective, which incorporates the heterarchical structure and multilateral knowledge transfer. The IC design industry provides ideal samples for testing these concepts and developing improved understanding of both theory and practice. The internationalization of the IC design industry results in a complex pattern of global knowledge creation; the clear focus on knowledge-based assets is reflected in the emphasis on patents, IC designs, algorithms, and specialized design expertise. This study provides both insights of the modern semiconductor industry and a better understanding of a group of knowledge-intensive and entrepreneurial MNEs in the early 21st century.

By reviewing the theory debates on multilateral knowledge transfer and the limitations of existing studies on the semiconductor industry, this thesis proposes four research questions for the empirical analysis of the cross-level interdependency perspective and the investigation of a knowledge-intensive and design-intensive new industry. To begin with the background of knowledge creation in the IC design industry, the first and second research questions of this thesis intend to identify and analyze the knowledge sources of the industry. Based on this knowledge, the third and fourth research questions proceed to evaluate the impacts of the heterarchical structure and cross-level interdependencies on knowledge creation and multilateral knowledge transfer. Specifically, these questions are:

Research question 1: *what are the sources of technological knowledge flows? The question intends to identify and analyze external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

Research question 2: *what are the intensities of technological knowledge flows? The question intends to analyze and compare the intensities of knowledge flows from external (host country environment) and internal (the headquarters and other subsidiaries) knowledge sources of the IC design MNEs.*

Research question 3: *what are the impacts of the heterarchical structure and cross-level interdependencies on subsidiary knowledge seeking and creation? The question intends to analyze their impacts on the creation of subsidiary knowledge.*

Research question 4: *what are the impacts of cross-level interdependencies on the multilateral transfer of technological knowledge? The question intends to analyze their impacts on the transfer and integration of subsidiary knowledge.*

8.2.1 Findings about knowledge inflows

The following discussion briefly summarizes the replies to these questions. The first and second research questions ask *what are the sources and intensities of technological knowledge flows.* The analysis of patenting and citation records reveals the diverse external knowledge sources of the 28 IC design MNEs beyond the Western countries and the semiconductor industry. The geographical distribution of these sources covers most of the technologically advanced OECD countries, which are the traditional leaders of physical science and technology. The United Kingdom, Germany and France top the list as the knowledge sources in Western Europe. Canada and the United States in the North America are home to most of the companies in the sample. Western countries have remained the main source of technology even as newly-industrialized economies in East Asia joined the picture in the 1980s. Within Asia, Japan, South Korea and Taiwan in East Asia and several countries in Southeast Asia also become the knowledge sources of more recently invented technologies

Subsequently, the industrial distribution of knowledge sources is revealed by manually identifying the original assignees of cited patents. A manual identification process attributed 90.67% of cited patents to original assignees, which were grouped in 39 industry categories. These industry categories covered other sub-industries of the overall semiconductor industry and various user industries of IC products, such as the IT and communication industries. That almost three-quarters of the citations went to patents originating in these industries empirically confirms their close relationship with the IC design business. Where citation count statistics become less telling are several categories that are traditionally considered as advanced knowledge sources. These categories include patenting entities in the aerospace and defense industries, governmental organizations, universities, public and private laboratories, consortiums, instrument producers and supercomputing companies. Conglomerates and other highly diversified business groups also created a sizable amount of technological knowledge, which is subsequently utilized by the IC design companies. These giant conglomerates, which have had sufficient scale, budget and technological base, have pioneered and continued to developed advanced semiconductor technologies.

Time efficiency is another interesting aspect of knowledge flows uniquely addressed in this research. It was found that the velocity of knowledge inflows into these IC design MNEs appear to vary by specific sources. Across industry categories, the filing year gap between the citing and cited patents suggests that knowledge inflows from more relevant sources achieve higher velocities. Between competing IC design MNEs, market leaders seem to draw upon new technologies sooner. Besides inter-firm knowledge flows, year gaps among headquarters-to-subsidiary and inter-subsidiaries citations are shorter. That intra-firm knowledge flows in different directions may reach different velocities has implications for the dynamics within MNEs. Lastly, citation records also show citations made to older technologies, which imply the value and continuous relevance of specific technologies.

8.2.2 Findings about subsidiary knowledge creation

Subsequently, the third and fourth research questions ask *what are the impacts of the heterarchical structure and cross-level interdependencies on subsidiary knowledge seeking and creation and multilateral flows of technological knowledge*. Although knowledge creation at the headquarters level remains central to most IC design MNEs, subsidiary-level knowledge seeking and creation is observed in both annual reporting and patenting records. Company annual reports and composite patent metrics are incorporated in a further examination of intra-firm knowledge flows. The empirical findings, however, vary between mandated knowledge creation and entrepreneurial knowledge creation, which are based on company annual reporting and patenting records, respectively.

