Article:

Lee, JJ and Yoon, H orcid.org/0000-0003-1423-9808 (2015) A comparative study of technological learning and organizational capability development in complex products systems: Distinctive paths of three latecomers in military aircraft industry. Research Policy, 44 (7). pp. 1296-1313. ISSN 0048-7333

https://doi.org/10.1016/j.respol.2015.03.007

Citation Information: Lee, J. J., & Yoon, H. (2015). A comparative study of technological learning and organizational capability development in complex products systems: Distinctive paths of three latecomers in military aircraft industry. *Research Policy*, *44*(7), 1296-1313.

A comparative study of technological learning and organizational capability development in complex products systems: Distinctive paths of three latecomers in military aircraft industry

Joosung J. Lee*
KAIST (Korea Advanced Institute of Science and Technology), Department of Business and Technology Management, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea

Hyungseok Yoon
De Vinci Research Lab, Pôle Universitaire Léonard de Vinci, 12 Avenue Leonard de Vinci, 92400, Courbevoie, France

*Corresponding author. Tel.: +82 42 350 4914
E-mail addresses: jooslee@kaist.ac.kr (J.J. Lee), davidhsyoon@gmail.com (H.S. Yoon)

Abstract

This paper identifies different patterns of latecomers' technological learning in developing complex products systems (CoPS). The experiences of South Korea, China, and Brazil in military aircraft development are compared to explain the learning process in attaining indigenous technological capability. The military aircraft development programs involving international technology transfer agreements have been documented to investigate the technological learning patterns. We find different technology acquisition modes determined by latecomers' focus of knowledge-base: technological for "make" and production for "buy". We also find that these modes may influence the process of learning-by-doing. In addition, we find how the role of foreign partners influences technology acquisition mode. Whereas an active role results in co-production or co-development arrangement, a passive role leads to the vitalization of reverse engineering. We also shed light on the role of government policy initiatives that facilitate technological learning. Lastly, this paper extensively documented the successful technological learning in South Korea's T-50 and Brazil's AMX joint venture projects.

Keywords: Complex products systems, Latecomer technological learning, Military aircraft industry, Technology acquisition

1. Introduction

Complex products systems (CoPS) are systems, networks, infrastructure and engineering constructs, and services that are highly costly and technology-intensive. They shape and enable modern industrial and economic progress with the introduction of new technology to the economic system (Hobday, Davies, Prencipe, 2005). Most CoPS research has until recently focused on developed countries, as latecomers have shown their intrinsic weaknesses stemming from the high entry barriers (Park, 2012). In order to fill in this gap, we document the cases of KAI (Korea Aerospace Industries) for South Korea, Embraer for Brazil, and AVIC (Aviation Industry Corporation of China) for China that have successfully acquired indigenous technological capability to develop their own military aircraft (Goldstein, 2002; Vertesy and Szirmai, 2010). Although these three countries are generally considered as latecomers owing to their late-industrialization, Brazil and China have entered the aircraft industry quite early. In order to avoid the confusion on the extent of a latecomer, we define latecomers as firms who have been recipient of technology transfer whether through a formal or informal mechanism from the beginning of their aircraft industry.

For latecomers, this industry presents special challenges, as it is one of the most technologically intensive and complex industries with a steep learning curve for new entrants (Frischtak, 1994; Smith and Tranfield, 2005). This is the reason why cross-border alliance in aerospace and defense sector is a common behavior and constitutes a significant portion of the partnerships set up in manufacturing industries (Hergert and Morris, 1988; Dussauge and Garrette, 1995; Garrette et al., 2009). Regardless of the challenges and difficulties, latecomers recognize its importance and pursue technological breakthrough with the support of foreign partners. Since the industry involves a wide range of technology, it has a large ripple effect across all industries. In fact, military aircraft industry requires state-of-the-art technology not only confined to aviation engineering, but also across all high-tech disciplines such as mechanical, electronic, computer science, materials, systems engineering, etc. Despite its importance, very little is known about how cross-border technology transfer contributes to successful technological learning in latecomers' military aircraft industry (Hobday, Rush, Tidd, 2000).

Most of the time, latecomer's initial learning is limited to performing production work as a subcontractor to major foreign integrators. Later, this is extended into absorption of design and system integration experiences through co-development schemes such as joint venture (Hobday, Rush, Tidd, 2000). However, our strand of literature suggests that this typical pattern of latecomers' technological learning may differ contingent on the context of countries and industries (Gerschenkron, 1962; Pavitt, 1984; Nelson, 1993; Teece et al., 1997; Kim, 1998). First, the difference is derived from the focus of their knowledge-base influenced by industrial policy prior to the formal embarkation of the industry. Secondly, security-sensitive nature of military aircraft industry influences latecomers' accessibility to external resources which is reflected in the extent of foreign partners' role whether it is active or passive (Cho and Lee, 2003; Li, 2010). Thus, we posit that these factors may shape the patterns of technological learning in acquiring indigenous technological capability.

Based on these contextual factors, we identify patterns of technology acquisition mode and major technological advancement made through the cross-border alliance that facilitates knowledge and technology transfer in their respective military aircraft industry (Mowery, 1987; Hergert and Morris, 1988; Dussauge and Garrette, 1995). We also document milestone projects "AMX for Brazil" and "T-50 for South Korea" to shed light on key technological asset and skillset acquired throughout the development stages which has not been addressed in previous studies on latecomers' technological catch-up in CoPS (Choung and Hwang, 2007; Jun, 2011; Park, 2012). Lastly, we also identify the role of organizational capabilities in orchestrating latecomers' technological learning in CoPS. Previous literature on CoPS mainly emphasized the role of organizational capabilities in creating similar projects at minimum cost which may not be applicable to latecomers' cases (Davies and Brady, 2000). In fact, this conventional approach in CoPS with its emphasis on cost-minimization hinders us to address latecomers' main concern raised by technological barriers throughout the lifecycle of CoPS (Hobday, 1995). Thus, this paper mainly focuses on the technological learning outcomes instead of focusing on economic outcomes of aircraft development programs involving foreign partners. In addition, existing literature on organizational capabilities have been applied at firm-level. However, it is important to note that latecomers' military aircraft industry involves active participation of government policy makers (King and Nowack, 2003; Cho, 2003). In other words, existing organizational capabilities should be applied at government-level. In fact, three companies including Embraer, KAI, and AVIC for our study are state-owned companies in our analysis time frame. Thus, we find how latecomer government policy initiatives successfully facilitate technological learning.

Our study intends to contribute to the literature in three important aspects. First, while the conventional studies of latecomers' technological learning in aircraft industry claim that technological capability is obtained after practicing some production activities, we move beyond this sequence by identifying its determinants. Specifically, we ask how the focus of knowledge-base affects technology acquisition mode and learning by doing process. For this purpose, we compare the cases of Brazil with South Korea and China. Second, we find how the role of foreign partner influences latecomer's technology acquisition mode by comparing the cases of China with South Korea and Brazil. Third, we attempt to make a contribution to the literature by documenting the joint venture project "T-50" of South Korea and "AMX" of Brazil. With these projects, South Korea and Brazil gained global recognition for their aerospace technologies. The cases offer practical methods and detailed process of project-based technological learning. Lastly, we clarify the role of the government policy initiatives for CoPS in orchestrating latecomers' technological learning. We further advance the current operationalization of each capability by applying the recent stream of research in latecomers' CoPS (Lee et al., 2009; Park, 2012; Choung et al., 2012). By doing so, we find the key success factors of each case from strategic, functional, and project capability-building perspectives.

The remainder of this study is organized as follows. Section 2 begins with the theoretical background by reviewing the streams of literature in latecomers' technology acquisition strategies and organizational capabilities for CoPS. With the theoretical foundation, an analytical framework is built to examine the technological learning. Section 3 entails methodological approach and process along with brief background information on our cases. Section 4 compares the technology acquisition mode determined according to the focus of knowledge-base and the role of foreign partners. We also document the technological advancement and learning outcome of the three latecomers and the summary of T-50 and AMX joint venture projects. Section 5 provides a summary of the latecomer government policy initiatives to discuss implications, followed by concluding remarks on our theoretical and practical contributions.

2. Theoretical background

2.1. Major determinants of latecomers' technology acquisition strategy

In the past, literature on latecomers' technology acquisition strategy focused on cross-border knowledge transfer mechanism. In order to imitate, improve existing technologies, and create new products, latecomers absorb information and know-how by collaborating with foreign partners from advanced countries (Pack and Westphal, 1986; Lall, 1993; Kim, 1999; Ahuja, 2000; Powell et al., 2005). Kim (1997) developed a framework "knowledge transfer mechanisms" which consisted of formal and informal mechanisms and commodity trade to explain latecomers' learning with foreign support. Based on this theoretical establishment, scholars in latecomers' technology acquisition and learning highlight the success of East Asian economies with their active learning strategies (Viotti, 2002). In a similar manner, Etzkowitz and Brisolla (1999) investigated the reasons why Brazil of Latin America had fallen behind South Korea of East Asia after an apparent head start. Whereas the former concentrated its resources on indigenous basic research to be thoroughly convinced of technological superiority, the latter focused on reinforcing its production capacities to replicate foreign partners' manufacturing techniques. In spite of such evidences, the existing studies on latecomers seem to have accomplished little. The main reason is that most of the studies have conducted national-level analysis which hinders us from considering industry or firm-specific success. In addition, the limitation of the previous literature lies in mainly considering commodities or mass-produced goods. Although CoPS industry requires foreign partners' assistance just as in commodity and mass-produced goods industries, there are some differences in the extent of higher technological barriers and strategic uncertainties (Cho and Lee, 2003; Li, 2010).

In order to overcome the limitations, we refer to technology acquisition strategies for latecomers' military aircraft industry identified by Institute for National Strategic Studies (see Saunders and Wiseman, 2011). Acquisition strategies consist of purchase (buy), indigenous development (build), espionage (steal), reverse engineering, co-production, and co-development. For the sake of theoretical clarity and unbiased analysis, we exclude the option of espionage (steal). Given these information sources, we can distinguish between the different strategies that can be employed for latecomers to acquire and develop technology. The theoretical literature that exists on these strategies stresses the choice between internal development and external development is "Make" or "Buy" approach. Whereas "Make" corresponds with indigenous development (build) option, "Buy" is preferred by latecomers with limited technological capabilities. These two options are closely related with the very first stage of the aircraft industry development and the focus of latecomers' knowledge-base determined by industrial policies. Whereas Asia's national development policies were primarily focused on improving production capabilities, Brazil of Latin America focused upon raising the level of basic research to create new industries (Etzkowitz and Brisolla, 1999). In a consistent manner, whereas "Make" is available for latecomers with significant resources invested in research and development, “Buy” is preferred by production-oriented latecomers with relatively low technological resources. In general, “Buy” is the most preferred mode of initial acquisition, as most latecomer countries ‘begin with maintenance shops, move next to the assembly of imported planes, and to the manufacture under license of military planes for the local market with some eventually doing subcontract work for major aircraft producers’ (Moxon, 1987; Frischtak, 1994).

These initial acquisition strategies lead us to the subsequent stage of acquisition. Acquisition modes in this stage consist of reverse engineering, co-production, and co-development that are by-product of “Buy” option. In this subsequent stage, the degree of foreign partners’ role determined by the political relationship between knowledge transmitters and receivers is an important factor. For instance, developed countries often restricts export of the sophisticated technology such as avionics and weapon systems due to their strategic concerns or to maintain a technological advantage of their own (Lee, 2008; Saunders and Wiseman, 2011). Consistent with this fact, reverse engineering is preferably adopted by a latecomer with low level of accessibility to foreign knowledge-base which may be reflected in passive role of foreign partner. As a result, reverse engineering requires an accumulated knowledge base to proactively imitate and add a little modification to the original product. In contrast, co-production and co-development are facilitated when foreign partners show their active role (Kim, 1998; Saunders and Wiseman, 2011). Co-production refers to a contract for latecomers to retain their right to produce copies of a complete aircraft or key components. This deal includes assembly of imported complete knock-down (CKD) kits that may give latecomers an independent production capability. Co-development refers to cooperation in the design stage of aircraft development and latecomers gain design and system integration expertise. The partners typically share the cost and work content. This way, the profit made from selling a new complete aircraft to third parties may be shared by the partners (Saunders and Wiseman, 2011).

