Learning by decomposition and recombination in technological catching-up: a case study of a Chinese leading air separator system manufacturer, 1978-2008

ABSTRACT - By selecting a Chinese leading enterprise and world-class manufacturer in the air separator system industry, HASSMC, as the research subject of this case study, the present study investigates in depth its technological catching-up process during 1978-2008 to examine a proposed learning-based model for capability building in technological catching-up, in which the learning process is decoupled into two complementary processes as learning by decomposition and learning by recombination. The typical mechanisms in learning by decomposition and recombination have been investigated and summarised with empirical evidence. This study attempts to extend the absorptive capacity perspective for the context of technological catching-up in emerging economies, with an argument that latecomer firms can build up their absorptive capacity to effectively acquire and utilise external technology through externally accessible expertise other than internally possessed knowledge base, especially at the initial stage of technological catching-up.

Key Words: technological catching-up; capability building; technological learning

1. Introduction

For academic researchers, industrial practitioners or government decision-makers, how to understand and accelerate the capability building and catching-up process of developing countries remains an interesting issue during the past four decades. There has been a lot of firm-level research on technological catching-up in the context of less developed economies (Dantas and Bell, 2009), where well-structured typologies and frameworks have existed for a considerable time (e.g. Bell and Pavitt, 1995; Choung et al., 2000; Figueiredo, 2003; Kim, 1997, 1998; Lall, 1992; Lee and Lim, 2001; Mathews and Cho, 1999; Scott-Kemmis and Chitravas, 2007). Among them, the importance of learning and local capability formation has long been recognised for technological catching-up of latecomer firms (Bell and Pavitt, 1995; Kim, 1998; Lall, 1992) and long-term sustainable growth in the economic development of less developed countries (Amsden, 1989; Iammarino et al., 2008; Lee and Lim, 2001).

Firm-level technological catching-up, which can be understood as a continuous process to absorb, utilise and create technical knowledge, is determined partly by external factors and partly by past accumulation of skills and knowledge (Lall, 1992, p.166). Hence, we focus on two related questions in this paper. On the one hand, in the process of technological learning for knowledge acquisition, how do the late-comers in emerging economies mitigate the potential negative influence of a large technology gap between the late-comer and its forerunners (especially at the initial stage of catching-up) on technological learning and capability building? On the other hand, in the process of technological learning for knowledge utilisation and creation, how do the late-comers in emerging economies capture the business opportunities in domestic or even global market through technological innovation, and thereby effectively accumulate financial resources from market returns to sustain long-term technological catching-up?

China's emerging economy provides a good context in which to investigate those two questions. During the last three decades, along with the gradual and partial reform that shifted China's economy toward a market system, Chinese manufacturing industries have played an important role and have made great achievement in China's economic and technological catching-up process (Jefferson and Rawski, 1995; Gu, 2000; Jefferson et al., 2003). By selecting a Chinese leading company and world-class manufacturer in the air separator system industry, HASSMC, as the research subject of this longitudinal case study, the present study attempts to reveal the mechanism how Chinese latecomer firms mitigate the potential negative influence of technology gap and capture the catching-up opportunities by purposively and strategically using learning mechanisms (learning by decomposition and learning by recombination) for knowledge acquisition, application and creation. We aim to contribute to the literature on technological catching-up in the following aspects. First, as a pertinent and influential concept in the applied literature on capability building and catching-up in developing countries, 'absorptive capacity' is defined as 'the ability of a firm to recognise the value of new, external information, assimilate it and apply it to commercial ends' (Cohen and Levinthal, 1990, p. 128). A growing number of studies have highlighted the importance of absorptive capacity for late-comers to efficiently assimilate foreign technologies and transform themselves from imitation to innovation (Kim, 1997, 1998; Liu and White, 1997; Mu and Lee, 2005; Scott-Kemmis and Chitravas, 2007). There are two important elements of absorptive capacity, i.e., prior knowledge base and intensity of effort (Cohen and Levinthal, 1990). It is worth noting that concerning these two elements, there are two interesting issues that need to be further explored. One is that the existing studies on absorptive capacity and catching-up mainly focus on the prior knowledge base internally possessed by late-comers at a given time point, and posit that the late-comers should have enough prior knowledge before they can absorb a certain external technology. By contrast, with few exceptions (e.g., Dantas and Bell, 2009; Ernst and Kim, 2002), it is less explored whether late-comers can build up their absorptive capacity to effectively acquire and utilise external technology through externally accessible expertise other than internally possessed knowledge base. The other issue is that the literature has emphasised the essential role of investment in research and development in capability building for catching-up. However, as argued by Kim (1998) and Lee and Lim (2001), those catching-up firms in developing countries generally reverse the sequence of research, development and engineering of the advanced countries -- they started with engineering for products and processes imported from abroad, then progressively evolved into the position of undertaking substantial development and research at a later time. As such, China's emerging economy provides a rich context in which to investigate the following issues and thereby extend the absorptive capacity perspective in technological catching-up research.

Second, we attempt to introduce an analytical framework for technological catching-up from a perspective of learning by decomposition and recombination. The literature on learning and capability has already proposed several related concepts, such as 'knowledge recombination' in Kogut and Zander (1992), 'combinative capability' in Mathews and Cho (1999) and 'knowledge integration' in Tsekouras (2006). However, it is worth noting that limited research has been put in the context of technological catching-up for latecomer firms in emerging economies. Another less investigated issue in the previous studies is what the typical learning mechanisms are for knowledge decomposition and recombination. By using the case of HASSMC, the present study attempts to examine and validate the research framework, in which the learning process is decoupled into two complementary processes as learning by decomposition and learning by recombination. The typical mechanisms of learning by decomposition and recombination are also systematically investigated with empirical evidence.

The rest of the paper is organised as follows: Section 2 introduces our conceptual framework from a perspective of learning by decomposition and recombination; Section 3 describes the research method; a longitudinal case study that traces HASSMC's technological catching-up process during 1978-2008 is presented in Section 4 to examine and validate the conceptual framework; and finally, Section 5 provides a summary of the research findings.

2. Conceptual framework

Capability building in technological catching-up is a cumulative and time-consuming process of learning by trial-and-error (Bell and Pavitt, 1995; Figueiredo, 2003; Scott-Kemmis and Chitravas, 2007). In this process, on the one hand, latecomers need to effectively assimilate external technology by mitigating the gap in the technology ladder between them and foreign companies. On the other hand, they should support their capability building with resources through taking advantage of market opportunities, and continuously profiting from imitation and innovation. Based on these ideas, we propose an analytical framework in which learning by decomposition and learning by recombination are outlined to address the issues on technology gap and resource accumulation in the process of technological capability building.