In brief, mandated knowledge creation—locations for knowledge-creating activities according to annual reports—is found closely associated with internal knowledge flows; meanwhile, entrepreneurial knowledge creation—locations of pioneering patenting according to patent class information—is found to benefit from external knowledge inflows. Interestingly, the two types of knowledge creation rely on either internal or external knowledge sources. Instead of simultaneously using internal and external knowledge sources, mandated knowledge creation deeply embeds in the internal corporate network and knowledge flows and actually avoids external sources. Meanwhile, entrepreneurial knowledge creation benefits from advanced external knowledge sources, but knowledge inflows from internal sources seem less relevant.

This interesting finding challenges the existing literature in two ways. Firstly, the definition of knowledge creation is actually unclear: it varies among scholars and practitioners. In the IB literature, the two lines of thinking are really talking about two different types of knowledge creation. Research on R&D internationalization follows the Schumpeterian tradition, highlighting the exploration of external knowledge sources and the potential for ground-breaking inventions. Research on subsidiary evolution considers the organizational issues of MNEs, accentuating the interdependencies between members of corporate internal networks and the importance of intra-firm knowledge sharing. Emphasis on the internal network does not prohibit knowledge exploration, but strong intra-firm interdependencies and embeddedness in internal knowledge flows naturally encourage inward-looking knowledge creation. These different emphases of two lines of thinking led to the difference among scholars in the theorization and vision for subsidiary knowledge creation.

Beyond the scholarly discussion, this difference can, however, become genuinely worrying when researchers intend to engage with practitioners. The empirical findings of this thesis suggest that the subsidiary knowledge creation found in the narratives of company annual reports is likely the inward-looking type. In this corporate account of business activities in a given year, the company explicates its internal division of R&D labor and locations of knowledge-creating activities. The statement implies the importance of recognition and assignment from the headquarters for subsidiaries in specific locations to perform knowledge-creating activities. Instead, the type of subsidiary knowledge creation advocated in the literature is mostly outward-looking, spontaneous and entrepreneurial. In other words, there is a discrepancy between researchers and practitioners regarding their definition and vision for subsidiary knowledge creation.

This disparity reflects the disconnection between academia and real-world business. It also provides a very realistic answer to the impact of the headquarters on subsidiary knowledge creation. From the viewpoint of the MNE headquarters, knowledge creation at the subsidiary level should have specific goals and close alignment with the interests of the headquarters and the overall MNE group. Essentially, both subsidiary-level knowledge creation and headquarters-level knowledge creation are industrial R&D, which intends to solve specific problems and technological challenges faced by the firm. Instead, exploratory R&D in new technological fields is of unknown risk and profitability. It is unlikely that the headquarters would assign such tasks to foreign subsidiaries, which are more difficult to coordinate and communicate, and skip the R&D unit in the home base.

Secondly, the proposition of dual- and multiple-embeddedness in the existing literature is challenged. Regardless of the type of knowledge creation, this thesis finds no support for the proposition that subsidiaries simultaneously embed in the local external network and the corporate internal network. In fact, both types of knowledge-creating subsidiaries access knowledge from only one network while avoiding the other. This may imply that the challenge to balance between external and internal knowledge sources is greater than previously believed. The idea of cross-level interdependencies does not seem to reconcile well with the business reality observed from IC design MNEs.

There can be an alternative explanation, which again emphasizes the impact of the headquarters on subsidiary knowledge creation. It has been suggested previously that the headquarters may decide and assign the specific type of knowledge creation to be pursued at the subsidiary level. It is likely that the interdependency to be encouraged has been decided simultaneously. The headquarters may commit resources for subsidiary knowledge creation. Similarly, the headquarters may provide resources for subsidiaries to build interdependencies with and seek knowledge from specific knowledge sources. In other words, subsidiary knowledge seeking and accumulation are actually formulated in line with the goals for subsidiary knowledge creation. If the goal were to enter technological fields new to the MNE, subsidiaries would be encouraged to develop the interdependency with external knowledge sources, which have developed related expertise in those fields. Instead, if the goal were to cultivate the firm-specific knowledge repertoire further, the headquarters would naturally prioritize and strengthen the internal interdependencies between subsidiaries and the headquarters.

In brief, the empirical findings of this thesis indicate both the potential value and the impossibility of the proposition of dual- and multiple-embeddedness. Extensive external interdependency improves the absorption of external knowledge-based assets, which fuel entrepreneurial knowledge creation. Strong internal interdependencies develop the contributory role of knowledge-creating subsidiaries but curb exploratory knowledge creation. However, MNEs do need both incremental knowledge creation to enhance competitiveness and entrepreneurial knowledge creation to survive environmental changes.

Internal international R&D collaboration appears to be a feasible solution. Given the low correlation between internal R&D collaboration and both types of knowledge creation, there is no indication that the incidences of such collaboration are concentrated in entrepreneurial knowledge (see Table 7.1). However, there is indeed empirical evidence for a positive impact on the knowledge transfer from subsidiaries to the headquarters, especially when the collaboration is led by subsidiaries. This thesis argues that such collaboration establish incidental interdependency between members of the MNE corporate network. Because such collaboration increases internal interdependencies only temporarily, it avoids altering the specialization and differentiation of individual members and protects their interdependencies with external knowledge sources.