2.2. Policy initiatives for technological learning in CoPS

With the introduction of CoPS by Miller, Davies, and Hobday, researchers have focused on the cases of developed economies such as Europe and U.S. One of the main interests in their conventional studies was to understand the organizational capabilities required for the development of CoPS. Organizational capabilities in CoPS have applied ‘dynamic capability’ to explain the importance of mobilizing various resources and technologies for system integrators to meet and satisfy clients’ requirements (Davies and Brady, 2000). In contrast, Chandler (1990) proposed an organizational capabilities framework avoiding a top-down, strategic management view of the firm, by including non-strategic capabilities. Chandler’s work has been extended by Davies and Brady (2000) and Hobday (2005) to understand capabilities required for CoPS. Whereas Chandler (1990) addressed the importance of strategic and functional capabilities for mass-production, Hobday (2005) emphasized strategic and project capabilities for CoPS development.

Accordingly, Davies and Hobday (2005) introduced three organizational capabilities required for CoPS which consisted of strategic capability, functional capability, and project capability. First, strategic capability is defined as an ability to allocate resources and implement long-terms plans for the purpose of maintaining, renewing, and expanding organizational capabilities. The role of leadership in monitoring internal operations and adjusting strategies to a changing environment was emphasized. Secondly, functional capability in CoPS is structured near the technological aspects including designing, engineering, and integrating the diverse knowledge inputs and subsystems. Lastly, project capability is essential in managing relationships with partners in designing and implementing CoPS throughout the project life-cycle (Davies and Brady, 2000).

However, the organizational capabilities derived from the cases of developed countries may neglect the technological barriers faced by the latecomers (Davies and Brady, 2000). In other words, how organizational capabilities facilitate technological learning is the key issue to be addressed for latecomers’ successful CoPS development (Hobday, 1995). A few studies on latecomers’ technological catch-up in CoPS have been carried out by using the cases of telecommunication systems. Choung and Hwang (2007) explained that South Korea’s success stemmed from the critical role of public research institutions in technological evolution. In addition, Jun (2011) identified integration capability, network effects and the national installment base as required capabilities for survival and growth of latecomers' CoPS. Similarly, Park (2012) identified major capabilities in South Korea's success as networking, knowledge base, and leveraging policies. Above all, the authors commonly emphasized the importance of acquiring technology from foreign partners through technology licensing, joint development, and joint research agreement. Nevertheless, none of the studies specifically addressed the degree of foreign partners' role through which latecomers' technological learning is orchestrated with the development of organizational capabilities.

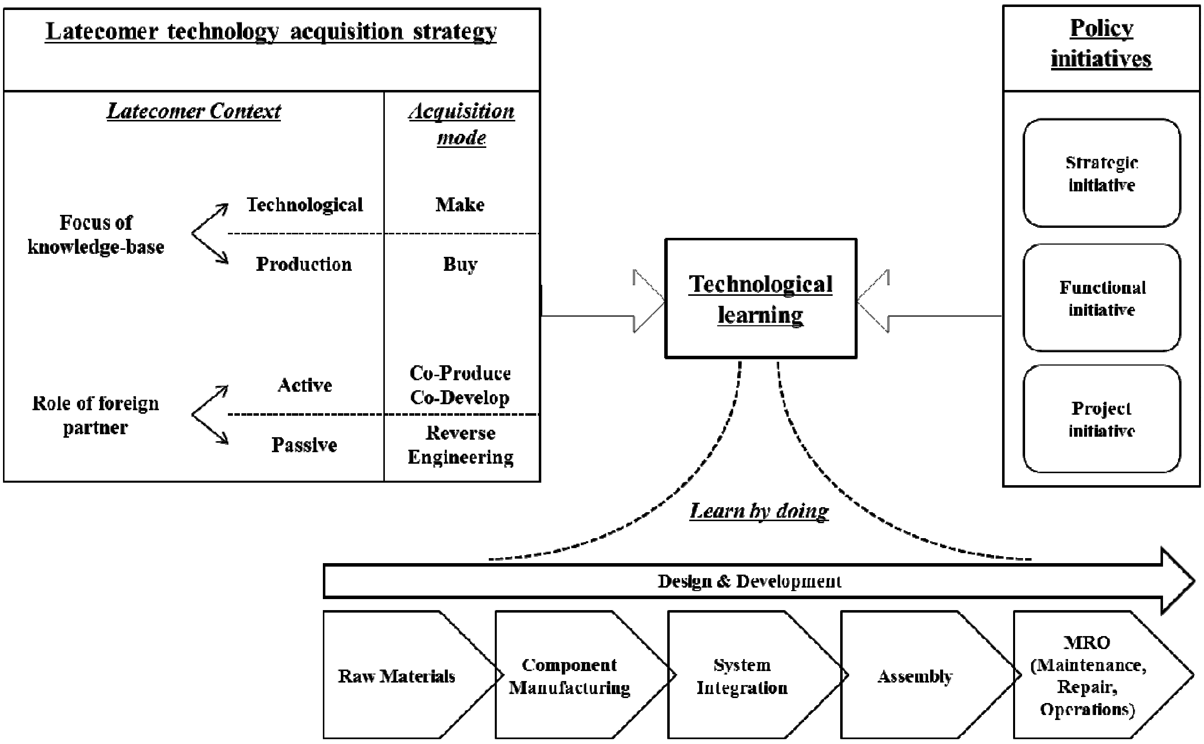
In addition, organizational capabilities have been mostly applied at firm-level in previous literature. This necessitates observing the role of government in facilitating the development of organizational capability for technological learning. For instance, the rise of latecomer firms should be explained with latecomer governments' sophisticated sector-specific policy initiatives, as these industrial policy initiatives have a wide-ranging impact on firm-level competitiveness (Ham and Mowery, 1995; Nelson, 1995; Vogel, 1996; King and Nowack, 2003). Also, offset agreements are one of the most prevalent technology transfer modes in military aircraft industry. In fact, when arms sales involve offsets, government policies represent an important environmental factor that needs to be considered by corporate managers (King and Nowack, 2003). This is reflected in the status of latecomer firms engaged in military aircraft industry where most of them are state or government-owned companies. Thus, we examine latecomers' government policies or initiatives in military aircraft development by applying the organizational capabilities.

2.3. Analytical framework

This study discusses latecomers' technological learning from the perspective that the learning is facilitated by technology acquisition strategies and policy initiatives (See Figure 1). In order to look into latecomers' technology acquisition strategy, we adopt technology acquisition mode determined by latecomers' context. The first context is derived from the focus of latecomers' knowledge-base which is explained by the establishment order of innovation meso-systems for CoPS (Miller et al., 1995; Principe, 2013). In this study, we adopt the supply-side of meso-systems composed of two main groups including the system integrators (aircraft manufacturers) and the innovation infrastructure (government-funded laboratories and universities, the suppliers). In general, latecomers' military aircraft industry begins by building the innovation infrastructure in the first hand. Depending on the focus of knowledge-base determined by latecomers' industrial policy, the establishment of innovation infrastructure may vary. On one hand, government-funded laboratories and universities are established, if latecomers' focus is on building technological capabilities to generate and manage technological change. On the other hand, suppliers are established, if latecomers' focus is on the development of production capabilities to produce goods at given levels of efficiency and given input combinations (Bell and Pavitt, 1993; Etzkowitz and Brisolla, 1999). For the second context, we adopt the role of partners in determining the acquisition mode. Whereas an active role of foreign partner results in co-production or co-development agreement, a passive role of foreign partners induces latecomers to focus on reverse engineering (Saunders and Wiseman, 2011). Above all, we posit that technology acquisition modes have an impact on the process of technological learning which is represented by "Learning by doing". In order to capture the process, we have referred to the value chain of aerospace industry proposed by World Economic Forum (2013) consisting of design & development, logistics, raw materials, component manufacturing, systems integration, assembly, and aftermarket MRO (Maintenance, Repair & Operations). Since we are focusing on the dimensions of technological learning, we exclude logistics from our analysis. By analyzing milestone projects along with major technological advancement, we figure out the order of activities comprising "Learning by doing".

Latecomers' technological learning is essentially facilitated by their policy initiatives (Hobday, 1995; Matthews and Cho, 2000; Amsden and Chu, 2003; Dodgson, 2009). As most of aviation industry starts with the involvement of government, we modify the operationalization of organizational capabilities in existing literature to be applied at national-level. First, the strategic initiative is represented as latecomers' national strategic intention to enter dynamically into technological fields with strong intent and clear goals (Lee et al., 2009; Park, 2012; Choung et al., 2012). The intention requires promoting the necessity of R&D activities, forming an aerospace cluster and executing lavishing investment. Secondly, the functional initiative requires acquiring broad, deep, and integrated knowledge and skills for understanding many diverse elements of aircraft. This initiative is represented in the form of technology policies to build knowledge base and educate human capital (Lee et al., 2009; Park, 2012). Thirdly, the project initiative is represented in the form of an ability to collaborate with various actors in order to orchestrate technological learning and product development in an efficient manner. Since military aircraft development features high-confidentiality and even causes political tension, it is important to select and work with right domestic and foreign partners (Lee et al., 2009; Park, 2012). We refer to government procurement and export policies as well as other relevant policies vitalizing the participation of multiple actors.

Fig. 1. Analytical framework



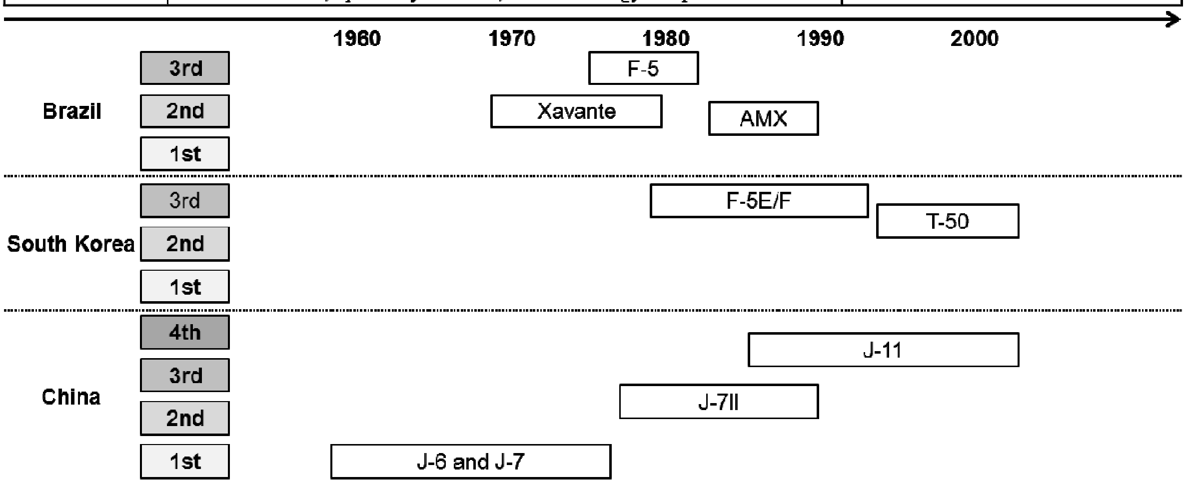
3. Methodology

This study documented the military aircraft development projects by South Korea, Brazil, and China to compare the difference in technological patterns between East Asia (China and South Korea) and Latin America (Brazil). In particular, this study investigated the patterns by observing the technological advancement via international technology transfer arrangements including co-production and co-development projects (See Figure 2). The military aircraft industries and projects of 1945-1999 in Brazil, of 1969-2012 in Korea, and of 1952-1999 in China have been analyzed. Despite the different time period of analysis, our comparative approach is rationalized with the following reasons. First, the different time period of analysis does not compromise the comparability of this study, as the main objective of this study is not to compare latecomers' different strategies to gain competitive position within the industry, but to analyze different patterns of technological learning to become indigenous developers. Second, the three latecomer governments have initiated their industries with the support of military regimes. This allows us to focus on the military aircraft development programs that have been the main interest of the governments during the time period of our analysis. In this sense, comparative case study methodology was adopted to historically analyze the overall evolution of the industry and study new product development involving the participation of foreign partners (Skocpol, 1979; Freeman, 1991; Dittrich et al., 2007).

Our approach is also based on event analysis by focusing on the embarkation of the industry and the technological advancement via cross-border alliance events. This allows us to increase our understanding of latecomers' key technological advancement through milestone projects with foreign partners (Prencipe and Tell, 2001; Brady and Davies, 2004). However, there are some methodological concerns arising from the fact that our cases show the variance in the technological level of jet fighters. For instance, China produced prototypes of stealth and achieved its status as a producer for 4th generation jet fighters in 2000s. On the other hand, Brazil achieved its indigenous technological capacity to produce only a subsonic ground-attack aircraft in 1984. In addition, South Korea achieved the technological capacity as an indigenous developer by producing a supersonic trainer in 2002.