2.1. Technology gap and catching-up

Capability building in technological catching-up requires sufficient time and opportunities for latecomers in developing countries to benefit from learning when facing the competitive pressure from the technology and products of their foreign counterparts (Bell and Pavitt, 1995; Figueiredo, 2003; Scott-Kemmis and Chitravas, 2007). In line with the absorptive capacity perspective, the literature has highlighted the important influence of technology gap between latecomer firms and their foreign forerunners on technological catching-up (e.g. Figueiredo, 2003; Findlay, 1978; Lall, 1992; Wang and Blomström, 1992; Lee and Lim, 2001; Perez and Soete, 1988; Scott-Kemmis and Chitravas, 2007).

The impact of the technology gap on technological catching-up is twofold. On the one hand, the technology gap may represent the potential that latecomers could learn from their counterparts in developed countries. As a consequence, some earlier research hypothesised that spillovers increase with the size of the technology gap between local and foreign invested firms (e.g., Findlay, 1978; Wang and Blomström, 1992). On the other hand, large technology gaps can constitute obstacles to technological catching-up for latecomers. For instance, Haddad and Harrison (1993) reported that large technology gaps inhibit FDI spillovers. Several studies also suggest that there exist a knowledge threshold in a given sector or technology field that latecomers need to cross in order to catch up with their forerunners (Jang et al., 2009; Perez and Soete, 1988). In some extreme cases, latecomers may fail to establish their technological capabilities as a necessary of the indigenous catching-up process due to the large technology gap that makes them unable to absorb and use advanced technology from their foreign competitors. Consequently, how to mitigate the potential negative influence of technology gap on technology acquisition and assimilation, becomes a critical issue for late-comers to deal with before they can fully make use of the opportunities embedded in their catching-up context.

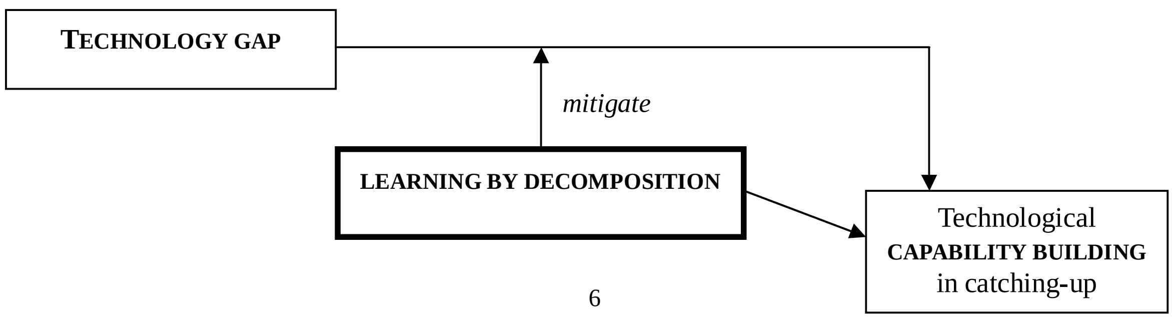
2.2. Resource accumulation and catching-up

Resources have two kinds of implications for technological capability building. First, in building up their technological capabilities, latecomers will consume all kinds of resources, especially financial resources. Learning and capability building certainly require purposive investment in activities such as intentional searching, hiring new or more capable employees, and improved training for existing employees (Scott-Kemmis and Chitravas, 2007). At the same time, as posited by the absorptive capacity perspective, the development of technological capability has a strong nature of path-dependency (Cohen and Levinthal, 1990). Thus, ‘if success prevails, the profits from market success are, of course, a source of investment for future R&D, which thus constitutes one element of the firms' R&D capacities’ (Lee and Lim, 2001; Mu and Lee, 2005, pp.765-766).

Second, existing resource conditions will greatly constrain the space of decision-making about investments into capability development. As a result, the efficiency for a latecomer to accumulate resources will, to a large extent, influence its efficiency and effectiveness in capability building. For latecomer firms in emerging economies, they often suffer from the negative influence of financial constraints in their innovation and capability building processes. Because of the relative scarcity of capital and the inefficient banking system, a relatively heavy cost will be imposed on local firms in obtaining financial resources from the market system (Cai and Tylecote, 2008; Gregory and Tenev, 2001). Hence, the initial difficulty faced by latecomer firms is often the lack of financial resources (Mathews and Cho, 1999). Even for those state-owned enterprises with relatively larger firm size, it is vital to get market return as quick as possible by taking effective technology development strategy.

2.3. A proposed analytical framework: learning by decomposition and recombination

Technological learning is the process by which firms acquire technology and accumulate technological capabilities (Bell, 1984; Bell and Pavitt, 1993; Dodgson, 2000; Hobday, 1995). The variety and intensity of intra-firm learning processes can lead to significant inter-firm differences in technological capability building in latecomer context (Figueiredo, 2003). The importance of technological learning for capability building has been emphasised in the literature from the following perspectives. First, the capability building process itself is a kind of continuous learning process (Kim, 1998; Xie and White, 2004). Second, as to the market and technology opportunities in a given catching-up context, it does not mean that all firms in such a context have an equal chance to make use of these opportunities. That is, building technological capability is not an automatic process (Bell and Pavitt, 1995; Figueiredo, 2003). For a certain firm, whether these opportunities exist and to what extent the catching-up potential behind these opportunities can be utilised greatly depend on the learning strategy it takes during technological catching-up (e.g., Dantas and Bell, 2009; Kim, 1998; Scott-Kemmis and Chitravas, 2007). Third, the efficiency in the learning process will be related to how a latecomer effectively gets market return from market opportunities and supports the further investments required by capability building (Kim, 1997; Mu and Lee, 2005). The more efficient and effective the learning process in catching-up is, the easier it is for the firm to accumulate sufficient financial resources for capability building.