8.2.3 Implications for the global semiconductor industry

The knowledge developed in this thesis improves the current understanding of the IC design industry, which also contains several implications for policy makers. The observation that IC design MNEs coordinate global knowledge creation and administrate multilateral knowledge transfer is a clear departure from the technological view commonly held in existing studies. This view based on technical modularity suggests that interdependencies and interfaces between activities decide the convergence of activities and the division of labor within different organizations (Ernst, 2005c). In other words, the emergence of specialized IC design companies is mainly based on the technological feasibility to finely slice the semiconductor value chain and contract for related productive activities.

This technological view, however, disregards the international distribution of expertise and demand and neglects the capabilities of MNEs to link different activities and leverage location-bound factors. In the case of the semiconductor industry, universities and research centers in the US create new design techniques, design software and chip architectures while educating young engineering talents (Macher & Mowery, 2004). The US and Western European countries have deep knowledge in industrial standards and specification-making, and Japanese companies have aggressively pursued material science (Chang & Tsai, 2002). In China, electronics manufacturing service companies have generated enormous local demand for IC products (Fuller, 2014). More recently, software engineers in India have been valued for their software expertise, which is increasing important for semiconductor companies to develop complementary software in parallel with IC products (Brown et al., 2005).

Case studies in this research show that most IC design companies initiated R&D internationalization soon after founding (see Chapter 5). In principle, R&D sites can be located in proximity to foreign knowledge sources, but geographical distances can increase the costs of inter-unit communication and coordination (Casson, Pearce, & Singh, 1992). Therefore, effective R&D internalization demands both the creative potential of international locations and effective coordination across these locations. Casson (1997) suggests that consolidating the ownership of adjacent activities, such as marketing and production, ensures the quality of information which then improves the quality of information synthesis. It is likely that the internalization of knowledge-creating activities in foreign locations internalizes the flows of information with organizational hierarchy. The question is why IC design companies are capable of coordinating across borders, while other semiconductor companies are less capable of doing so.

From the observations of IC design MNEs, it is likely that the internalization of geographically-separated design units and the specialization in design allow effective communication and coordination across locations. In other words, common ownership and focus on design activity facilitate intra-firm coordination and internal division of design labor, including heterarchical knowledge seeking and accumulation. While manufacturing foundries and physical equipment constrain the mobility of IDM companies, IC design MNEs become focused and agile, specializing and coordinating design internationally. Their moderate size and the collaborative nature of customized IC design also increase the likelihood of engaging in the local interaction structure of clusters (ter Wal, 2013). While vertically-integrated IDM companies benefit from internal coordination between design and manufacturing, IC design MNEs achieve efficient communication and coordination of geographically dispersed design activities.

8.2.4 Implications for national economy

For national governments intending to develop a domestic semiconductor industry, the fabless business model could be an ideal starting point for both developing and developed countries. Relative to other popular semiconductor business models, the fabless model requires relatively little financial capital, technology and basic infrastructure. Starting from less advanced IC products, companies in the Taiwanese IC design industry were suppliers for consumer electronics firms manufacturing watches, toys and other less sophisticated applications. The experience in design workflows and design competence allowed its later entry into the supply chain of the IT and telecommunication industries (Chang & Tsai, 2002; Hu et al., 2011). In India, despite limited infrastructure development and negligible local demand for IC products, design service companies have emerged as subcontractors for semiconductor MNEs (Fuller, 2014). In Europe, where domestic demand and venture capital are limited, the IP vendor business has become popular. These IP vendors focus on designing reusable design blocks and profits from licensing fee and royalties and raise higher technological entry barriers (Brown & Linden, 2009; Ernst, 2005c). Even in the US, semiconductor startups in the last quarter of the 20th century were mostly fabless (Brown & Linden, 2009). These observations from various time backgrounds and national contexts suggest that the fabless model is not just accessible to potential entrepreneurs but also adaptive to various country environments.

Moreover, the collaborative nature of the IC design business can stimulate entrepreneurship within national economies by linking different industries and reallocating resource use (Casson, 2000, 1997; Godley, 2013). Firstly, the necessity to collaborate with external service providers and business customers implies that IC design companies are more likely to leverage external knowledge and resources. For instance, MediaTek provided technological solutions and other additional support to numerous Chinese startups in the local mobile phone industry (see 5.2.15 MediaTek). Some of these companies were highly creative in adding novel functions and started to compete with world-leading brands within a decade. In the UK, ARM collaborates with professional foundries and licensee IC design companies (see 5.2.27 ARM), accumulates a diverse knowledge base through its external network and creates designs that are suitable for the future demand of business customers worldwide (Ernst, 2005c).

Secondly, fabless semiconductor startups have much lower overhead and rapid decision-making and may, therefore, pursue ideas and opportunities neglected by industrial incumbents (Brown & Linden, 2009). For instance, both Atheros and Qualcomm were founded by academic researchers, who developed and brought new telecommunication technologies to commercial applications. As the primary source of demand shifts to consumer electronics, business customers are relying on both in-house IC design teams and IC design companies to develop novel IC products, which incorporate customized functions, multimedia support, Internet connectivity and energy efficiency in ever smaller dimensions.