Fig. 2. Generation of fighters (Tirpark, 2009) and matching of aircraft in this study

Generations	Technological features	Relevant fighters
Generation 1	Jet propulsion	F-80, German Me 262
Generation 2	Swept wings; range-only radar; infrared missiles	F-86, MiG-15
Generation 3	Supersonic speed; pulse radar; able to shoot at targets beyond visual range	"Century Series" fighters such as F-105; F-4; MiG-17; MiG-21
Generation 4	Pulse-doppler radar; high maneuverability; look-down, shootdown missiles	F-15, F-16, Mirage 2000, MiG-29
Generation 4+	High agility; sensor fusion; reduced signatures	Eurofighter Typhoon, Su-30, advanced versions of F-16 and F/A-18, Rafale
Generation 4++	Active electronically scanned arrays; continued reduced signatures or some "active" (waveform canceling) stealth; some supercruise	Su-35, F-15SE
Generation 5	All-aspect stealth with internal weapons, extreme agility, full-sensor fusion, integrated avionics, some or full supercruise	F-22, F-35
Potential Generation 6	Extreme stealth; efficient in all flight regimes (subsonic to multi-Mach); possible "morphing" capability; smart skins; highly networked; extremely sensitive sensors; optionally manned; directed energy weapons	



Note: The military aircraft development programs in this study focus on the technological learning dynamics in international technology transfer programs for jet fighter development projects. The projects that have carried out in the form of co-production and co-development with foreign partner were selected.

This may have been due to the fact that generation of jet fighters differs depending on latecomers' geo-political environment and national strategic focus. South Korea and China are focusing on defense aviation, due to political tensions in their respective geographic locations. In contrast, since the 90s, Brazil has shifted their strategic focus from military aviation to civil aviation. In fact, 90 percent of the Brazilian aircraft industry is derived from civil aviation, while 8.5 percent is from defense sector (Maculan, 2013). In this sense, the technological momentum gained with the AMX presented Embraer's engineers with an 'opportunity' to exploit the capabilities acquired fully, and led eventually to design civilian aircrafts in the category of CBA (Frischtak, 1994). In fact, between 1997 and 1999, the new family of regional jets (ERJ –145 and ERJ -135) accounted for more than 60 per cent (195 units) of the total of 310 aircraft which has become the most important marketable good for Embraer (Cassiolato et al., 2002). In contrast, the successful development of T-50 have led Korea and KAI to develop and produce other defense-related products ranging from light attack jetfighters (T-50 families) and multirole helicopters "Surion". In order to conduct case analysis, our approach captures how each country walked through unique paths to become an indigenous developer of military aircraft rather than comparing the results of producing higher generation jet fighters.

The approach may raise some methodological concerns over the definition of "indigenous developer of military aircraft". However, there are no self-evidently obvious criteria for judging "indigenous developer of military aircraft". The variation over the term is caused by procurement strategies, acquisition styles and philosophies, technological change, technical uncertainties, and so forth. Therefore, "indigenous military aircraft industry" is simply defined as having technological and production capabilities for indigenous aircraft development. Measuring their extent with secondary data is extremely difficult. Due to its arbitrary nature, interviews with engineers in product development and project managers of Korea Aerospace Industries (KAI) and Embraer have been conducted. To be more objective, we posited that the mastery of systems integration leads latecomers to achieve their status as indigenous aircraft developers. The reason is that systems integration is a core technological capability for complex product systems which is the most difficult capability to be mastered (Brusoni and Prencipe, 2001; Brusoni et al., 2001; Magnusson et al., 2005).

In addition, our historical and comparative approach also suffers from some limitations for arriving at universal conclusions with a process of verification or falsification (Goldstein, 2002). In fact, there exist variations in the time frame of each case which gives us difficulties to make direct comparisons. Still, it is important to approach the technological learning from evolutionary perspective to understand more in-depth and comprehensive view on the technological learning in military aircraft industry from different institutional background (Phillips and Su, 2009; Su and Hung, 2009). To overcome the methodological issues, we mainly have relied on secondary materials such as government reports and research articles (Goldstein, 2002). These secondary materials have been cross-checked through our interviews with experts. Despite the limitations, our approach offers insights that may be valid in the context of this study.

We have conducted research with the director of Golden Eagle Engineering Research Center who successfully spearheaded the development of South Korea's T-50. We also have interviewed the chief engineer for T-50 development. Both of our interviewees were dispatched to Lockheed Martin to learn design and system integration know-how. With their experiences, they helped us to validate our analytical framework composed of technology-specific dimensions and identify the technological learning dynamics through the cross-border alliance. Interviews with the former chief engineer of product development at Embraer have been carried out to obtain data on Brazil's jet fighter projects. Secondary data were also collected through library research to cross-check and complement our field data (See Table 1).

Table 1
Data sources for the study

Type of data	Collection period	Location and data source	Major content and data coverage period
Primary Data			
Interview by e-mail and direct contact	Dec. 2012-Nov. 2013	Brazil & South Korea	Embraer's technological learning in "AMX" project (1980-1999)
Interview by e-mail and direct contact	Jan. 2011-Sept. 2013	South Korea	KAI's technological learning in "T-50" project (1989-2012)
Secondary Data			
Annual Financial Data of Embraer	Dec. 2013	Data Stream	R&D investment (1985-2012) CAPEX (1999-2012) Sales (1985-2012)
Annual Financial Data of KAI	Dec. 2013	KISVALUE	R&D investment (2002-2012) CAPEX (2002-2012) Sales (2002-2012)
Annual Financial Data of AVIC	Dec. 2013	Data Stream, Annual Report	R&D investment (2009-2012) Sales (2009-2012)
SIPRI Arms Transfers Database	Jan. 2014	SIPRI (Stockholm International Peace Research Institute) Website	Inward transfer of military aircraft (1950-2012)
Patent data	Jan. 2014	OECD Patent Database	Patents filed under the PCT in air vehicle classes (1978-2011)
SIPRI Arms Transfers Database	Jan. 2014	SIPRI (Stockholm International Peace Research Institute) Website	Export of military aircraft (1976-2004)
Other secondary data	Nov. 2013-Dec. 2013	South Korea	Company annual reports and other reports on AVIC and Chinese aircraft industry

4. Paths of latecomers' technological learning

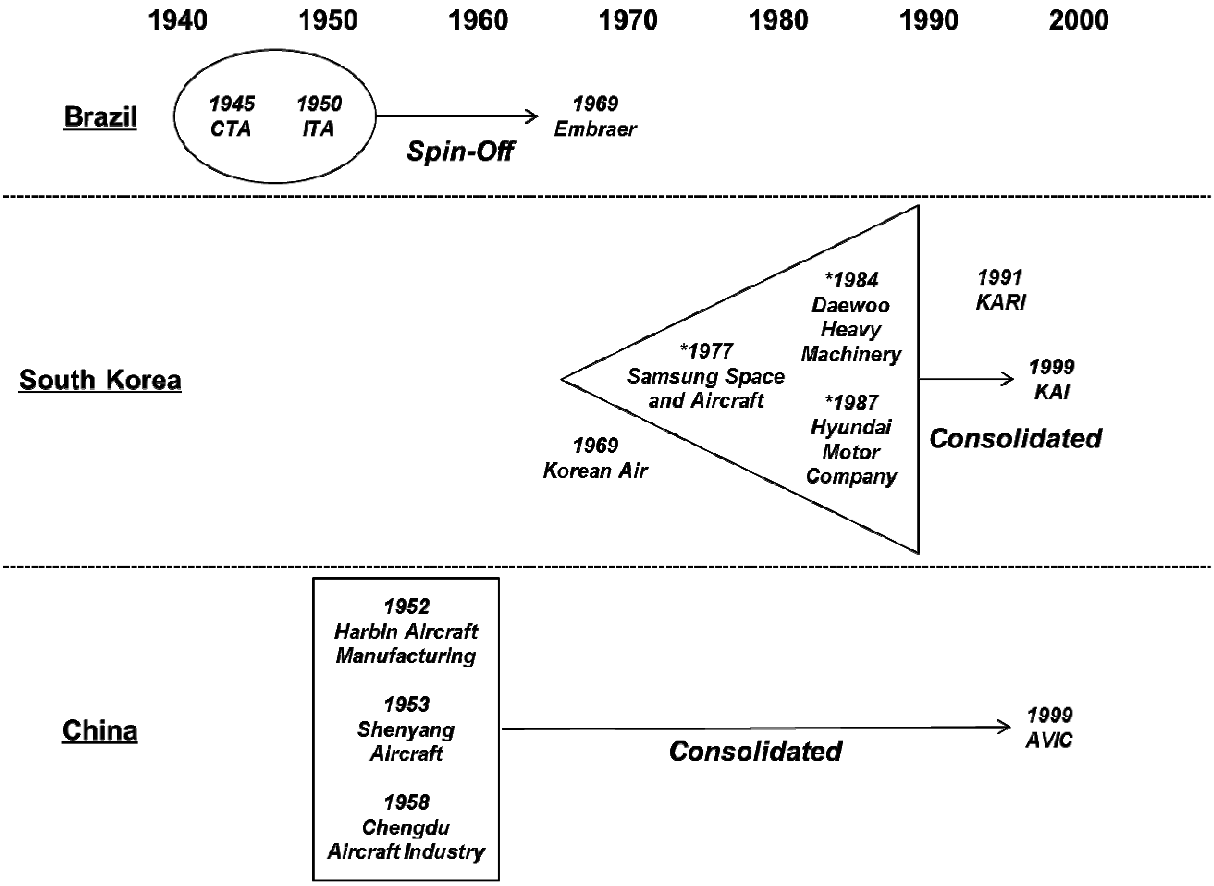
4.1. Determinants and patterns of technology acquisition modes

4.1.1. Knowledge-base and technology acquisition modes

Brazil's military aircraft industry is well represented by Embraer which is responsible for around 80 percent of the production activity in the sector (Maculan, 2013). In the early years, Brazil adopted industrial policies to raise the level of local technological research rather than focusing on enhancing their production capacities. In a consistent manner, Moxon, one of the first scholars to argue the features special to Embraer's development paradigm, held that "Embraer had focused on the design and manufacture of airframes, and systems integration and testing. Not that it was never involved in pure assembly operations of both military and civilian planes, or in subcontract work, but these were never the company's main concern" (Moxon, 1987). Likewise, Brazil's acquisition mode was based on "Make" approach with their focus on technological knowledge. In order to understand the argument, it is important to address the origins of Embraer. After the Second World War, an influential Brazilian military general Carlos de Meira Mattos promoted ideas on enhancing Brazil's international structure through the modernization of technological and industrial base (Sikkink, 1991). In reflection of his thought, CTA (Aerospace Technical Center) was established in 1945 to coordinate aerospace research activities (See Figure 3). The engineering school "ITA" (Aeronautics Technological Institute) was also established in 1950 with the inspiration of Air Force hero Casimiro Montenegro Filho. In the early years, ITA established international cooperation with MIT (Massachusetts Institute of Technology) and Caltech (California Institute of Technology) to make sure that the aviation sector would engage in self-sustaining R&D. The successful launch of education system at both undergraduate and graduate-level resulted in supporting CTA, the ITA's umbrella organization, by fulfilling its demand for engineers. More importantly, the first president of Embraer was an engineer graduated from ITA who had spearheaded the development of the very first aircraft prototype "Bandeirante". Not only the president of Embraer, but most of the engineers and staff of Embraer had been graduates of ITA or researchers at CTA. In other words, Embra, established in 1969, was a natural spin off of the CTA (Maculan, 2013).

In contrast, South Korea and China of East Asia adopted industrial policies mainly oriented toward improving their production capabilities. This is why the focus of their aircraft industry in the early years was on depot-level maintenance and manufacturing activities based on "Buy" approach (Heymann, 1975; Cho, 2003). Although there were some Chinese initiatives for design and indigenous development, much of their final work appeared to be imitation of their partnering country's technology. For instance, SADO (Shenyang Aero-Engine Design Office) was established in 1956 which later was re-named into SARI (Shenyang Aero-Engine Research Institute). Aeronautical Engineering Society was also established in 1963 and promoted "design reform campaign" in 1964. However, the first native-design Chinese military aircraft "F-9" was appeared to have imitated much of its airframe and engine design from the Soviet MiG-19. In short, the successes the Chinese achieved were not in design technology, but in manufacturing through reverse engineering (Heymann, 1975). South Korea also initiated the project KTX-1 in 1988 with the support of government R&D funds and public research institutes. However, this national R&D program had failed even before the commercial launch, due to lukewarm support of the government. This may have been due to the lack of lavishing initial investment required to foster domestic aircraft production in the early stage. As a result, South Korean producers concentrated on final assembly and productions of airframes and aero-engine. Most of avionics and design-related technology were imported directly from abroad (Cho, 2003).