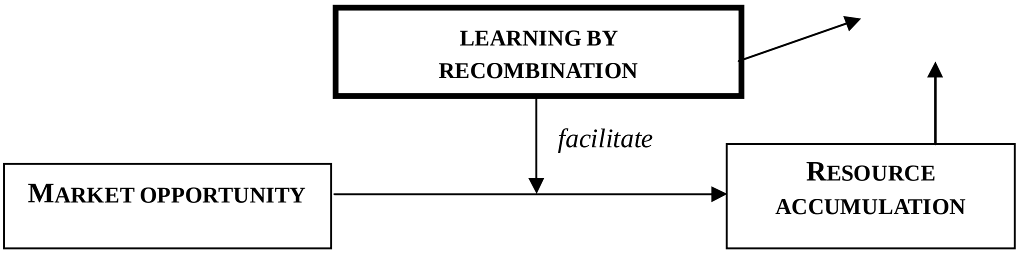


Figure 1 A proposed analytical framework

There are two core issues concerning the capability building in technological catching-up processes of emerging economies. First, in spite of the potential learning and catching-up opportunities offered by foreign advanced technologies, the large gap in the technology ladder between foreign and domestic firms may constitute a barrier for domestic latecomers to gain from the technology potential. As a result, how latecomer firms can effectively assimilate external technology by mitigating the gap in the technology ladder between them and foreign companies (or other agents in the upper part of the technology ladder), becomes a crucial issue in analysing and understanding the features of technological catching-up. Second, because of the resource- and time-consuming feature of capability building, as well as the finance constraint problem faced by latecomers in emerging countries, how a latecomer firm sustains its capability building and technological catching-up through continuously profiting from imitation and innovation, is another critical issue to be explored. The efficiency difference in technological learning will make some latecomers succeed in achieving their sustainable catching-up while the others fail in the same catching-up context.

Therefore, we propose an analytical framework as in Figure 1. In this model, the technological learning process is decomposed into two interconnected and complementary processes, i.e., learning by decomposition and learning by recombination.

Learning by decomposition is a process through which latecomers take some strategic learning mechanisms to mitigate or overcome the potential negative influence of a large technology gap between latecomer firms and foreign forerunners on capability building. On the one hand, learning by decomposition will greatly decrease the capability threshold for latecomers to acquire and make use of external technology in the higher end of the technology ladder. On the other hand, it will help latecomers to greatly reduce the cost, resource, and time consumption in technology assimilation to accelerate the capability building in catching-up process.

In parallel with the concept of learning by decomposition, **learning by recombination** is a process through which latecomer firms in large emerging economies fully capture the business opportunities in domestic or even global market, and thereby effectively accumulate financial resources from market returns to sustain long-term technological catching-up. In the process of learning by recombination, on the one hand, latecomers can integrate technologies and expertise from a wide variety of external source or even combine these technologies with their own internal expertise into new technology and product developments. On the other hand, through learning by recombination, they can localise or adapt technologies acquired to meet the specific demand in the highly segmented domestic market, or transplant the technical expertise built in learning by decomposition into new market segmentation or new market applications. As such, learning by recombination is not only a learning and knowledge creation process in which latecomer's technological capability is built and enhanced, but also a moderator for the latecomers to take advantage of market opportunities to increase the possibility and efficiency in obtaining market returns, which would be critical to their long-term capability building and sustainable technological catching-up.

3. Research Method

3.1. Case selection

In the present study, we conducted case analysis of the technology development and capability building process of a worldwide leading air separator manufacturer, Hangzhou Air Separator System Manufacturing Company (HASSMC), during the period of 1978-2008.

Table 1. The technological catching-up history of HASSMC

Technology generations	**Time period**	**Key events**	**Catching-up performance**
The 1st generation: Aluminium-tape cooler-type high and low pressure process air separator system	1950s	In 1954, engineers in HASSMC had done reverse engineering work on an air separator system of Heilongjiang Jixi Coal Mine imported from the former Soviet Union, and finally obtained a first set of blueprints and product specifications. Since 1957, it had sent some engineers to the former Soviet Union to learn about advanced technologies and production management, and obtained a complete set of design blueprints and product specifications from the technical experts from the former Soviet Union	During this period, HASSMC kept trying indigenously to develop its own system products, and achieved some successful results in July 1957. HASSMC successfully developed the first set of aluminium-tape-type high and low pressure air separator systems in China in April 1958.
The 2nd generation: stone-cooler-type low	1960s	In 1965, HASSMC served *the shore-based acceptance checkout* for the	HASSMC successfully developed the first air separator system based

pressure process air separator systems		imported air separator systems of Shijingshan Steel Plant from Japan Kobe Steel (KOBELCO), by reconstructing and integrating imported equipments with the existing production facilities of their clients according to their clients' specific demands	on the second generation of technology architecture in China in 1968.
The 3rd generation: low pressure process air separator systems with reversing heat exchangers	1978-1980	During 1978-1980, HASSMC imported a complete set of technology and technological know-how in design, manufacturing and production management in terms of technology licensing from Linde (German).	HASSMC actively assimilated these imported technologies, and developed the first set of air separator systems based on the third generation of technology architecture in 1979.
The 4th generation: pre-purifying molecular sieve-type low pressure process air separator systems	1980-1985	Since 1980, HASSMC had participated in the joint design and manufacturing projects of air separator systems with Linde Company.	HASSMC indigenously designed and manufactured the air separator system based on the fourth generation of technology architecture in December 1982, which reached the technology level of foreign leading counterparts at the end of the 1970s.
The 5th generation: air separator systems with processes based on normal temperature purification by molecular sieve and booster expanders	1986-1995	In the middle of the 1980s, Linde had introduced the new fifth generation of air separator systems with increased yield rate of industrial gases, reduced energy consumption and improved level of automatic control, which put great market competition pressure on domestic manufacturers.	In October 1989, a fifth-generation air separator system had been successfully developed. The technology level of the newly developed system reached that of international leading producers in the middle of the 1980s.
The 6th generation: air separator systems with processes based on normal temperature purification by regular packing columns and argon columns	1996-2002	HASSMC internally developed a pilot system based on the sixth generation of technology architecture in 1996. In 1997, it participated in joint production projects with Linde for the air separator systems of Shanghai Bao Steel, and served as the production subcontractor of air and water cooler tower and molecular sieve units.	HASSMC won a contract for air separator systems based on the sixth generation of technology architecture from Jinan Steel Plant as the first 'test customer' in 2000. Two years later, the air separator system designed and manufactured by HASSMC successfully passed through a full-load trial run.
The 7th generation: large-scale air separator systems with internal compression processes	2001-2008	To meet the market demand of domestic petrochemical industrial clients, HASSMC carried out research and development of large-scale internal compression air separator systems since the end of the 1990s. In December 2003, HASSMC began, for the first time, to produce two sets of air separator systems based on the seventh generation of technology architecture for the Anqing Branch of China Petrochemical Corporation.	HASSMC had designed and produced an air separator system for Shanghai Bao Steel with the largest scale of oxygen making capacity in domestically made system products during 2001-2002, which had reached the same level of international advanced technology in terms of all of the main technical indicators.