Thirdly, the global dispersion of external service providers and suppliers of related technology implies that companies in the modern semiconductor industry are inevitably international, regardless of the business model adopted. For instance, many vertically-integrated IDM companies also license IP cores from Western vendors and utilize professional testing and packaging companies in Southeast Asia. However, for the reasons explained previously, fabless IC design companies have a stronger tendency to look outwards and perform multilateral knowledge transfer. Previous studies show that IC design companies usually have smaller sales scale and less patenting, but longitudinal patenting records suggest that they are also less home-bounded and more decentralized than IDMs (Macher et al., 2007).

The flexibility and connectivity of the fabless model allow IC design companies to move quickly to foreign locations and develop relationships with proximate business customers. However, this does not mean that fabless companies are necessarily footloose. Case studies in this thesis confirm previous studies on the semiconductor and other knowledge-intensive industries, which suggest that knowledge flows and knowledge-creating activities tend to be locally bounded (Mowery & Nelson, 1999). Reconfiguration and reallocation to highly-competent knowledge-creating subsidiaries were observed in the cases of PMC-Sierra and DSP Group, but their corporate headquarters remained operative in the home country.

8.3 Policy implications for the IC design industry

In the past few decades, researchers in academia and policy research units have devoted significant efforts to discover the conditions for a favorable policy environment for the semiconductor industry. Decades of studies provided insights for technology policy and identified several developmental factors, such as industrial cluster, a national innovation system, science and technology education, policy support and inward FDI by leading semiconductor MNEs, among others. Most of these recommendations remain applicable to the IC design industry (Chang & Tsai, 2002). However, the fact that IC design companies are fabless, flexible and connective implies that some factors may be less relevant in the context of IC design. Also, the time background of most of these studies implies that environmental conditions may have changed, which reduces their applicability to the modern semiconductor industry. The contemporary setting of the IC design industry did not appear until the early 2000s. Considering the recent proliferation of the fabless business model, the economic consequence of neglecting these differences can be substantial. Several implications are discussed in this section.

8.3.1 Departure from traditional semiconductor business models

Firstly, IC design companies utilize external service providers for manufacturing and assembly and usually occupy much smaller land space for business operation. Previous studies have suggested government support for land development in science and industrial parks (Scott, 1987). However, IC design companies usually have their offices located in metropolitan areas in proximity to the headquarters of the main business customers (see Chapter 5). Several companies, which formerly operated internal manufacturing facilities, reported drastic reductions in land and floor space during their transition into the fabless business model. Some companies may retain internal facilities for specialized product lines, but their scale tends to be small. The difference in land use also includes lower requirements on basic infrastructure and much lower environmental impacts. Instead, IDMs, professional foundries and packaging and testing companies, which operate manufacturing and assembly facilities, usually require highly reliable utility supply and large pieces of land.

Secondly, preferential tax regimes and subsidies on capital investment (Chen & Sewell, 1996) are also less relevant to the IC design industry, because of lower capital investment and less debt financing. Previous studies suggest that national governments may invest in a number of semiconductor companies and provide various financial support and tax reduction schemes for capital investment. Several IC design MNEs in this research indeed mentioned host country tax benefits in annual reports (see 5.2.9 DSP Group), but these are rare cases and seem unrelated to the scale of local R&D sites. In fact, the focus on intangible assets of IC design companies also increases the difficulty for governments to select ‘national champions’ through the evaluation of their business activities and longer-term contribution to national economies.

The time background and the focus on semiconductor manufacturing in previous studies imply that their recommendations are likely more relevant to semiconductor companies with internal manufacturing. These companies pursue scale economies and efficient internal coordination between design and manufacturing activities. In addition, while many Asian semiconductor companies are affiliated with business groups, which provide financial support, such a situation is rare in the case of IC design companies (see 5.2.24 VIA).

Thirdly, as a feature of host countries, the wage level among skilled workers may be less relevant to IC design MNEs because of the amount of training and design experience required.

Previous studies point out that the geographical distribution of assembly facilities for IC packaging and testing follows local wage level and labor supply (Scott, 1987), but IC design companies in general employ much less labor and offer competitive wages for experienced designers, especially those with experience in the US (Brown & Linden, 2009). In their analysis of semiconductor industry offshoring, Brown and Linden (2005) point out that a vast majority of the workforce in IC design are engineers instead of production line workers, and offshoring investments are located in both high- and low-wage countries. Moreover, the cost savings from offshoring are often overestimated due to additional costs of training, monitoring and IP protection and managerial challenges to coordinate geographically separated design teams. Especially regarding analog- and mixed-signal IC design, Fuller (2014) points out that companies have largely relied on well-paid repatriated engineers due to the lack of such expertise among locally-trained engineers.