Fig. 3. The evolution of military aircraft industries in Brazil, South Korea, and China



Source: Modified from Cho (2003), Maculan (2013), Nolan and Zhang (2002)
Note: * The establishment date of Chinese and Brazilian firms may be the same as their entrance into aircraft industry. However, since some of South Korean suppliers' establishment date does not match their entrance into aircraft industry, we use their entrance years.

Table 2
Stylized differences derived from the origins of latecomer firms in military aircraft industry

	Brazil - Embraer	South Korea - KAI	China - AVIC
Origin of firm	Research institute and university →Spun-off as a state - owned company	Multiple suppliers →Consolidated as one government-owned company	Multiple suppliers →Consolidated as one government-owned company
Innovation ecosystem	Concentrated on one location	Moderately dispersed over few locations	Dispersed over multiple locations
Focus of knowledge-base	Research	Production	Production

Likewise, the role of research institutes and universities for East Asian latecomers was somehow limited, but that of various suppliers were significant in enhancing maintenance and manufacturing capacities. In the 1990s, South Korea and China have consolidated the existing suppliers. South Korea and China aimed to transform the group of existing suppliers into an internationally competitive aviation company. For China, AVIC (Aviation Industries of China) was established to directly responsible for managing the industry's assets, and formulating the industry's business strategy. In a similar manner, South Korean government forced a consolidation in aerospace manufacturing to drive economic reform in the late 1990s when Asian economy was under crisis. The three subsidiaries of Korean conglomerates including Samsung Aerospace, Daewoo Heavy Machinery and Hyundai Space and Aircraft were consolidated into KAI (Korea Aerospace Industries).

Although South Korea and China have eventually pursued the national champion model of Brazil, there are some differences in terms of firm status, innovation ecosystem, and focus of knowledge-base (See Table 2). Whereas Embraer was privatized in 1994, AVIC and KAI have remained as government-owned enterprises. In terms of their innovation ecosystem, Brazil's aerospace industry is concentrated around the single cluster "São José dos Campos". In contrast, China has its multiple suppliers in a dozen of locations all over China involved with aeronautical maintenance and production work. Their locations include Shenyang and Harbin in the northeast, Chengdu in the southwest, and other facilities around Shanghai, Xian and Taiyuan (Vertesy and Szirmai, 2010). Korea also has its suppliers dispersed over several locations but to a lesser extent. Multiple Korean suppliers were the beneficiary of the Aircraft Industry Promotion Law in 1984 which allowed the new entry of the subsidiaries controlled by Korean conglomerates.

Above all, these differences are reflected in each country's approach toward research and production activities. In order to empirically validate the difference in their focus of knowledge-base, two firm-level measures have been used. First, R&D intensity is the amount of R&D investment divided by annual sales. As indicated in Figure 4, the average R&D intensity of Embraer from 1985 to 1991 marks 26.5 percent, which is significantly higher than that of AVIC and KAI in 2000s. Before 1985, Embraer's R&D intensity records 3.8 percent in 1983 and 7.5 percent in 1984 (Frischtak, 1994).[1] Even in the 2000s, Embraer focus on R&D activities in both commercial and executive jets. Their R&D goals include reducing fuel efficiency and using bio-fuel as an alternative energy source. Composite material and structures for aircraft wings and fuselage are also Embraer's key focus in order to reduce the aircraft weight as much as 15 percent. In the case of AVIC, although AVIC is catching up with Embraer in terms of R&D intensity, its R&D intensity is incomparable to that of Embraer in earlier years. KAI shows its insufficient R&D activities with its lowest R&D intensity among the three latecomer firms. This is consistent with Cho (2003)'s observation that the level of know-how related to system integration design, test, and evaluation is poor. Cho (2003) also stressed the weaknesses in avionics and flight control due to the lack of local R&D in these areas.

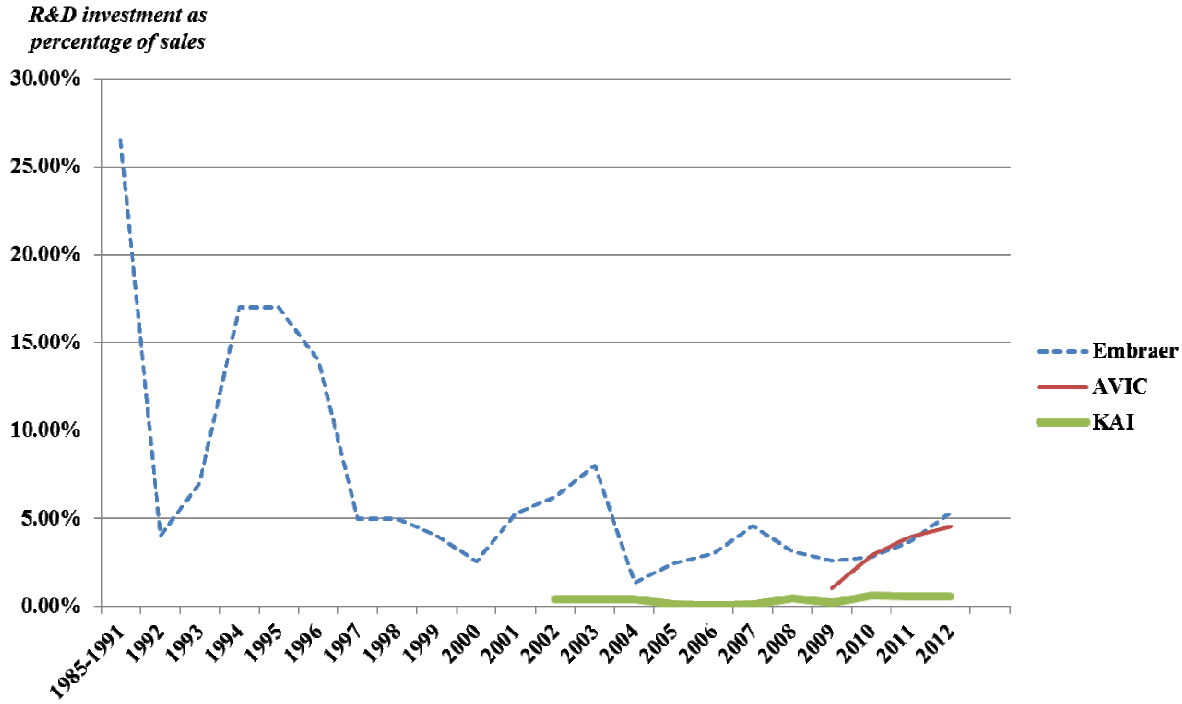
We have also developed a surrogate measure for production intensity which is the amount of CAPEX (Capital Expenditure) divided by annual sales. In fact, capital expenditures are integral to the operations of most manufacturing companies including aircraft manufacturers within aerospace industry, which must regularly upgrade physical assets (equipment, plant and property, and industrial building and warehouses) or acquire new ones in order to remain competitive (DTI, 2006). Despite the above logic, we admit that there are some limits to this measure, due to the lack of its confirmatory nature. However, we cannot negate the importance of using capital expenditure as a surrogate measure to compare the production intensity of the latecomer firms.

Embraer shows a lower level of production intensity compared to that of KAI (See Figure 5). Nevertheless, it may be inappropriate to claim that Embraer has weakness in production capacity. In fact, Embraer strategically uses risk-sharing partnership for production activities. To sum up, we may assume from our empirical data that the focus of knowledge-base for Brazil has been technological research. In contrast, the foci of East Asian latecomers have been enhancing their production capacity which is consistent with previous literature on industrial policies of Latin America and East Asia.

---

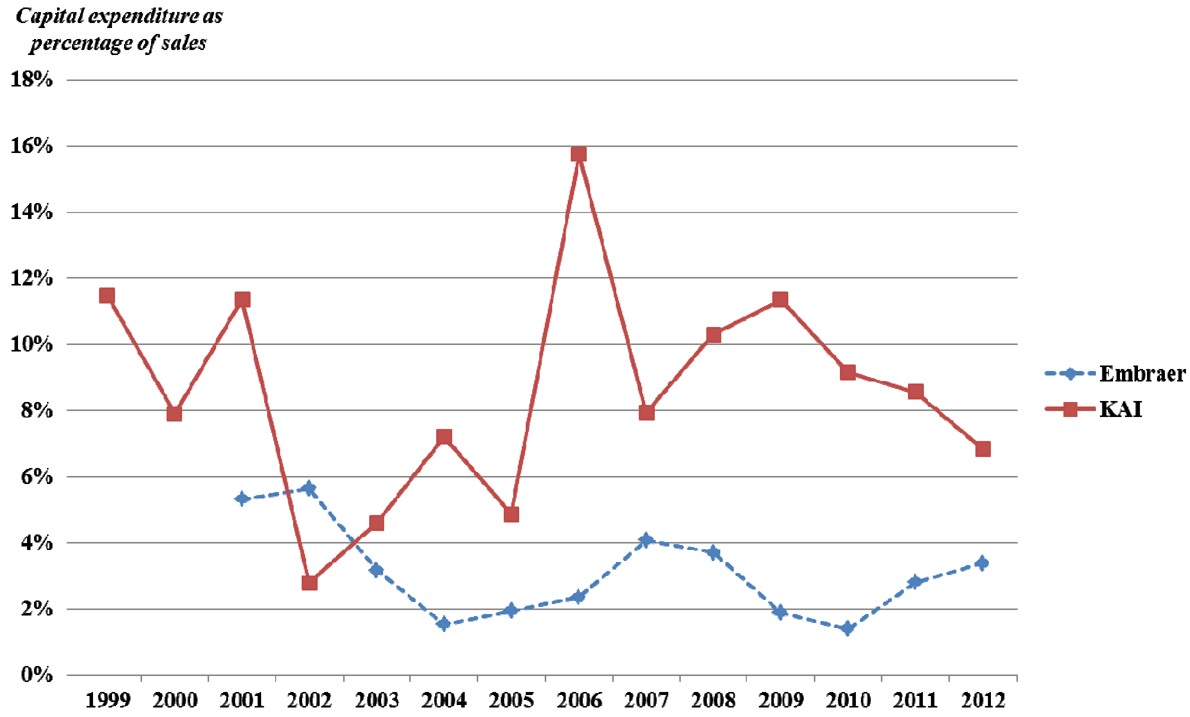
[1] The data on Figure 4 and 5 has limitations, as it does not address military aircraft-specific nor project-specific R&D intensity and production intensity. Also, the data does not exactly correspond to the time period of the analyses results in Figure 3 and Table 2. The limitations are derived from the absence of secondary data. Despite the limitations, Figure 4 and 5 are complementary in nature that still validate our claim on the different overall strategic orientations of Embraer (Research-oriented), and KAI and AVIC (Production-oriented). Thus, Figure 4 and 5 may partially complement the analyses results indicated in Figure 3 and Table 2.

Fig. 4. R&D intensity of latecomer firms in aircraft industry



Source: Annual reports, KisValue, Frischtak (1994), Goldstein (2002), Casanova et al., (2009)
Note: R&D intensity of Embraer from 1985 to 1991 is more focused on military aircraft. R&D intensity of Embraer throughout 1990s is inclusive of R&D investment in both military and commercial aircraft. R&D intensity of Embraer from 2001 to 2012 consists of R&D investment extended to commercial and executive jets. Since the R&D intensity data of Embraer from 1940s to 80s do not exist, we took an inferential approach in interpreting the data which may still be of use to validate our claim.