3.2. Case analysis method

The procedure adopted in the case analysis followed the logic of analytic induction (Yin, 1984), which is a method of extending or refining existing theories by constantly comparing them with typical instances (Cressey, 1953, p.16). More specifically, the data were analyzed as follows. First, we established tentative relationships between technology gap, market opportunity, technological learning and capability building from literature review. Second, the extended case method (Burawoy, 1991; Danneels, 2007), which consists of two 'running exchanges' between literature review and data analysis, and between data analysis and data collection, was employed to guide our data collection and analysis. Thus, we used the tentative relationships as a benchmark, comparing our data against them. We continuously matched and contrasted the data collected with those relationships to refine theoretical understanding, and thereby assess how well or poorly the model fit with the case data. In analysing the technological catching-up process of HASSMC during 1978-2008, two typical cases were selected from the company's two core businesses (i.e., the air separator system[1] and the ethylene cold box[2]). With regard to the ethylene cold box case, it is worth noting that the core technology of ethylene cold box products, i.e., the plate-thin heat exchanger, is established in the technology development process of air separator system products.

4. Technological catching-up of HASSMC, 1978-2008

In this section, the technological catching-up processes of HASSMC in the air separator system and the ethylene cold box during 1978-2008 will be used as two typical cases to validate the analytical framework in Figure 1.

4.1. Capability building through learning by decomposition

Firm-level technological catching-up involves a continuous process of acquiring, absorbing, utilizing and creating technical knowledge. The core issue in learning for technology acquisition and absorption is to mitigate the potential negative impact of the gap in the technology ladder on technology assimilation and localization, which thus enhances the

[1] Air separator systems are widely used in the metallurgical and petrochemical industry to produce industrial gases (such as oxygen, nitrogen and argon). Technically, an air separator system can be decomposed into the following subsystems or modules: the purification subsystem (with molecular sieve absorption unit as the core technology), the refrigeration subsystem (with compressor and expander as core parts), the heat exchange subsystem (with the plate-thin heat exchanger as a core part), the rectification subsystem, and the control subsystem. With regard to the design and manufacturing of large-scale air separator systems, the critical expertise or capabilities a producer should have are system process computing and design technology (that is related to the linking of separate subsystems or modules into a complete system), the design capability of the function and structure for unit equipments or modules, and manufacturing and production engineering capability.

[2] As the core part of the ethylene apparatus, the ethylene cold box is composed of several bunches of plate-thin heat exchangers and a steel-shelled lagging-casing tank. The key technologies for designing and manufacturing the ethylene cold box include the heat exchange computing and structure design for plate-thin heat exchangers, specialised production processes and equipment with high processing precision (especially vacuum brazing technology and a vacuum brazing furnace), and a strict quality control system with advanced testing technology.

possibility and the efficiency in technological learning and capability building. As shown in Figure 1, the role of learning by decomposition is important in that process. Based on this idea, we first analyze the technology-related context for catching-up, and then propose the typical mechanisms in learning by decomposition found from the process of technology development in HASSMC.

4.1.1. Technology gap and catching-up

Before the Open Policy era that began in 1978, it was difficult for Chinese manufacturing enterprises to directly import technology from Western countries. Technology development in this stage was mainly dependent on the reverse engineering of technology and equipments imported from the former Soviet Union and Eastern European countries (Liu and White, 2001). Since the 1980s, China has begun to speed up its open progress to foreign countries. In this situation, Chinese manufacturing enterprises became more and more active in acquiring advanced technology and equipment from Western countries.

Interestingly, joint ventures (JV) were not a major learning mechanism that contributed to the capability building of HASSMC. Moreover, the potential advantage of bargain power in establishing and operating JVs due to the huge domestic market size was not a critical factor either. Such experience is somewhat different from that of other catching-up cases in Chinese manufacturing sectors. For example, the case analysis of the development history of the Chinese telecommunication industry in Mu and Lee (2005) found that the joint venture with Alcatel Company played a very critical role in the development of Chinese domestic leading companies. As such, the effectiveness of JVs as a learning mechanism in technological catching-up, to a certain extent, will vary dynamically at the different stages of the catching-up process. Furthermore, the dynamic changes in learning effectiveness are closely connected with the technology gaps between latecomers and their foreign counterparts because the accessibility of foreign advanced technology is influenced by such technology gaps. Generally speaking, JV will be a useful learning mechanism at the beginning of the catching-up process. However, its effectiveness will gradually decrease along with narrowing technology gaps, which will make foreign partners become not so willing to transfer their technologies as they were at the initial stage. Even in the case of technology licensing, the barriers of technology accessibility may arise because the forerunner firms refuse to sell or give licenses to successful catching-up firms who thus have to design the product by themselves (Lee, 2005).

During its catching-up, HASSMC as a latecomer began to challenge the market position of foreign manufacturers in shifting from the low-end to the high-end market and from the domestic to the international market, as well as from parts to systems and from production to design and manufacturing integration. Since the 1990s, global leading companies have begun to see HASSMC as their potential competitor, and adopt active strategies to limit technology transfer via licensing to HASSMC. At first, HASSMC attempted to find foreign partners to set up JVs to trade market for technology. Then, a JV with Air Liquide was founded, and Air Liquid controlled the major equity of the JV. But, the core technologies in design and manufacturing were still strictly controlled by foreign partners, and HASSMC in fact had not obtained access to these core technologies and expertise as it expected. There is no reason for foreign firms to transfer their most advanced core technologies to a Chinese partner over whom they do not have management control.

4.1.2. Mechanisms in learning by decomposition

During the process of technology development in HASSMC, the following learning mechanisms can be found to be implemented as learning by decomposition (see Table 3).

Table 3. The learning mechanisms for learning by decomposition in HASSMC

Learning mechanisms	Case A: air separator system Illustrative examples	Case B: ethylene cold box Illustrative examples
1. Gradual participation in cooperative production as subcontractors	HASSMC had jointly designed and produced 8 sets of molecular sieve adsorption units for large-scale air separation systems with Linde During 1978-1998, HASSMC had jointly produced 17 sets in all of air separator systems with Linde under this mechanism. HASSMC introduced the pressure swing absorption technology from Linde in terms of cooperative production contracts in July 1988. HASSMC had jointly produced the sixth generation air separator systems with Air Liquide during 1996 - 2001.	HASSMC exported plat-thin heat exchangers in accordance with USA ASME design guidelines to America and Canada, through cooperation with the Stewart-Warner Corporation in terms of joint project biding and system designing in 1993.
2. Universities and research institutes as technology mediators for mitigating the gap in the technology ladder	HASSMC cooperated with Xi'an Jiaotong University in 1986 to develop the new technology of high-efficiency plate-type condensers and evaporators, and finally obtained two invention-type patents and the China National Technology & Invention Awards.	HASSMC cooperated with the Lanzhou Petroleum Processing Equipment Research and Design Institute to decompose the technology of the ethylene cold box, with HASSMC focusing on