Fourthly, government-coordinated R&D collaborations may be less relevant for IC design companies in the modern semiconductor industry. Previous studies have discussed the impact of R&D collaborations coordinated by national governments, such as the VLSI project in Japan and SEMATECH in the US (Browning et al., 1995; Irwin & Klenow, 1996; Langlois & Steinmueller, 1999). In the early stage of the Taiwanese semiconductor industry, the government-sponsored ITRI-ERSO developed a set of software and standards to assist the development of sophisticated IC products and shorten the testing time (Chang & Tsai, 2002). While these findings appear to advocate for government support for collaborative R&D, it is noteworthy that the modern semiconductor industry already encompasses a complete ecosystem of IP vendors, EDA software companies, equipment suppliers and various specialized external suppliers (see Chapter 6).

Most of these supporting industries and sub-industries in the modern semiconductor industry are highly mature with a small number of global leaders with established product offering (Brown & Linden, 2009; Ernst, 2005c). Meanwhile, world-leading foundries and IDMs are competing to develop cutting-edging manufacturing processes at the nanometer scale. The effectiveness of replicating such a policy, therefore, becomes questionable in the contemporary setting.

Lastly, geographical separation has become relatively common in the modern semiconductor industry, which is vertically specialized (Macher & Mowery, 2004), and the cost and benefit of developing industrial clusters to host an entire supply chain should be reconsidered. Fuller (2014) considers the absence of local semiconductor manufacturing capacity as a developmental limitation for the Indian IC design industry, which constrains them to a supportive role for the global value chain. The decision to obtain equity control over manufacturing capacity through joint ventures was also observed in several cases (see 5.2.20 SanDisk). However, at least in terms of leading IC design MNEs, longer-term contracts and collaborations with specific external service providers and firm-specific capability in forecasting demand are more important in the management of a vertically disintegrated supply chain, according to company annual reports.

8.3.2 Important factors for the IC design industry

The first and foremost factor in the development of the IC design industry is geographical proximity to business customers in user industries, which facilitates a deep understanding of customer demand and close inter-firm collaboration in the process of customized IC design. For instance, the electronics manufacturing industries in China and Southeast Asia have attracted IC design companies, both domestic firms and MNEs, to establish a local presence and collaborate with systems companies in the region (Fuller, 2014; Macher et al., 2007). As shown in several case studies in Chapter 5, Chinese cities Beijing and Shenzhen have become popular IC design locations as booming demand for IC products started to come from manufacturers of consumer electronics and personal mobile devices (see 5.2.8 CSR and 5.2.15 MediaTek among others). The recent development of the maker culture of empowered individual inventors and close relationships with manufacturers (Lindtner, 2014) may also create new demand for customized IC products.

The experience from Sophia-Antipolis, France, seems to suggest the agglomeration of semiconductor user industries (Dang, 2009) and local public research institutes, which supply high-quality labor and new technologies (ter Wal, 2013). Although none of the three European IC design MNEs was headquartered in the area, both ARM and CSR have knowledge-creating subsidiaries in Sophia-Antipolis, while Dialog Semiconductor works closely with the automotive industry in Germany (see Chapter 5). Considering their focus on knowledge-based intangible assets, customized IC design and proximity to business customers, IC design companies may actually bear a resemblance to those in the service sector.

Secondly, government support in terms of specialized education and training for IC design talent is crucial. In practice, although most companies would have different design processes, specialized product lines and familiar manufacturing processes and design tools, the general training of IC design engineers may reduce the time and amount of additional training required. The complete training for IC design engineers may rely more on MNEs and personal work experience (Fuller, 2014), but education and academic research programs for IC design require much lower budgets, which save the costs of constantly upgrading manufacturing facilities in academic institutions (Macher & Mowery, 2004).

Taiwan, which has been more successful in promoting fabless startups, has established government-sponsored programs and research centers to provide both academics and industry members with access to EDA software tools and prototyping and testing of IC designs (Chang & Tsai, 2002). In particular, modern sub-micron manufacturing processes are highly-sophisticated and reliant on customized EDA software packages, while those obtained from universities or other informal sources are usually suitable only for less advanced manufacturing processes (Brown & Linden, 2009). The more complex SoC IC design would require both advanced software tools and comprehensive prototyping and testing (Ernst, 2005c).

Thirdly, an effective patent regime is crucial to the operation and development of the IC design industry. Patenting provides a useful legal framework for the access to and transaction of intangible assets as well as litigation (see 5.2.12 Lattice and 5.2.24 VIA). Patenting matters from the early stage of development in order to identify and monitor both internal and external knowledge-based assets and facilitate close collaboration with IP legal specialists (Hurtarte et al., 2007). While semiconductor companies generally have more patenting activity, IC design companies particularly benefit from a strong patent regime (Hall & Ziedonis, 2001). Patent protection is also critical when companies pass IC designs to external parties, which necessarily reveals the critical information (Brown & Linden, 2009).