Fig. 5. Production intensity of latecomer firms in aircraft industry



Source: Thompson Datastream, KisValue, Annual Reports

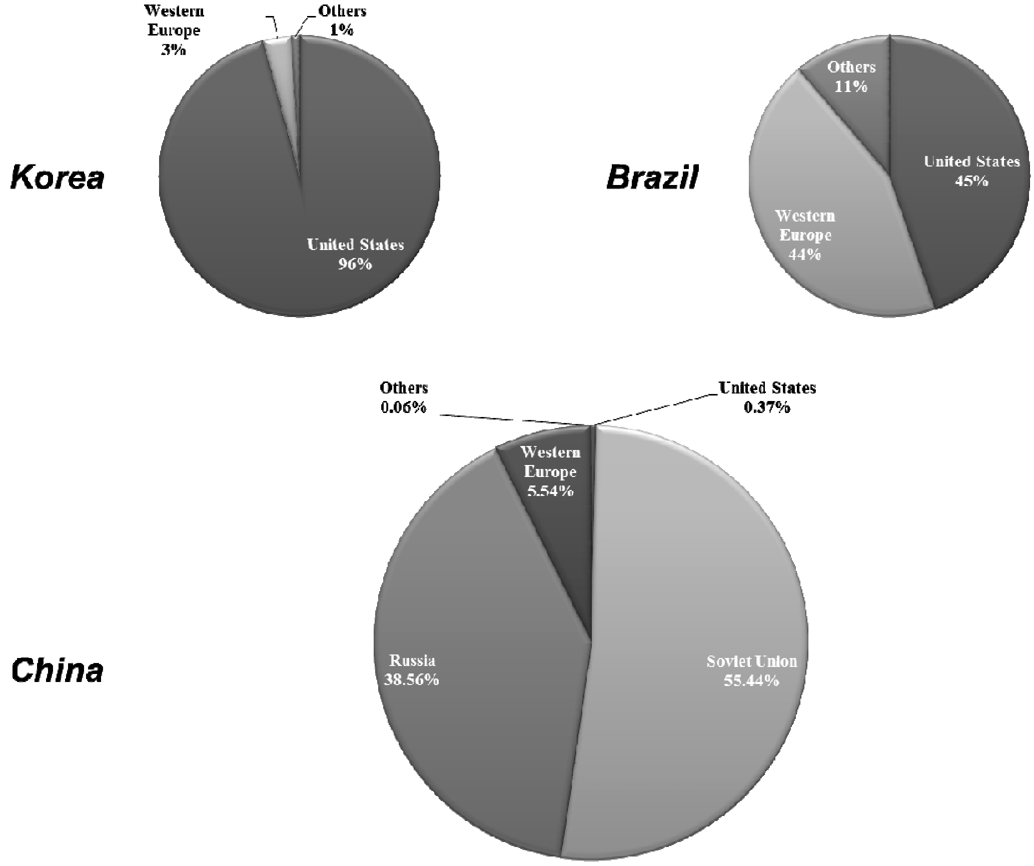
4.1.2. Role of foreign partnership and technology acquisition modes

For latecomers to build a military aircraft, it requires extensive R&D at high costs and reliance on subsequent demand to offset these costs. Relying solely on domestic demand is risky for latecomers, as it is extremely difficult for them to take advantage of economies of scale. More importantly, many latecomer firms in military aircraft industry encounter difficulty in acquiring core technologies. In order to acquire core technologies, latecomers absorb information and know-how by collaborating with foreign partners from developed countries (Ahuja, 2000; Powell et al., 2005). Since military aircraft industry represents security-sensitive features, various technology acquisition strategies are used by latecomers. In particular, China shows its distinctive strategies in acquiring technology from abroad, as it has been isolated from access to western knowledge-base (See Figure 6). The history of Chinese military aircraft formally dates back to the 1950's when high political tensions were created by the Cold War. At the time, China essentially had no groundwork to indigenously design and produce military aircraft with its limited industrial capacity and Western countries banned manufacturers from exporting military aircraft to China. As a result, China relied on Russia (Formerly the Soviet Union) and Eastern European countries that were more accommodating than Western countries. In the early stage, China benefited from the Soviet Union, which committed human and financial resources to transform its communist partner China into a self-sufficient defense partner. For instance, China purchased Soviet fighters in order to arrange co-production agreements and resolve technical constraints (Saunders and Wiseman, 2011).

After the Sino-Soviet split in 1960s, Soviet advisors and its technical assistance withdrew. This resulted in the isolation of Chinese military aircraft industry, as the country lacked relationships with Western countries to access cutting-edge military technologies. This forced China to focus on reverse engineering on aircraft that were previously purchased from the Soviet Union. Since then, access to foreign knowledge-base via formal mechanisms has been limited. However, with Deng Xiaoping's open policy and reform in the late 1970s with the introduction of 16 Character Policy, China began to enter into a few co-production projects in commercial aircraft in the late 1980s. Despite the economic reforms in the 1970s which enhanced the accessibility to Western technology, China still had a hard time establishing a stable relationship with foreign suppliers which limited itself to licensed production projects with little room to acquire advanced technologies. Not long after partially regaining the access to foreign knowledge-base, China faced economic sanctions stemming from the Tiananmen Square incident in 1989. As a result, China put its efforts to purchase small quantities of advanced fighters and aviation components in the 80s and early 90s. However, the United States and other western countries had no motivation to sell even a small number of fighter aircraft to China, as reverse engineering was the most preferred strategy for China. In order to cope with the circumstance, China adopted a spin-on approach which allowed acquired knowledge on civilian aviation to be adapted to its military applications. In fact, Chengdu Aircraft Industry's subcontracting facilities operated both military and commercial production lines close to one another (Fisher, 2004). Regardless of their hardships, China became capable of producing fourth-generation fighters based on reverse engineering efforts which were the by-product of co-production agreement with the Soviet Union and Russia. This co-production agreement provided China with complete knock-down kits for indigenous production. Although they made limited developments in genuinely new innovative technology, China benefited significantly from "follower's advantage" through imitation and modification (Saunders and Wiseman, 2011).

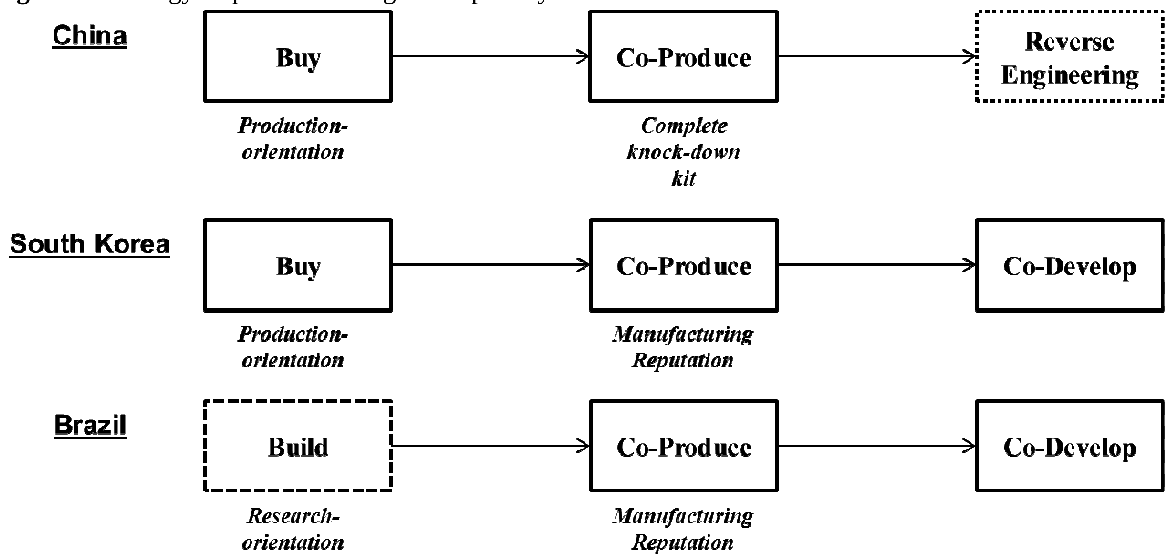
In contrast, South Korea and Brazil had stable and favorable collaborations with their Western partners (See Figure 6). For instance, whereas China's sub-contractors were generally able to contract for Level 3 agreement, South Korea and Brazilian firms were familiar with Level 4 or 5 agreement involving co-financing and co-designing (Nolan and Zhang, 2002). This is consistent with the argument that with the reputation earned from co-production arrangement, a form of co-development scheme such as joint venture project is realized for latecomers (Luo and Tung, 2007). The main difference between Brazil and South Korea's technology acquisition lies in the fact whereas the former relied on a number of foreign actors including research institute and universities; the latter was somehow dependent on foreign suppliers. Embraer established a procurement agreement with NASA to transfer information on wing sections and foreign universities for training highly qualified engineers in research skills. Embraer also entered into an agreement with a general aircraft manufacturer "Piper" to build marketing capabilities and post-sales servicing. In contrast, South Korea focused on collaborating with foreign partners confined to military aircraft manufacturers. Likewise, whereas the focus of Korean manufacturer was on enhancing technological capabilities in military aircraft, that of Brazilian manufacturer "Embraer" was improving its technological capabilities with the strategic purpose of diversifying aircraft production by engaging in commercial aircraft industry.

Fig. 6. Import of military aircraft to Korea, Brazil, and China



Source: SIPRI Arms Transfers Database
Note: The period over 1950 to 2012

Fig. 7. Technology acquisition strategies adopted by the three latecomers



Source: Elaborated from the analysis in this article

4.2. International technology transfer and latecomers' technological advancement

4.2.1. China

The first technological advancement in China's military aircraft extends from 1957 to 1977. The J-6 was the first Chinese-produced product which benefited from licensing agreement made in 1957 and 1959 with the Soviet Union. Through this project, China gained their competence in manufacturing the necessary tooling and assembling the aircraft. However, when Soviet advisors and its technical assistance withdrew after Sino-Soviet split, China had to focus on reverse engineering of aircraft previously purchased from the Soviet Union. The J-7 program which was a follow-up project of J-6 provided China with opportunities to master reverse engineering to produce a moderate level of fighters without the support of foreign partners (Saunders and Wiseman, 2011). Since the economic reforms in 1978, the rest of the period was marked by enhanced access to Western technology for China. In 1979 China and British defense firm GEC-Marconi entered into a license agreement to produce the J-7II tactical fighter, as well as F-7 with a complete avionic suite. This avionics included radar, weapons-aiming computer and state-of-the art display systems, and marked a huge advance in Chinese military aircraft industry. China also cooperated with Israel starting from 1982 and obtained FBW (Fly-by-wire) technology. Advances in Chinese military aircraft from the late 1970s to the late 1980s primarily resulted from the enhanced exposure to more sophisticated Western technologies. The knowledge acquired by collaborating with these two foreign partners led China to perform reverse engineering in modifying design to accommodate new systems (Saunders and Wiseman, 2011). From 1989 to 2004, China actively pursued acquisitions of advanced aircraft from Russia, Ukraine and Israel using a combination of co-production and reverse engineering to make improvement in design of subsystems and integration of advanced technologies into their own weapon systems. For instance, in 1996 China entered into a licensing agreement of J-11 with Russia which moved up China's military aviation industry from third-generation to fourth-generation. The terms of the agreement were finalized and China received manufacturing document of the Su-27 along with complete knock-down kits from which they assembled its first two J-11s. In addition to acquisition and coproduction with Russia, China also continued to pursue alliance efforts with Israel. Ukraine also served as an important source for Russian military hardware that China had been unable to procure directly. As a result of all the efforts, China came up with innovations in their own indigenous capacity in building military aircraft (Saunders and Wiseman, 2011).