	It collaboratively developed with Zhejiang University the ALC control technologies that formed the technological basis of automatic control subsystems in large-scale air separator systems developed later. It collaborated with Shanghai Chemical Research Institute and Shanghai Molecule Sieve Factory to jointly develop domestically made substitutes for molecule sieve and silica gel imported from foreign countries.	manufacturing and the institute design. In 1993, HASSMC cooperated with Zhejiang University and jointly developed a complementary software package for thermodynamic properties computing to meet the multi-composition design requirement for the petrochemical industry on the basis of an imported computer-aided design software package (for plate-thin heat exchangers used in the metallurgical industry) from the Stewart-Warner Corporation (USA).
3. Adaptive and/or localised technology improvement	Combining the technical expertise in design and manufacturing of plat-thin heat exchangers acquired from Linde with, those from production engineering expertise it internally accumulated in the period between 1963 and 1978, HASSMC further developed related technology and specialised processing equipments of plat-thin heat exchangers, which were reversely transferred to Linde in 1979. According to the demand feature in the domestic market, HASSMC made some adaptive changes to redesign the product's parameters and restructure the production engineering details for the medium- and low-pressure turbo-compressor manufacturing technology imported from Hitachi Corporation in 1981.	HASSMC mastered the key technological know-how in designing and manufacturing large-scale product systems with complex structures through learning from a large failure in an in-house development project of the ethylene cold box in 2001.
4. Gradual extension from peripheral to core subsystem or from parts to product modules and system products	Through the partial participation for the design and manufacturing of expander modules for their clients, HASSMC gained a chance to learn from the gradual extension of peripheral to core subsystems and from parts to product modules and system products.	HASSMC started its ethylene cold box business by providing spare parts for heat exchangers for the Yangzi Petrochemical Corporation in 1992.
5. Inter-temporal learning in technology modules / subsystems	HASSMC had established the initial technology base from the automatic control technology acquired from Linde in 1986. The expertise in designing and manufacturing automatic control systems accumulated from prior experience has contributed a lot to a new control technology (automatic variable-load control for air separation systems) since 2000.	N.A.

4.2. Capability building through learning by recombination

As discussed earlier, learning by recombination can facilitate knowledge creation. Through learning by recombination, firms can capture the market opportunities in catching-up context, and thus effectively accumulate financial resources from market returns to sustain long-term technological catching-up. It worth noting that for capability building in catching up, learning by decomposition and learning by recombination are closely interplayed and sometimes they can even concurrently co-exist in a given capability building practice. Nevertheless, we can conceptually divide the learning mechanisms for capability building into two types, i.e., one for knowledge acquisition and absorption, and the other for utilization and creation of technical knowledge. Therefore, after a discussion on the market-related context for catching-up, the mechanisms in learning by recombination are demonstrated from the process of technology development in HASSMC.

4.2.1. Market opportunities and catching-up

As observed in the prior studies (e.g., Mu and Lee, 2005; Xie and Wu, 2003), Chinese firms are mostly local market-focused, or at least the products made by local firms were sold first in the domestic market rather than in markets abroad during the process of technological catching-up. As a whole, so far, the domestic market has been the major target for Chinese air separator system producers. Thus, the growth of domestic market demand is one of the most influential drivers of the development of the Chinese air separator system industry. During the past two decades, a significant growth of the petrochemical industry and the metallurgical industry has been observed. The market demands for air separator systems (especially large-scale systems) increased greatly and steadily during these years.

The transition from a planned economy to a market economy since the 1980s has also offered some market opportunities for local manufacturing firms in China. During the 1980s and the early 1990s, the Chinese central government followed a double-goals policy toward imports, with import-substitution policies to promote indigenous capability building of domestic enterprises and export promotional policies to facilitate economic growth. A common thinking in the literature is that the import-substitution policies to promote the purchase of locally-made equipment have greatly benefited the technology development of Chinese manufacturing enterprises (especially state-owned enterprises). However, it is worth noting that, in some capital and technology-intensive industries, such import-substitution policies may not give state-owned enterprises such an advantageous position as was expected. The petrochemical industry is a typical case. Before 1996, all of the over twenty sets of ethylene production facilities were imported from abroad. Similarly, at the end of the 1980s, almost all of the large domestic steel producers preferred importing production equipment from abroad.

Along with the shifting of China from a planned economy to a market economy, industrial enterprises such as potential clients of HASSMC (especially large state-owned enterprises) suffered from great competition pressures from the market by private sectors and foreign firms. Cost control became a key factor in market competition. In such a situation, equipment and products that were produced by domestic firms began to be an attractive choice for industrial customers. For example, during the Eighth Five-Year (1991-1995) Economic Plan, China deepened its reformation of economic institutions. The central government enforced a new investment policy to mandate that all of the capital investment in engineering projects be raised by the enterprises themselves. Thus, in order to save capital investments, as the superior administrative departments in charge, the former Ministry of Chemical Industry and the China Petrochemical Corporation (Sinopec) encouraged large state-owned enterprises to purchase indigenous equipment in reconstructed or extension projects, if the equipment was suitable in character and proper in price. As a result, the import-substitution project for the ethylene production facility came into implementation for the first time in December 1999 (with the ethylene production facility extension project of Yansan Petrochemical Corporation as the first exemplary project).

The typical marketing strategy for HASSMC was to adjust its product structure according to the changes in China’s industry development policies. For example, before 2004, the sales from the metallurgical industry accounted for 60% to 80% of the total sales revenue. So, the marketing focus was on the clients in the metallurgical industry. Since 2005, along with the adjustment of Chinese energy strategy and the increase in market demand of chemical products, the sales portion for large-scale air separator systems in the petrochemical industry increased steadily to more than 50%. HASSMC’s marketing and sales department closely monitored the changes in the market and tried to find some unsatisfied requirements in segmented markets. This market information and feedback helped HASSMC in designing some modified systems targeted toward creating attractive values for their existing and potential clients.

4.2.2. Mechanisms in learning by recombination

As discussed earlier, the core issue in learning by recombination is to capture the market opportunities in catching-up context, and thus effectively accumulate financial resources from market returns to sustain long-term technological catching-up. During the process of technology development in HASSMC, the following learning mechanisms can be found to be implemented as learning by recombination (see Table 4).