In the multinational context of the modern semiconductor industry, the US remains the single largest market for the end products of the semiconductor value chain. Infringement of US patents can result in the sales ban of end products. However, imitators often exploit emerging country markets in weakly regulated countries. When patent protection is ineffective, an experienced engineer in Taiwan suggested the use of design techniques to provide protection at the product level (see Note 1 to Chapter 4). They also mention that emerging country MNEs have started to hire experienced foreign engineers in local subsidiaries. While a similar phenomenon was observed in the US semiconductor industries decades ago, it is important to recognize that the appropriation concern does affect the willingness of MNEs to allocate knowledge-creating activities in emerging economies (Brown et al., 2005; Thursby & Thursby, 2006). Fuller (2014) point out that MNEs have committed more resources and conducted more sophisticated IC design in India instead of China due to IP protection concerns.

Lastly and particularly relevant to IC design MNEs, government policies which promote outward FDI and internationalization may help IC design companies leverage the flexibility and connectivity features of the fabless business model. The internationalization of the semiconductor industry is often subject to the influence of national policies either to acquire or to protect advanced semiconductor technologies and related applications. National governments continue to monitor the technological development and spillovers of the domestic semiconductor industry (Chu, 2008).

However, the attempt to regulate international knowledge flows can be frustrated by the geographical and technological flexibility of fabless companies. Without sizeable physical facilities, the fabless nature of IC design activity increases the inherent difficulty in monitoring and interferes with their presence and mobility. The diversity of product lines and related technologies also complicates the introduction and enforcement of appropriate trade and investment regulations. Considering that profit generation and knowledge creation in the modern semiconductor industry are essentially global and transnational, policy environments that allow IC design MNEs to improve external connectivity and internalize information flows may instead help maintain the level of local knowledge-creating activity and employment in the home country.

In fact, case studies and patenting records show that most surviving IC design MNEs have largely remained home-bounded. While constantly reconfiguring international R&D, these MNEs only move the headquarters between nearby towns once in a while. The most successful and fast-growing companies tend to operate an extensive network of international R&D sites and respond to emerging demand timely and internationally (see 5.2.26 Zoran). Apart from identifying and responding to emerging demand in proximity, IC design MNEs based in less technologically advanced countries may also leverage their knowledge-creating activities in advanced countries. For instance, Taiwan-based IC design MNEs—MediaTek, Realtek and VIA—have all benefited from subsidiaries in California, as indicated by their patenting records.

8.4 Implications for the IB literature

The flexibility and connectivity of the fabless business model have allowed IC design MNEs to coordinate global design and exploit multinationality effectively. On one hand, IC design MNEs may enter foreign locations faster and easier simply with sales offices and technological services. The fabless model also allows the IC design MNEs to extensively customize or introduce new products for customers in foreign markets. On the other hand, knowledge-creating subsidiaries may seek and accumulate knowledge, building subsidiary knowledge bases that can be utilized by other members of MNE group. Continuous circulation of information between marketing, production and R&D functions fosters the knowledge development of MNEs, which are in general more entrepreneurial and better at organizing R&D (Buckley & Casson, 2009).

8.4.1 The entrepreneurial MNE and knowledge-creating synthesis

Entrepreneurship is essential for the creation and revamping of MNEs in response to changes in technology and market demand (Casson, 1997). More recent studies on subsidiary-level knowledge creation often focus on organizational and managerial challenges and neglect the concept that entrepreneurship is inherent in the subsidiary evolution literature (Birkinshaw, 1997; Birkinshaw & Hood, 1998; Pearce, 1999a). The findings of thesis, especially entrepreneurial knowledge creation, follow the same tradition and further connect to other lines of thinking, including internalization theory and business model innovation.

Buckley and Casson (1985: 185) discuss information-processing in different configurations of R&D. Companies with centralized R&D often strategically deploy listening posts, which gather and transmit information to be synthesized by the headquarters. Companies with decentralized R&D empower entrepreneurial managers to undertake their own synthesis of the market and technological information, which permits flexible and timely responses to local business opportunities. The two configurations have different implications for MNE knowledge creation. Although subunits access local knowledge sources and create products pertaining to the demand of local customers, the headquarters gathers and synthesizes information with a global perspective and pursues knowledge with wider and longer-term impacts (Argyres & Silverman, 2004). In other words, between centralized and decentralized knowledge creation and between internal and external interdependencies, the fundamental difference is the perspectives and information synthesis for knowledge creation (Alvarez, Godley, & Wright, 2014; Casson, 1997).

8.4.2 Heterarchy and internalization of diversity

This thesis has argued that a heterarchical structure is essential to cross-level interdependencies. However, the heterarchical structure, which essentially encourages intra-firm diversity and a flexible arrangement of cross-level interdependencies, has the inevitable side-effects of internal cognitive gaps and less efficient intra-firm communication and coordination. When the headquarters and subsidiaries are embedded in different business and national contexts, their perspectives and knowledge bases may gradually diverge and become incompatible with each other (Verbeke & Yuan, 2005). Paradoxically, the heterarchical structure empowers subsidiary knowledge creation but inevitably weakens internal network and information flows and impedes intra-firm multilateral knowledge transfer, hindering the global knowledge creation of the MNE. The headquarters may strengthen the interdependencies between members of the internal corporate network, which transfers the knowledge created by subsidiaries. However, internal interdependencies would gradually homogenize subsidiaries and undo the heterarchical structure.