4.2.2. South Korea

South Korea embarked on their journey of technological advancement by maintaining a close cooperative relationship with Lockheed Martin of the U.S. The first technological advancement was marked by the period from 1970s to 1990s. In the early days, Korea did not have enough experience in developing and producing the final product, as the human resources had been accustomed to performing simple maintenance and production activities. Also, due to the weak industrial base for producing components and sub-systems, Korea had been relying on imports. In other words, the industrial base had a low value-added structure. At this stage, Korea had weaknesses in overall design, manufacturing and flight testing. In order to cope with the situation, Korea started assembling F-5E/F military aircraft throughout the early 1980s resulting from the offset purchase of military aircraft from Lockheed Martin. In 1986 this assembly work was extended into a follow-up project of F-5E/F, license production of KF-16. Under the agreement, Lockheed Martin was obliged to provide software tools, equipment, technical data, technical assistance and personnel payroll .With the skillful use of offset orders and agreements, Korea gained an important experience in enhancing production capabilities (Lee et al., 2009; Lee and Chung, 2011). With the establishment of KAI, Korea showed its proactive intentions to pursue exploration-oriented learning and achieve its status as an indigenous developer. Unlike the manufacturing capability which was accumulated through the assembly and licensed production projects throughout the 1980s and 1990s, design and system integration capabilities were the weakest areas without prior learning experience. Korea was able to make up for the weak points and achieve the status of an independent developer of military aircraft by completing "T-50" project, a state-of-the art supersonic trainer under the joint venture scheme with Lockheed Martin. Further details on Korea's T-50 project are followed in the later section

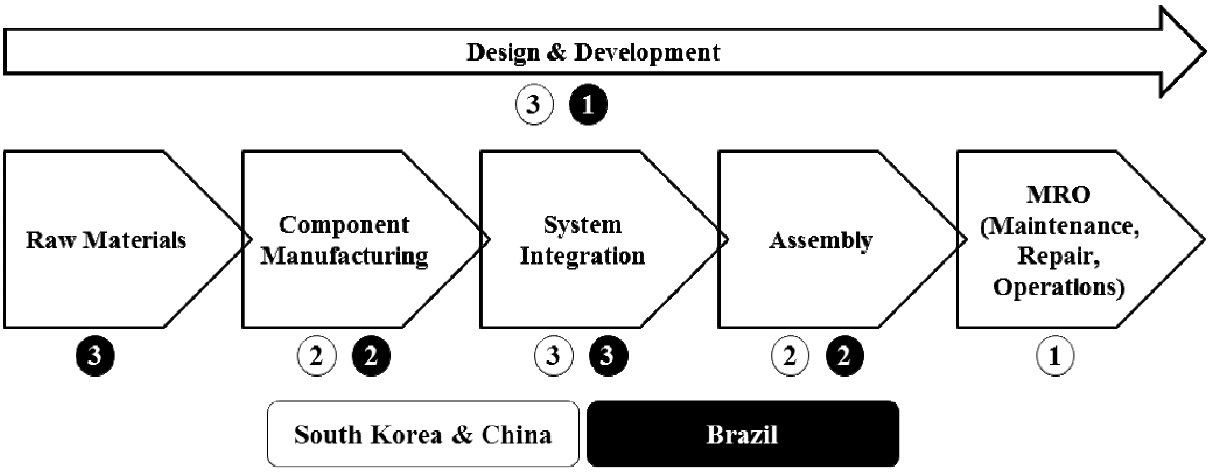
4.3.2. The due diligence report generated by Lockheed Martin in 2001 remarked that Korea had reached the technological level to carry out indigenous aircraft development. To sum up, Korea effectively used this subcontracting agreement in the early years to build reputation and credibility, which eventually contributed to attracting investment of Lockheed Martin in T-50 project.

4.2.3. Brazil

In the case of Brazil, the first technological advancement was pursued when Brazil was facing problems with limited knowledge and capacity to manufacture and assemble the first modern Brazilian aircraft prototype "Bandeirante" on an industrial scale. To cope with this issue, Embraer entered into a licensing agreement with an Italian firm "Aermacchi" in 1970 to produce a small jet trainer and fighter "Xavante". This agreement provided Brazil with opportunities to acquire critical production knowledge in tooling and parts manufacturing, tracing technology and assembly of planes (Ramamurti, 1985). The second technological advancement in production skills of Embraer took place in 1975 with an offset purchasing of forty-nine Tigher II supersonic fighters. As a result, Embraer signed a licensing agreement to produce F-5 fighter parts and components for Northtrop. It was an offset contract Embraer signed in for the construction of a hundred F-5 vertical fins, rudders, wings and belly pylons, against the procurement of fifty F-5. Thanks to the procurement made between the Brazilian Air Force and Northrop, Embraer employees learned how to efficiently implement cutting-edge technologies such as metal-metal bonding, aluminum-magnesium alloy machining and aluminum honeycomb manufacturing. A number of major technologies were learned during the process, including chemical milling, metal-to-metal and structural bonding and the use of composite materials. In addition, the contract also forced the use of numerically controlled machine tools in improving tool design, quality assurance and other production techniques. By the mid-1970s Embraer had acquired significant know-how in aircraft design, manufacturing, commercialization and servicing (Frischtak, 1994; Rodengen, 2009). Embraer also entered into a co-development agreement with Italian aircraft manufacturers, "Aeritalia" and aerMacchi in 1981. The agreement led Embraer to join the development of ground-attack aircraft "AMX" and absorb highly-sophisticated technologies such as computer integration and fly-by-wire technology. The deal also provided Embraer with avionics engineering knowledge that would prove especially useful for Embraer's future technological development. By the end of this development project, Brazil became technologically independent and gained strong military aircraft technology to carry out indigenous development programs (Balbinot, 2006; Rodengen, 2009).

4.3. Summary of learning process and milestone projects

Fig. 8. Process of learning-by-doing for the three latecomer countries in military aircraft sector



Note: MRO for Brazil and Raw Materials for South Korea and China were not captured in our secondary data. The numbers in the figure refer to the order of learning-by-doing.

The analysis in previous section led us to understand technological advancement in each country's military aircraft industry. Based on the analysis, Figure 8 describes the process of learning-by-doing. Component manufacturing and assembly activities associated with learning-by-doing took place in the second place for all three latecomers. What differentiates one from another is that for Brazil, design and development was emphasized in the early stage which is a bit unusual for latecomers. In contrast, South Korea and China practiced their learning via maintenance, repair, and operations of purchased aircraft. As addressed in the earlier section, the difference is derived from the pattern of establishing knowledge-base influenced by latecomers' industrial policy. However, all three latecomer countries focus on system integration activities during the last stage of learning-by-doing. In order to focus on this key technological capability "system integration" for CoPS, we have documented milestone projects of Brazil and South Korea that were carried out in the form of joint venture: AMX project for Brazil and T-50 project for South Korea.

4.3.1. AMX of Brazil

Embraer entered into the co-development agreement with the two Italian firms "Aeritália" and "Aermacchi" to co-design and produce AMX in 1980. The project was carried out in the form of joint venture with a share of 46 percent for Aeritália, 24 percent for Aermacchi, and 30 percent for Embraer (Cassiolato et al., 2002). The project was very important for Embraer, as the opportunity to gain knowledge in more advanced technologies was given (Neto, 1991). Indeed, Embraer became the first Brazilian company to adopt and use CAD (Computer-aided Design) system. In addition, the project was fundamental for Embraer to gain experience in managing complex business relations. For instance, Embraer was able to practice and develop expertise in project management and system integration by collaborating with domestic suppliers located in the cluster.

The first prototype of AMX flew in May 1984. The production began in mid-1986, and the first thirty-unit batch rolled out in 1988. A second contract was signed in 1988 for Brazil to produce 25 AMX jets. A third production lot was authorized in early 1992. Approximately 190 AMX jets are currently in operation in the Italian and Brazilian Air Forces. In 1999, the AMX-T won a bid to supply Venezuela (Goldstein, 2002). Despite the contributions of AMX project to Brazil's technological advancement in military aircraft industry, most of the AMX jets were sold to the two participant countries including Brazil and Italy which was never an export success (Cassiolato, 2002).

Table 3

Division of labor for Brazil and Korea's military aircraft projects

Project	Participating firms	Share of labor	Share of equity	Work contents
AMX	Embraer (Brazil)	30%	30%	Wings and Elevators, Air Intakes, Pylons, Landing Gear, Fuel Tanks, Reconnaissance Pallet, and Installation of Cannons
	Aeritalia (Italy)	48%	46%	Central Fuselage, Rudder and Fin, Radome, Fiber-Carbon Components for the Wings and Tail
	AerMacchi (Italy)	22%	24%	Front and Rear Fuselage
T-50	KAI (South Korea)	50%	87%	Prime Contractor, Aircraft Design and Integration, Major Component Fabrication, Mate-Thru-Delivery
	Lockheed Martin (U.S)	50%	13%	Investor and Principle Subcontractor in Full-Scale Development, Flight Control, Avionics, and Wing Development, Technical Assistance

Source: Adopted from Balbinot and Lockheed Martin

In developing AMX, the division of labor was 48 percent for Aeritalia, 30 percent for Embraer, and 22 percent for Aermacchi. Embraer was responsible for the sections of the wing, tail unit and structure fatigue tests.

Aeritalia and Aermacchi would be responsible for producing the fuselage, onboard systems, and carry out the static tests and tests with weapons. The reason why Embraer's work contents were concentrated on minor parts is that Embraer preferred a strategy whereby its engineers design the aircraft body, wings and tail but use the global supply chain for components (Carrico, 2013). Likewise, Embraer's philosophy and technological strategy is focused mainly on the essential competencies. In the past, software and technological systems were developed largely within the company, but now they are ordered, purchased or jointly developed (Cassiolato et al., 2002).

4.3.2. T-50 of South Korea

In contrast to Brazil's case, KAI of South Korea designed and manufactured most of the parts with the technical support of foreign manufacturers. During the basic research phase of T-50 project from 1989 to 1991, Korea sought international collaboration made through offset (See Table 4). At the time, Korean defense acquisition regulations specified 30 percent of the purchase price as offset when purchasing weapons. Taking advantage of this situation, Korea was able to receive support from BAe in securing basic knowledge in aircraft design. Korea dispatched 24 engineers to BAe for 14 months. From 1992 to 1995, Korea collaborated with Lockheed Martin in designing T-50. Review sessions were held every three months which fostered the successful transfer of advanced knowledge in aircraft design. Market research activities led by Korean team resulted in forming a joint venture partnership with Lockheed Martin.

Table 4
History of T-50 development of South Korea

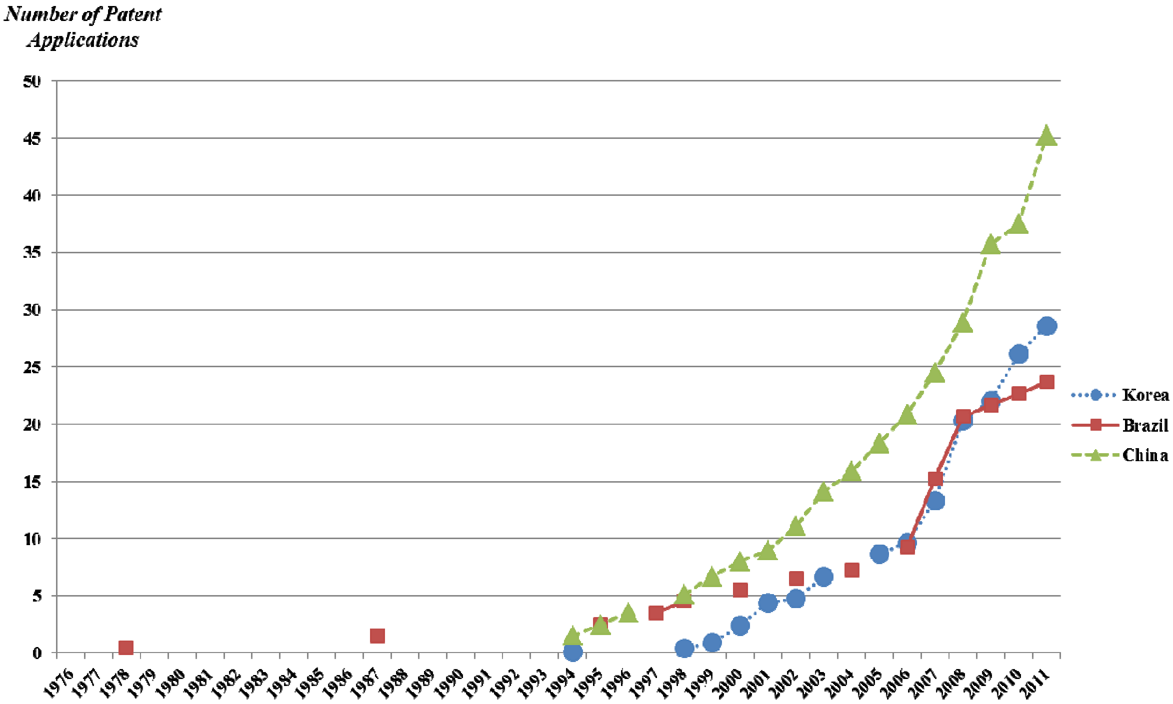
Period	Milestones	Acquired technological knowledge	Source of learning
1989-1991 Basic Research Phase	1989: Budget Approval 1991: Approval of Exploratory Development	- Design Source Code - Pilot Training Programs - Simulation Technology	BAe (UK)
1992-1995 Exploratory Development Phase	1992-1995: Attracted Investment from Lockheed Martin	- Design of Aircraft	Lockheed Martin (US) - Design Review Sessions
1996 Bridge Program	1996: Application of additional budget	Not Observed	Not Observed
1997-2005 Full Scale Development	1997: Approval of Full Scale Development 2000: Establishment of Joint Venture with Lockheed Martin 2002: Success of Test Flight	- Avionics - Flight Control System	Lockheed Martin (US) - Technical Advisory
2006-2012 Post-Full Scale Development	2010: Delivery to Korean Air Force 2011: Export Agreement to Indonesia	Not Observed	Not Observed

Source: Elaborated from the interview with chief engineer of T-50 project

After securing additional investment from the government through bridge program, full scale development began in 1997. At this phase, Lockheed Martin was responsible for providing 13 percent of the total cost and producing 50 percent of the total work contents including avionics and flight control system, and offering technical assistance to Korean engineers. Technical assistance of Lockheed Martin was provided in three forms: technical advisory, co-development and provision of technical documents. They also transferred the avionics and flight control system technologies to the Korean engineers. As a result, the prototype T-50 aircraft successfully completed the first flight in August, 2002 and supersonic test flight in February, 2003. In September, 2003, Korean Air Force approved the initial T-50 manufacturing plan. With the successful completion of the T-50 development program, Korea entered a post-full scale development phase and Korean Air Force began to receive T-50 aircraft from May, 2010 and operated the new training system. The project was launched in 1997 and, after the first trial flight in August 2002, T-50 succeeded in the supersonic flight in February 2003. A very significant aspect of this project was that the export contract of T-50s to Indonesia were signed in 2011, a $400 million order for sixteen T-50s. Additional twenty-four T-50s have been exported to Iraq as well (Lee et al., 2009; Lee and Chung, 2011).