Table 4. The learning mechanisms for learning by recombination in HASSMC

Learning mechanisms	Case A: air separator system Illustrative examples	Case B: ethylene cold box Illustrative examples
1. The integration of external technology and expertise from diverse sources	As a common practice for HASSMC in computing and design software package development, when introducing imported packages from foreign companies, HASSMC would also internally develop a firm-specific version of the software package or some special program modules for the imported packages. In this way, HASSMC has gained a deep understanding of the principles and techniques behind software design and also has established a strong capability for the internal development of products and technology.	Due to the difficulty of accessing advanced technologies from Western countries, HASSMC indigenously had to develop plate-thin heat exchangers through learning by trial-and-error in the early 1960s. Then, they imported plate-thin heat exchanger technology from Linde in terms of technology licensing in 1978. As a milestone in manufacturing capability building, HASSMC exported complete sets of processing machines for plate-thin parts to the Linde Company in 1979.
2. The coordinative development of product designs and the manufacturing process	Salt bath brazing technology was used by HASSMC for the welding process of plate-thin heat exchangers until the fifth generation of technology architecture for air separator systems. However, along with the development of large-scale air separator systems, the size of plate-thin heat exchangers became bigger and bigger, in that traditional salt-bath brazing technology could not meet the product quality requirement. Consequently, HASSMC had to adopt vacuum welding technology in order to replace it and, thus, solve the technology bottleneck emerging during the production process.	In 1975, the self-developed key production equipments were finalised and used in the production of plate-thin heat exchangers. During the 1980s, HASSMC began to indigenously develop a new generation of manufacturing processes for plat-thin heat exchangers, i.e., the vacuum brazing process. Some critical specialised machines and tools (such as non-standard punching machines) had also been developed during this period.
3. The fusion of internal and external	Under the strategic cooperation contract with Messer, HASSMC adopted a fusion strategy for its internal	N.A.

technical routines and standards	technical standards and the technical standards from Messer.	
4. Reconfiguration and exploitation of internal technological expertise	N.A.	Most of the complementary technologies for the ethylene cold box were developed by redeploying the technical expertise in the field of air separator systems.

4.3. Leveraging externally accessible expertise for capability building

The typical mechanisms of learning by decomposition and recombination systematically summarized with the empirical evidence from the case of HASSMC imply the important role of leveraging externally accessible expertise in capacity building. This section gives an extended discussion on the mechanism of absorptive capacity building through externally accessible expertise other than internally possessed knowledge base. According to the absorptive capacity perspective, a firm cannot absorb a certain external technology if it does not have enough prior knowledge (Cohen and Levinthal, 1990). However, as we have found in the case of HASSMC, even in cases when latecomer firms do not have enough existing internal capabilities, they still have the chance to absorb and utilise the external technology by effectively leveraging externally accessible expertise embedded in outside networks.

4.3.1. Leveraging external expertise by collective technology decomposition

In the 1980s, the Chinese government initiated a couple of key industrial construction projects to facilitate the modernisation of the Chinese industry and economic growth. However, due to the weak design and manufacturing capabilities of the Chinese industry at that time, almost all of the complete set of equipments had to be imported. Then, in 1983, the Chinese central government made an official decision to promote the localisation process of key industrial technologies and equipments. Since then, along with the gradual reform toward market system in China, the industrial innovation policy taken by the central government, i.e., a collective technology decomposition strategy, played an essential role in the technological catching-up of Chinese manufacturing.

The roles played by the government were most often as follows. First, the government played the role of general project manager in some collective technology decomposition projects, as revealed in the ethylene cold box case in the present study, the case of indigenous development of digital switches (HJD-04) in Mu and Lee (2005, p.763) and the development case of Korean TDX telephone switching technologies and CDMA wireless systems in Choung and Hwang (2007). The government was in charge of the progress monitoring and the coordination of resource configuration for the projects. Second, as the financial sponsor of the projects, the government would decide the amount of financial support according to the importance and complexity of the technologies involved in the industry-level technological catching-up process. In several instances, it would also help industrial participants to find some appropriate "test customers" in terms of the so-called "first exemplar project", to make the technology decomposition and secondary development proceed in a real industrial application context. Actually, the key industrial construction projects initiated by the central government were usually used as the first exemplar projects.

With regard to the ethylene cold box case, during the period from the late 1990s to 2003, the former State Economic and Trade Commission (SETC) was in charge of the national-level key industrial technology and equipment development projects. The common pattern of project organisation in the petroleum and chemical industry was as follows. An expert panel had been set up in the China Petrochemical Corporation to be responsible for the inspection and selection of key development projects. If a certain key project was selected, it would be reported to the SETC for official approval. Then, a group of partners from the industry, university and academic field would be organised to fulfil the project tasks with the funding support or subsidies from the SETC. As one of the task-specific projects of a national-level key industrial technology and equipment development project, "import-substitution for large-scale ethylene apparatus and system", the ethylene cold box project received two million RMB Yuan in project funding from the government during the period of 1999 to 2003.

Similarly, as to the air separator system case, the design and manufacturing technology of large-scale air separator systems (30,000 m3/h) was listed in the national-level key industrial technology and equipment development projects during the Eighth Five-Year Plan. As the main project undertaker, HASSMC participated in nine task-specific projects that covered all of the related core technologies in designing and manufacturing large-scale air separator systems. All of the development activities were carried out in a real industrial application context by using industrial clients in the non-ferrous metals industry as test customers. After that, HASSMC undertook four task-specific projects concerning the core technical fields of air separator systems for another national-level development project called the "large-scale coal chemical-processing complete sets of equipments" project in the Ninth Five-Year Plan.

By taking part in these collective technology decomposition projects, HASSMC established a relatively complete pool of technology and expertise in large-scale system design and manufacturing, and gained rich experience and deep understanding of client’s industrial application environments and product requirements.

4.3.2. Active involvement of technologically sophisticated domestic users in recombination

The active involvement of technologically sophisticated domestic users can play an essential role in successful technological catching-up in key equipment manufacturing areas (Lee, 1996). There are many ways for technologically sophisticated domestic users to be involved in the technology assimilation and improvements of latecomer manufacturers. A direct way is to serve as the “test customers” who agree to host the first specimen of the new machine or system. For example, Bao Steel, the largest steel producer in China, gave HASSMC a product order for a newly developed large-scale air separator system that was indigenously designed and manufactured by HASSMC in 2002. Sometimes, there are some clients who will be willing to try some new technologies in their ordered products. So, the producers are offered opportunities to test some new idea or technology and improve their newly developed products. In these clients’ plants, the functionality and reliability of a new machine or system could be tested in situations that cannot be simulated in producers' in-house testing facilities. Furthermore, large customers require specific adaptations, or put some generic pressure on the solution of long-standing problems and bottlenecks (Lissoni, 2001, p.1489).