The growing importance of external knowledge sources, subsidiary external embeddedness and the heterarchical structure suggest a new dimension for internalization decision. Existing applications of internalization theory are centered on the efficiency gain from internalizing foreign business activities. Internalization imposes connections and internal interdependencies between activities, which foster internal knowledge transfer. However, internalization and centralized coordination would inevitably homogenize subunits and generate the tendency to look inward, indirectly merging diverse knowledge bases and curbing the inflows of external knowledge and creativity. In other words, the internalization of diversity within the MNE also gradually removes it. The MNE may decentralize knowledge creation with an internal division of R&D labor across locations, but the resultant heterarchical structure increases the difficulty to transfer and integrate subsidiary knowledge.

8.4.3 The information efficiency of MNEs

This paradox should be solved by a flexible use of a heterarchical structure—in which the information efficiency implied by internalization can also improve the management of diversity for global knowledge creation. That diversity can be internalized and retained in a heterarchical structure implies that MNEs have the power to affect the differentiation and specialization of subsidiaries. The heterarchical structure and external interdependency empower subsidiaries and make MNEs more responsive to environmental changes and emerging market demand. However, when the external environment and market demand are relatively stable, centralization and internal interdependencies improve internal communication, coordination and knowledge sharing. Based on specific strategic goals, MNEs should constantly optimize flows of information, which link subsidiaries in various locations (Casson, 2000). As long as MNEs can reconfigure the internal corporate network more efficiently than the self-organization by a group of individual firms, the internalization of foreign activities remains justified.

In fact, internalization theory assumes neither homogeneity nor perfect alignment of interests among activities to be internalized. Instead, it is exactly the diverse and divergent orientations among transacting entities in the arm’s length setting that create the efficiency gains of internalization. The internalization of market transactions does not intend to homogenize transacting parties but to create a common institution through which the coordination between heterogeneous entities becomes more efficient. The common ownership of these entities concedes to the MNE headquarters better access to reserved information and unilateral intermediation of flows of information (Casson, 1997). Leveraging the internalized access to information in foreign subunits, MNEs may constantly revise global strategy and reconfigure international R&D. In other words, MNEs should remain flexible when imposing cohesion and aligning interests. If heterarchy better satisfies the strategic goal, such as global knowledge creation, MNEs may also explicitly incorporate and encourage diversity at the subsidiary level.

Incorporating and encouraging diversity at the subsidiary level will not only benefit global knowledge creation but also create greater potential for internal international entrepreneurship (Casson, 2000; Pearce, 1999b). MNEs can actively establish and manage productive linkages between differentiated and specialized entities, which would otherwise remain isolated in the absence of the MNE’s global perspective, internal information efficiency and joint decision-making (Cantwell, 2014; Casson, 2000, 1997). External interdependency, which is necessary and inevitable for knowledge-creating subsidiaries, can affect internal cohesion and hinder communication with the headquarters. However, internalization and ownership control should give the headquarters the option as well as the confidence to allow knowledge-creating subsidiaries to develop external interdependency.

8.4.4 Incidental interdependency and internal entrepreneurship

In an industry subject to diverse and fast-changing market demand and technological development, decentralized knowledge creation and intra-firm R&D collaboration can be a useful means to harness the power of internal entrepreneurship and venture into new technological fields. Without changing the organizational divisions of specialization and expertise, knowledge-intensive organizations may encourage employees to actively collaborate and form semi-formal organizations (Biancani, McFarland, & Dahlander, 2014). The headquarters can influence the process of internal ventures by inventive individuals, which produces internal entrepreneurship within diversified corporations (Burgelman, 1983).

Similarly, MNEs may augment the heterarchical structure with intra-firm R&D collaborations between geographically-separated subunits. These intra-firm collaborations momentarily impose cross-level interdependencies onto the existing division of R&D labor and temporarily reconfigure R&D for effective global knowledge creation.

Incidental interdependencies can be briefly triggered by imminent requirements to fulfill customer demand with novel solutions. However, the headquarters should always plan ahead by synthesizing information about subsidiaries knowledge bases, future market demand and external technological development. The timing for incidental interdependency, therefore, hinges on the headquarters' foresight (Buckley & Casson, 1992; Casson, 2000). MNEs might choose to neglect some environmental changes and withhold incidental interdependencies when the information is less decisive, while the outcomes of market competition should ultimately verify the validity of decision-making (Casson, 2000).

Table 8.1 Entrepreneurial knowledge creation by intra-firm R&D collaboration across countries

		1st inventor's country of residence	
		Home country	Host country
Other inventors	Host	HQ-Sub 37/1,124 (3.3%)	Subs-Subs 23/173 (13.3%) Subs-solo 357/3,974 (9.0%)
	Home	HQ-solo 902/24,909 (3.6%)	Subs-HQ 28/784 (3.6%)

Source: This research.