4.4. Learning outcome

Fig. 9. Cumulative patent applications filed under the PCT in air vehicle classes

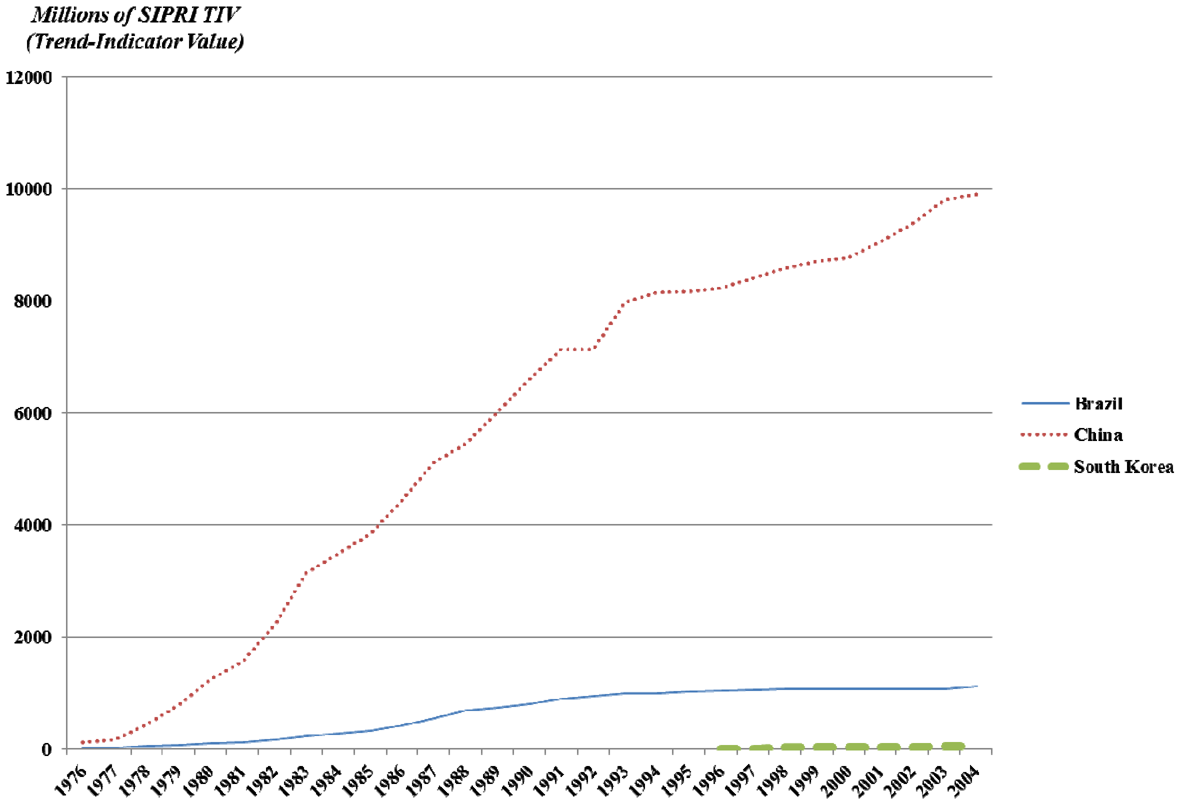


Source: OECD Patent Database

In order to measure the learning outcome, we have gathered patent applications filed under PCT by referring to IPC (International Patent Classification) on lighter-than-air aircraft (B64B) and airplanes and helicopter (B64C). We used PCT applications as a relevant measure of learning outcome, as the patent count data reflects technological advancement in aerospace industry (Beaudry, 2001; Winthrop et al., 2002). In fact, since applying for a PCT patent involves considerable costs and time, firms file as a PCT patent applications inventions that they consider as important and deemed to be profitable and applicable in other countries (Noailly and Batrakova, 2010). Many scholars used WIPO data to compare the number of PCT patents in a number of industries throughout various time periods (Jung and Imm, 2002; Hullmann and Meyer, 2003; Noailly and Batrakova, 2010). In their patent analysis, the number of PCT patents owned by Korea in 1990s has also been taken into account.

As Brazil put immense efforts on research activities, Brazil is the only latecomer to apply for PCT patents from 70s to early 90s (See Figure 9). Starting from the mid-90s, South Korea and China's technological learning outcome was on its way to surface. China entered into several co-production deals with Russia to improve its capability to develop advanced fighter aircraft. China also gained access to advanced computers in the mid-1990s which in turn helped China retain more sophisticated design capabilities (Saunders and Wiseman, 2011). In a similar context, South Korea entered into a period of full-scale development for T-50 in 1997 with the technical support of Lockheed Martin. Above all, consolidation of existing suppliers into one system integrator in the late 90s for both China and South Korea may have contributed to sharp increase in the number of patents. Not only could patents be proxy measures for technological learning outcome, but export is a good proxy in innovation literature. With the rapid catch-up in generation of jet fighters and quantity-oriented production system, China's export constantly has grown (See Figure 10). In contrast, Brazil's growth in export market has been quite modest, since Brazil redirected their strategic focus to commercial aircraft and executive jets in the 1990s. South Korea has exported some products but the amount is incomparable to the former two latecomers. This may have been due to Korea's relatively late entry into the military aircraft industry compared to Brazil and China.

Fig. 10. Cumulative export of military aircraft by each of the three countries[2]



Source: SIPRI Arms Transfer
Note: SIPRI TIV is based on the known unit production costs of a core set of weapons and is intended to represent the transfer of military resources rather than the financial value of the transfer (See SIPRI Website: http://www.sipri.org/databases/armstransfers/background/explanations2_default)

[2] Owing to the absence of military aircraft export volume at project-level, we have adopted the cumulative export of military aircraft at sectoral-level. The approach is rationalized, as we have confirmed in our interviews and various secondary sources that Embraer for Brazil, AVIC for China, and KAI for South Korea are the biggest exporters of military aircraft in their respective countries.

Localization rate of parts and components produced and supplied by domestic firms is another important indicator of defense industrial performance (Bitzinger, 2011). South Korea's KT-1 trainer had a localization rate of only 44 percent, while the localization rate for T-50 advanced trainer/light attack jet was 61 percent (Bitzinger, 2011). In a similar context, the localization rate of China's J-11 has reached almost 100 percent. Nevertheless, in terms design capabilities; Asian latecomers have not fully developed design and program management skills as evidenced by full-scale program involving global partners (Bédier et al., 2008). As for Brazil, more than half of Bandeirante consisted of imported parts with low localization rate (Casanova et al., 2009). Even after gaining indigenous technological capability, the localization rate of Embraer's aircraft ranged from 50 to 60 percent which reflects the firm's strategy of ordering and integrating parts and components produced abroad (Neto, 1991). As a result, Brazil still shows some weakness in local aerospace-manufacturing base (Bédier et al., 2008).

5. Industrial policy initiatives to attain indigenous technological capability

Based on the analysis results, we now examine government policies related to three areas: strategic, functional, and project initiatives. Approaching government policies from these three perspectives will provide groundwork for latecomers' technological learning in CoPS (See Table 5).

5.1. Strategic initiatives to set national goals

"Although the country has had other initiatives and aircraft factories, it was in São José dos Campos that the modern Brazilian aerospace industry was born." (Brazilian Aerospace Cluster)

The success of military aircraft industry depends on government support for R&D activities requiring components and parts which may be widely dispersed in terms of both industry and location (Niosi and Zhegu, 2005). In other words, government needs to understand the importance of forming industrial clusters to support the R&D activities in an efficient manner. Successive Brazilian government understood its importance and formed an aerospace cluster in the city of São José dos Campos in São Paulo State. The education and research institutions including CTA, ITA, IPD (Research and Development Institute) and INPE (National Institute of Space Research) were established within the cluster. This group was to have considerable influence on the creation of Embraer later in 1969 which made the cluster region become a hub of aerospace companies. Although Niosi and Zhegu (2005) found that the role of universities and government laboratories is secondary in aerospace cluster by using the cases of developed countries, we found that the formation of aerospace cluster helped Brazil to concentrate key infrastructure and thereby maximize the agglomeration effect.

"The senior body of China's Communist Party is the Politburo's standing committee. Making up its nine members are eight engineers, and one lawyer." (Economist, 2009)

Since 2000, China has increased R&D spending roughly 10 percent each year and sustained their commitment even during the crisis period in 2008 and 2009. Such unprecedented efforts in a national innovation initiative are part of China's national plan "indigenous innovation" to leapfrog into a leadership role in science-based industry worldwide. However, this may not have been possible without recognizing the importance of science and technology in modern day economy. For instance in 2006, President Hu Jintao stated that "In the face of international scientific development and increased international competition, by seeing the development of science and technology as a central thread in the development strategy and actively committing to its progress, China can seize the opportunity for development." One month after his speech, Chinese government announced the national plan "indigenous innovation" (McGregor, 2010). Likewise, technocrat leadership which recognizes the importance of R&D and makes a lavish investment has been a critical factor for the success of the complex product project at national level.

"T-50 development program was initiated to stimulate Korean aerospace industry and promote its self-defense and own air weapons system." (Director of Golden Eagle Engineering Research Center)

Before T-50 development project, Korea relied entirely on its allies for air weapons system.

Accordingly, the project goals were set to develop and provide an advanced trainer and key component parts to Korean Air Force. However, policy makers were skeptical about investing in the project. Major issues were Korea's technological capabilities and inexperienced manpower to develop aircraft. In addition, there were insufficient societal recognition for the development and general consensus favoring the use of purchased aircraft. In response to these issues, new goals and needs were created to persuade decision makers. The new goals and needs included technological, industrial and national security perspectives. First, from a technological perspective, the project goals were to (a) acquire the ability to design the aircraft, (b) establish a data management system that efficiently secures accumulated technologies through systematic data collection, storage and management (c) maintain and manage manpower, and (d) acquire facilities, equipment, software and other tools required to develop aircrafts. In other words, the goals were created to satisfy the needs of Korean Air Force such as taking advantage of some important components (e.g., canopy and landing gear) during their operations. Secondly, the potential impact of component parts on Korean manufacturing industries was addressed, which would engage a number of industries and firms in Korea and its future aerospace industry. Lastly, from a national security perspective, the outcome of the project that could provide Korea with a firm foundation to pursue self-reliant defense systems was strongly put forward. With visionary leaders' numerous attempts of persuasion after addressing the needs of stakeholders along with the goals above, Korean government was able to reach a decision to make a transition in their approach from "buy" to "make" and initiate T-50 development project.

5.2. Functional initiatives to organize for innovation

"ITA is the beginning of everything at Embraer" (Interview with Embraer)

It is important to understand that in latecomers' setting, the role of universities and research institutions is critical to conducting basic research prior to the embarkation of the industry. For instance, CTA and ITA were created in Brazil to reinforce their strategies to acquire knowledge and self-sufficiency in aviation industry. Most of the first generation aeronautical engineers graduated from ITA went to work for IPD. In other words, groundwork for basic science research should also be prepared in academia which is the basis for applied research. All these institutions have become a part of CTA and played important roles in Brazilian aviation industry.