Second, innovations have almost always originated by design efforts directed at meeting some key customers' specific requests, and from the feedback obtained from those customers after testing the new machine (Lissoni, 2001, p.1487). Since some of these active clients have purchased foreign advanced equipments for their sophisticated and customised requirements, their knowledge and experience of using imported products is useful for product improvements by the latecomer firms. In some instances, the workers of their clients would be more experienced in operating equipments and systems than those of the manufacturers. Hence, those sophisticated clients can use their own trouble-shooting experience to help domestic manufacturers effectively detect the flaws of newly developed products and solve technical problems on-the-spot.

4.3.3. Externally accessible knowledge redundancy for recombination

Externally accessible knowledge redundancy is crucial to technology recombination in technological catching-up. The importance of knowledge redundancy to learning by recombination leads to a key principle in the designing structure and process for R&D systems, that is, cost control and reduction cannot be viewed as the only element for consideration. By contrast, an organisation has to design and use certain types of organisational structures and mechanisms as the locus of knowledge redundancy occurrence, and improve its effectiveness in utilising knowledge redundancy. For latecomers, it is important to specially design strategies to make knowledge redundancy by leveraging externally accessible knowledge.

For example, HASSMC funds more than one hundred collaborative projects with universities every year, which covers basic research, design, testing, and toolkit development. It is worth noting that, among these projects, there are some that could have been carried out completed by the company on its own. At the same time, HASSMC purposely adopts the so-called "parallel project mechanism" while setting up collaborative R&D projects with universities and independent research units.[3] That is, when the company initiates a collaborative project with outside partners, it will simultaneously set up an internal development group to carry out a parallel project. By this parallel project mechanism, HASSMC can quickly assimilate the technology, experience and expertise accompanied with the project outcomes from outside partners. In doing so, both the base and the scope of HASSMC's technological expertise pool will be greatly expanded. Thus, gradually, it can develop a strong set of capabilities to monitor, screen and acquire external technology in the frontier.

5. Conclusion

By selecting a Chinese leading enterprise and a world-class manufacturer in the air separator system industry, HASSMC, as the research subject of case study, the present study investigates its technological catching-up during 1978-2008, to examine a structured model for capability building in technological catching-up from a perspective of learning by decomposition and recombination. Capability building in technological catching-up can be

[3] A similar case can be found in the technology catching-up of Hyundai's semiconductor business. Mathews and Cho (1999, p.150) described that, "[Hyundai] let two teams work in parallel to produce both a 'trench' and a 'stack' 4M DRAM, and test them to see which could be produced most efficiently. The parallel teams concept was simply one of a number of important organizational innovations which enabled the Hyundai R&D Lab to sustain a punishing pace of development at this time."

conceptualized as a process in which latecomer firms purposively and strategically utilise specific learning mechanisms of technological decomposition and recombination. The typical mechanisms in learning by decomposition and recombination have been investigated and summarised with empirical evidence.

By identifying the mechanisms of learning by technological decomposition and recombination, this study attempts to open the black box of latecomers' capability building in technological catching-up. First, it shows that even without enough prior knowledge and intense research and development, latecomer firms can rely on the mechanisms of learning by technological decomposition(e.g., gradual participation in cooperative production as subcontractor or seeking help from university and research institutes) to mitigate the potentially negative effect of technological gap between them and MNEs. Second, this study also contributes to the research on technological combination and integration. With suitable mechanisms of technological recombination being implemented in catching-up, latecomers can greatly improve the chance of moving from imitation to innovation in the long run.

Furthermore, the study extends the absorptive capacity perspective (Cohen and Levinthal, 1990) for the context of technological catching-up, which has been widely used in explaining the important role of in-house R&D to technology acquisition, technological learning and capability building in the context of emerging economies (e.g., Kim, 1997, 1998; Liu and White, 1997; UNIDO, 2005). Some previous studies emphasised the role of R&D in building absorptive capacity and posited that late-comers cannot effectively absorb foreign advanced technologies unless they have adequate absorptive capacities (Lall, 1992). However, during the technological catching-up phase of developing countries, a large portion of innovation activities is not based on research and development. Instead, these innovation activities are more related to technology imitation, reverse engineering and incremental improvements (Kim, 1997, 1998; Xu et al., 1998). Thus, the capability building for latecomer firms may take place in those incremental engineering activities other than R&D itself. More importantly, according to the absorptive capacity perspective, a firm's existing absorptive capacity at a given time is basically predetermined by the path along which the firm passes. This logic will lead to the conclusion that, for a certain external technology, a firm cannot absorb this technology if it does not have enough prior knowledge (Cohen and Levinthal, 1990). As a matter of fact, even in cases when latecomer firms do not have enough existing internal capabilities, they still have the chance to absorb and utilise the external technology by effectively leveraging externally accessible expertise embedded in outside networks along with the hierarchical technology ladder in national or regional innovation system, as revealed in the case of HASSMC.

References

Amsden, A.H. 1989. *Asia's Next Giant: South Korea and Late Industrialization*. New York: Oxford University Press.

Bell, M. 1984. 'Learning' and the accumulation of industrial technological capacity in developing countries. In *Technological Capability in the Third World*, ed. K. King, and M. Fransman. London: Palgrave Macmillan.

Bell, M., and K. Pavitt. 1993. Technological accumulation and industrial growth: contrast between developed and developing countries. *Industrial and Corporate Charge* 2(1): 157-210.

Bell, M., and K. Pavitt. 1995. The development of technological capabilities. In *Trade, Technology and International Competitiveness*, ed. I. Ul Haque, and M. Bell. Washington, DC: The Economic Development Institute, World Bank.

Boardman, J. 1990. *Systems Engineering: an Introduction*. New York: Prentice Hall.

Burawoy M. 1991. *Ethnography Unbound*. Berkeley, CA: University of California Press.

Cai, J., and A. Tylecote. 2008. Corporate governance and technological dynamism of Chinese firms in mobile telecommunications- a quantitative study. *Research Policy* 37(10), 1790-1811.

Child, J., and S.B. Rodrigues. 2005. The internationalization of Chinese firms: a case for theoretical extension? *Management and Organization Review* 1(3), 381-410.

Choung, J.-Y, and H.-R. Hwang. 2007. Developing the complex system in Korea: the case study of TDX and CDMA telecom system. *International Journal of Technological learning, Innovation and Development* 1(2), 204-225.

Choung, J.-Y., H.-R. Hwang, J.-H. Choi, and M.-H. Rim. 2000. Transition of latecomer firms from technology users to technology generators: Korean semiconductor firms. *World Development* 28 (5), 969-982.

Cohen, W.M., and D.A. Levinthal. 1990. Absorptive capacity: a new perspective on learning and innovation. *Administrative Science Quarterly* 35(1), 128-152.