To illustrate the entrepreneurial potentials of intra-firm R&D collaborations, Table 8.1 tabulates the pioneering patenting in technological fields new to the MNE each year by different forms of collaboration. It was found that R&D collaborations between subsidiaries in different countries generate more entrepreneurial inventions. Conversely, the participation of the headquarters seems to lower the innovativeness of R&D collaborations, led by either the headquarters or the subsidiary. However, this may suggest that R&D collaborations between subsidiaries and the headquarters may have different goals, such as intra-firm knowledge transfer. Test results in the previous chapter show that collaborations between subsidiaries and the headquarters provide an important mechanism for intra-firm knowledge transfer.

8.5 Conclusion

Existing research about the semiconductor industry has been influenced by the perspectives of technological development and industrial policy. As a result, discussion of internal and international coordination has been very limited. From the IB perspective, this thesis intends to fill the gaps with original insights and synthesis of the international R&D and subsidiary evolution literature. This chapter summarizes and extends this effort to include the policy and theory implications of this research on IC design MNEs.

Regarding policy implications, it is critical to recognize the differences between IDM companies and specialized IC design companies. These differences imply that many of the insights of previous studies may be less applicable. While IDM companies internalize production facilities in pursuit of scale economies and internal coordination of manufacturing, IC design companies prioritize flexibility to access foreign markets and serve interchangeable demand. This thesis, therefore, provides an important update to the literature on the semiconductor industry, which has greatly influenced both policy and business studies. Regarding theory implications, this thesis links subsidiary knowledge creation, cross-level interdependencies, internalization theory of the MNE and internal entrepreneurship. This chapter further discusses the strategic considerations for MNEs in internalizing diversity, leveraging the flexibility and managing cross-level interdependencies. All these can provide new insights for MNEs to improve internal and international coordination and global knowledge creation.

9 CONCLUSION

9.1 The entrepreneurial MNE in the 21st century

Seminal works that establish international business studies as an independent academic field have frequently dedicated sections or chapters on R&D, emphasizing the critical role of knowledge and knowledge-creating activities in the MNE as well as the theory for it. From the IB viewpoint, the concept of multilateral knowledge transfer adds possibilities for how MNEs may create competitive advantages by improving information efficiency. The economic approach of internalization theory suggests that the MNE is essentially an economic institution specialized in coordinating between geographically-dispersed activities.

The appreciation of external knowledge sources in the R&D internationalization literature recommends cross-level interdependencies but understates the challenges to coordinate geographically separated and individually-specialized subsidiaries. The emphasis on intra-firm knowledge transfer and integration in the subsidiary evolution literature recommends the role of headquarters and the heterarchical structure. The heterarchical structure embraces and internalizes diversity within the entrepreneurial MNE but requires innovative strategies and integrative mechanisms to manage cross-level interdependencies. *Heterarchy implies the internalization of diversity: differently-specialized and interdependent activities are internalized within the MNE when it provides or develops integrative mechanisms that are more efficient than the market institution.*

Moreover, the traditional IB literature has implicitly assumed a static environment where knowledge sources and business opportunities are either relatively stable or developing at a steady rate. When external knowledge sources are largely known and constant, MNEs can achieve an optimal configuration of international R&D according to the known properties and location of knowledge sources. Instead, the entrepreneurial MNE assumes a volatile environment in which technological breakthroughs and emerging opportunities necessitate collation and synthesis of transient information on a continuous basis (Casson, 1997). Decentralized knowledge creation is more sensible in such a volatile environment because it empowers entrepreneurial employees and enhances the responsiveness to external technological breakthroughs and emerging demands.

In addition to the environmental assumption, there are several avenues for future research. Firstly, internalization provides the option but not the necessity to exercise centralized control and internal coordination (Casson, 2000). Therefore, how to identify the right timing for the headquarters to intervene could be a direction worth exploring. It is argued that the headquarters may have the global perspective to coordinate between diverse knowledge bases, but a global perspective does not guarantee the speed and judgment of the headquarters in responding to new technological breakthroughs and emerging business opportunities in a volatile environment. The advantage of the entrepreneurial MNE may depend on its capability to time interventions correctly and adjust cross-level interdependencies—when new linkages between subunits should be are created and when redundant linkages are retired.

Secondly, one unique aspect of the research of the MNE is its imperative to recognize and harness the differences between locations and inherent diversity of a geographically-dispersed organization. However, the level of internal diversity has not been fully considered in internalization theory, which predicts the boundary of firm. Indeed, *the main difference between the MNE and a diversified or M-form corporation is that geographical separation and national differences cannot be easily assumed away to accommodate any organizational theories.* Incorporating diversity as a parameter of internal coordination may better the management of MNEs, which differs from domestic companies. An explicit consideration of diversity also highlights the potential of MNEs to leverage diversity and encourage internal entrepreneurship.

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