Cressey, D.R. 1953. *Other People's Money*. Glencoe, IL: Free Press.

Danneels, E. 2007. The process of technological competence leveraging. *Strategic Management Journal* 28(5), 511-533.

Dantas, E., and M. Bell. 2009. Latecomer firms and the emergence and development of knowledge networks: the case of Petrobras in Brazil. *Research Policy* 38(5), 829-844.

Dodgson, M. 2000. *The Management of Technological Innovation: An International and Strategic Approach*. Oxford: Oxford University Press.

Editorial. 2000. Innovation in complex products and system. *Research Policy* 29, 793-804.

Eisenhardt, K.M. 1989. Building theories from case study research. *Academy of Management Review* 14(4), 532-550.

Ernst, D., and L. Kim. 2002. Global production networks, knowledge diffusion, and local capability formation. *Research Policy* 31(8-9), 1417-1429.

Figueiredo, P.N. 2003. Learning, capability accumulation and firms differences: evidence from latecomer steel. *Industrial and Corporate Change* 12(3), 607-643.

Findlay, R. 1978. Relative backwardness, direct foreign investment and the transfer of technology: A simple dynamic model. *Quarterly Journal of Economics* 92, 1-16.

Gregory, N., and S. Tenev. 2001. The financing of private enterprise in China. *Finance & Development* 38(1), 14-17.

Gu, S.-L., 2000. Learning models and technology strategy in catching-up. DRUID Summer Conference on the Learning Economy – Firms, Regions and National Specific Institutions, Rebild, Denmark.

Haddad, M., and A. Harrison. 1993. Are there positive spillovers from direct foreign investment? Evidence from panel data for Morocco. *Journal of Development Economics* 42, 51-74.

Hobday, M. 1995. East Asian latecomer firms: Learning the technology of electronics. *World Development* 23(7), 1171-1193.

Hobday, M. 1998. Product complexity, innovation and industrial organization. *Research Policy* 26(6), 689-710.

Iammarino, S., R. Padilla-Pérez, and N. von Tunzelmann. 2008. Technological capabilities and global-local interactions: the electronics industry in two Mexican regions. *World Development* 36(10), 1980-2003.

Jang, S.-L., S. Lo, and W.-H. Chang. 2009. How do latecomers catch up with forerunners? Analysis of patents and patent citations in the field of flat panel display technologies. *Scientometrics* 79(3), 563-591.

Jefferson, G.H., Hu, A.G., Guan, X., Yu, X., 2003. Ownership, performance, and innovation in China's large- and medium-size industrial enterprise sector. *China Economic Review* 14(1), 89–113.
Jefferson, G.H., Rawski, T.G., 1995. How industrial reform worked in China: the role of innovation, competition, and property rights. Proceedings of the World Bank Annual Conference on Development Economics 1994, The International Bank for Reconstruction and Development / The World Bank, 129-156.
Kim, L. 1997. Imitation to Innovation: The Dynamics of Korea's Technological Learning. Boston, MA: Harvard Business School Press.
Kim, L. 1998. Crisis construction and organisational learning: capability building in catching-up at Hyundai Motor. *Organization Science* 9(4), 506-521.
Kogut, B., and U. Zander. 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science* 3(3), 383-397.
Lall, S. 1992. Technological capabilities and industrialization. *World Development* 20(2), 165–186.
Lee, K.R. 1996. The role of user firms in the innovation of machine tools: The Japanese case. *Research Policy* 25(4), 491-507.
Lee, K. 2005. Making a technological catch-up: barriers and opportunities. *Asian Journal of Technology Innovation* 13(2), 97-131.
Lee, K., and C.-S. Lim. 2001. Technological regimes, catching-up and leapfrogging: findings from the Korean industries. *Research Policy* 30(3), 459–483.
Lissoni, F. 2001. Knowledge codification and the geography of innovation: the case of Brescia mechanical clusters. *Research Policy* 30(9), 1479-1500.
Liu, X.-L., and S. White. 1997. The relative contributions of foreign technology and domestic inputs to innovation in Chinese manufacturing industries. *Technovation* 17(3), 119-125.
Liu, X.-L, and S. White. 2001. Comparing innovation systems: a framework and application to China's transitional context. *Research policy* 30(7), 1091-1114.
Mathews, J., and D.S. Cho. 1999. Combinative capabilities and organizational learning in latecomer firms: the case of the Korean semiconductor industry. *Journal of World Business* 34(2), 139-156.
Mazzoleni, R., and R.R. Nelson. 2007. Public research institutions and economic catch-up. *Research Policy* 36, 1512-1528.
Mu, Q., and K. Lee. 2005. Knowledge diffusion, market segmentation and technological catch-up: the case of the telecommunication industry in China, *Research Policy* 34(6), 759-783.
Perez, C., and L. Soete. 1988. Catching up in technology: entry barriers and windows of opportunity. In Technical Change and Economic Theory, ed. G. Dosi, et al. London: Pinter Publishers.
Scott-Kemmis, D., and C. Chitravas. 2007. Revisiting the learning and capability concepts -building learning systems in Thai auto component firms. *Asian Journal of Technology Innovation* 15(2), 67-100.
Shenhar, A.J. 1994. A new conceptual framework for modern project management. In *Management of Technology IV*, ed. T.M. Khalil, and B.A. Bayraktar. New York: Institute of Industrial Engineers.
Tsekouras, G. 2006. Gaining competitive advantage through knowledge integration in a European industrialising economy. *International Journal of Technology Management* 36(1-3), 126-147.
United Nations Industrial Development Organization (UNIDO). 2005. Capability building for catching-up: Historical, empirical and policy dimensions. *Industrial Development Report*, Vienna.
Wang, J.-Y., and M. Blomström. 1992. Foreign investment and technology transfer: a simple model. *European Economics Review* 36(1), 137-155.
Wu, X., R. Ma, and G. Xu. 2009. Accelerating secondary innovation through organizational learning: A case study and theoretical analysis. *Industry & Innovation* 16(4-5), 389-409.
Xie, W., and G.-S. Wu. 2003. Differences between learning processes in small tigers and large dragons: learning processes of two color TV (CTV) firms within China. *Research Policy* 32, 1463-1479.
Xie, W., and S. White. 2004. Sequential learning in a Chinese spin-off: the case of Lenovo Group Limited. *R&D Management* 34(4), 407-422.
Xu, Q.-R., J. Chen, and B. Guo. 1998. Perspective of technological innovation and technology management in China. *IEEE Transactions on Engineering Management* 45(4), 381-387.
Yin, R. 1984. *Case Study Research: Design and Methods*. Beverly Hills: Sage Publications.