- ITA: Provided high level education and research in aerospace science and technology
- IPD: Performed R&D in aeronautical engineering, electronics, new materials and mechanics
- IAE (Institute of Space Activities): Performed space-related R&D
- IFI (Institute of Development and Industrial Coordination): Coordinated and supported activities to consolidate and develop Brazilian aerospace industry

"Reverse engineering efforts led China to significant technological advancement that propelled their national defense industry to step forward" (Modified from Saunders and Wiseman, 2011).

Since the early 1950s, China established more than 400 research units to strategically focus on reverse engineering (Liu and White, 2001). Highly skilled Chinese scientists and engineers returned from the U.S. and finally the acquisition of foreign companies enabled China to access foreign technology and link up with global R&D. In addition, engineering and science majors have been the most favored academia in China. Among Chinese university graduates, 30 percent of them receive their first bachelor degree in science and engineering. Meanwhile, that of the U.S. only accounts for 4 percent. This indicates that China is well positioned to compete in advanced technology fields, even if they do not introduce dominant design in the first place (Stewart and Drake, 2011). This fact may also be relevant to explain the challenges that developed countries are facing in their emerging sectors such as energy and advanced materials. The avoidance of engineering careers coupled with the weakening of manufacturing industries and prevalent outsourcing practices hinders firms in developed countries from introducing innovations (Rotman, 2012). In particular, current trends of aviation industry reflect strong needs in integrating radical technologies from other sectors. Still, many firms tend to outsource manufacturing tasks to foreign countries in order to minimize production costs. In turn, this gives the companies little chance to gain knowledge in sophisticated technology across diverse sectors. Therefore, it is critical to secure highly-skilled human resources and practice in-house manufacturing efforts in order to prepare for next generation aircraft (Delbridge and Mariotti, 2009).

"T-50 is the first national project supported by private suppliers which resulted in successful collaboration with Lockheed Martin" (Director of Golden Eagle Engineering Research Center)

T-50 is the first national defense project involving a number of private suppliers. There were four major corporations that had previously earned the reputation as world leading exporters in manufacturing. With the participation of these corporations, Lockheed Martin decided to finance 13 percent of the total investment and produce 50 percent of the total work content for T-50 project. Not only the decision to involve private entities was critical in forming a joint venture with Lockheed Martin, but the long-term partnership between Lockheed Martin and Korea over the last 20 years was also a key enabler. In fact, Korea effectively used subcontracting agreement in manufacturing and assembling components in the early years to build reputation and credibility, which contributed to attracting investment of Lockheed Martin in T-50 project.

5.3. Project initiatives to manage innovation

"The government and the Brazilian Armed Force bought roughly a third of Bandeirantes produced before 1980. They usually paid up-front and directly contributed to development expenditures" (Casanova et al., 2009)

Brazilian government put a large amount of effort in helping Embraer with financial, marketing, regulatory and international activities. BNDES (Brazilian Development Bank) provided Embraer's customers with alternate financing along with export support scheme and tax holidays. In addition, BNDES and other public sector institutions have actively supported the R&D collaboration between Embraer and other research or academic institutions (Goldstein, 2002). The government also imposed a steep increase import duties to foreign aircraft manufacturers operating in Brazil, thereby inducing foreign manufacturers to provide assembly kits to Embraer.

"There are 33 institutes, 9 state-level key laboratories, 30 key aviation science & technology laboratories, 16 state-certified enterprise technology centers and 32 provincial-level enterprise technology centers" (AVIC)

As seen from the consolidation of AVIC, China has a number of suppliers in charge of producing jet fighters. Unlike other countries, multiple development projects have been implemented, thereby producing over 20,000 military aircraft of various types. As evidenced from a sheer number of different types of fighter aircraft produced over time, China shows its strong project capability in integrating various industrial participants in developing jet fighters. In fact, AVIC has become a corporation owning about 200 subsidiaries in 24 provinces and municipalities throughout China.

"We efficiently managed and controlled the project by establishing a platform to collaborate with Lockheed Martin and BAe" (Director of Golden Eagle Engineering Research Center)

After securing the budget for T-50, the greatest problem in keeping up with the project was the low level of technological knowledge. For instance, there were no engineers with experience in developing an actual aircraft and integrating entire systems. In order to cope with this issue, Korea skillfully used offset orders with BAe, Lockheed Martin and other overseas counterparts to transfer some key design technologies and knowhow. Korean defense acquisition regulations specify 30 percent of the purchase price as offset when purchasing weapons. From the agreement set with BAe, BAe was obligated to (a) transfer aircraft design technologies to develop the T-50, (b) transfer technologies to develop a simulator for the T-50, (c) train three teams of test pilots (i.e., test pilots and flight engineers), (d) educate and train aero manpower, (e) and pay for all these expenses. For (a) and (b), BAe would transfer the technologies to twenty-four Korean researchers over a 12 month period and provide them with an office, designing software, equipment and researchers from their company. For (c), BAe would cover the expenses, such as tuition, to train three teams of test pilots. For (d), an aviation academy in the U.K. would be used. In addition to the offset term with BAe, Korea was able to benefit from the purchase of the F-16 from Lockheed Martin. As a result, Lockheed Martin was obligated to transfer design technologies to Korean engineers as part of the offset deal. Lockheed Martin also provided $20 million worth of expenses required for the technology transfer at free of charge, including expenses for software tools, equipment, technical data, technical assistance and personnel payroll .

Table 5
Latecomers' organizational capabilities for technological learning

Policy dimensions	Brazil	China	South Korea
Strategic initiatives	Formation of aerospace cluster to construct efficient R&D platform	Lavish investment in national R&D projects with top-down support	Transitional approach from "buy" to "make" by acknowledging the importance of self-defense
Functional initiatives	Establishment of research and education institutions for basic research	Attraction of human resources with advanced degrees in science and engineering from developed countries	Involvement of Korean conglomerates with their reputation as world-leading exporters in manufactured products
Project initiatives	Implementation of various incentives via export, alternate financing, etc.	Management of multiple projects with various suppliers	Skillful use of offset orders and negotiation to arrange joint venture agreement with foreign suppliers

6. Conclusions

This comparative case study shows how latecomers' technological learning should be managed with technology acquisitions strategies and government policies. The authors answer the question by analyzing key technological advancement in developing an indigenous industry in military aircraft. Important gaps in the literature of complex product systems have been identified and addressed by our proposed framework based on theories of technology acquisition strategies and CoPS. The theoretical framework has been supported by presenting the cases of the three latecomers. These results lead us to a discussion of the prevalent ideas in the literature. Both literature in traditional and latecomers' learning mechanisms may have overlooked the sequence of learning from technological knowledge to production knowledge, as most of the literature focus on the success of East Asian economies. We have identified evidence on latecomers' shift from technological knowledge to production knowledge and vice-versa, which is contingent on their focus of knowledge base determined by industrial policy. By shedding light on the learning sequence and its antecedent, we also find specific technology acquisition methods in developing aircraft systems.

Whereas "buy" is more aligned with latecomers with production experiences, "make" is preferred by latecomers with the focus on basic research and technological knowledge. From the case of Brazil, we have witnessed the important role played by universities and government research institutes in developing CoPS with a focus on design capability. This phenomenon is similar to the catching-up of Korea and Taiwan in mass-produced goods (i.e. semi-conductor, electric products) that fostered the spin-offs and commercialization of the research outcomes from their universities and government research institutes. However, the institutions of the latter two East Asian countries have focused on production capability. Likewise, exploring the industry-specific success of latecomer countries bears of great importance, as they may show different technological learning patterns.

In addition, we have discovered that the role of foreign partners is crucial in acquiring highly-sophisticated technology through co-production, co-development, and reverse engineering. Although previous literature in catch-up adopted the Vernon's (1966) view that "production competence is routine or tactical and thus can be exported", we hereby learn the importance of manufacturing capability for latecomers to gain bargaining leverage in various joint venture schemes. As evidenced from the case of Korea, latecomer with higher accessibility to a foreign knowledge base tends to take advantage of their relationship with a foreign partner by running a close level of cooperation. In this sense, Korea has focused more on supporting existing export industries by producing related capital goods for foreign system integrators (Hobday, Rush, Tidd, 2000).

Furthermore, as evidenced from the case of Korea and Brazil, the co-development programs such as T-50 and AMX have been effective in acquiring core and advanced technologies. However, co-development programs are the most difficult forms of cooperation to carry out owing to their high cost (U.S. Congress, 1990). In particular, since the countries with less advanced aviation industries typically pay a premium price or commit to purchase significant quantities, latecomer countries need to possess relatively well-developed aviation industries to gain a bargaining advantage in co-development programs. This is the reason why many latecomer countries arrange co-production programs before entering into co-development programs (Saunders and Wiseman, 2011). Meanwhile, latecomers with a low level of accessibility to a foreign knowledge base due to political and diplomatic constraints, tend to make purchases from their diplomatic allies and conduct autopsies in a bottom-up mode. In fact, the bottom-up mode occurs as China sees to support strategic and high technology industries for national purposes with the seeds of "techno-nationalism" (Hobday, Rush, Tidd, 2000).

We also provide policy implications. As evidenced from our cases, CoPS in latecomer context requires strong government interventions along with relevant policy initiatives. In this sense, latecomer governments should play a significant role in innovation (Hobday et al., 2000). Specifically, achieving the status of an indigenous developer in CoPS requires government initiatives in three areas: strategic, functional, and project. The first step requires having a strong strategic intention to create a viable indigenous industry not to be over-dependent on imported goods. For instance, it is important to select a strategic industry and establish a national innovation cluster to spearhead and support relevant R&D activities. Although the government of these latecomer countries recognizes the importance of R&D, their research funding is still increasing slowly and are often not sufficient to stimulate and support the institutional reforms for industrial development. Secondly, groundwork for basic and applied research should be prepared in academia to train potential scientists and engineers. Also, incentives to attract and secure well-qualified human resources from abroad should be designed to promote the culture of technological innovation and entrepreneurship (Yoon and Lee, 2013). These two are important steps in securing a core knowledge base required for CoPS projects. Lastly, international collaboration through various mechanisms should be pursued to improve access to external knowledge, thereby fostering the transfer of core technology. Latecomer countries show their weaknesses in low degree of involving externalities in their innovation projects, due to closed organizational culture. Involving external parties into the development of CoPS could provide the latecomer firms with opportunities to receive investment and technical assistance.

The findings and implications presented in this study are beneficial to understand different patterns of technological learning and types of technology policies required for CoPS development programs. However, several limitations remain. First, due to the lack of quantitative data on the military aircraft programs, this study could not provide enough information on the cost and economic outcomes of the programs. Instead, this paper focused on technological aspects of the projects, as the cost and economic agenda were less prioritized than the national goal of self-defense in the analysis time frame (Davies and Brady, 2000). Despite the rationalization of our approach, future studies may be replicated to empirically examine the financial inputs and outputs of the CoPS projects, in order to better understand the economics of latecomers' CoPS projects. Second, there have been some mismatches between the empirical data and the period of analysis. In order to overcome the limitations of the data which partially supports our argument, we have confirmed that our argument is in line with the comparative studies on national economic development of Korea, Brazil, and China and qualitative analyses results. On the whole, this study investigated multiple environments and actors within a single industry in order to gain a fine-grained understanding and overcome the limitation derived from the empirical data (Kim and Lim, 1988).

Acknowledgements
The authors are grateful to Dr. Younghoon Jun and other interviewees for their cooperation with the case studies and valuable inputs. We appreciate Professor Fumio Kodama and several experts' comments that improved this manuscript. We also express our gratitude toward two anonymous referees for their comments on an earlier draft.

References

Ahuja, G., 2000. The duality of collaboration: Inducements and opportunities in the formation of interfirm linkages. Strategic Management Journal 21 (3), 317-343.

Amsden, A.H., Chu, W.W., 2003. Beyond Late Development: Taiwan's Upgrading Policies. MIT Press, Cambridge, MA.

Balbinot, Z., 2006. Building technological capability in Brazilian firms through alliances, Ph. D. Thesis, University of Montreal, Canada.

Beaudry, C., 2001. Entry, growth and patenting in industrial clusters: A study of the aerospace industry in the UK. International Journal of the Economics of Business 8(3), 405-436.

Bédier, C., Vancauwenberghe, M., van Sintern, W., 2008. The growing role of emerging markets in aerospace. McKinsey Quarterly.

Bell, M., Pavitt, K., 1993. Technological Accumulation and Industrial Growth: Contrasts between developed and developing countries, Industrial and Corporate Change 2 (1), 157-209.

Bitzinger, R. A., 2011. China's defense technology and industrial base in a regional context: Arms manufacturing in Asia. The Journal of Strategic Studies 34 (3), 425-450.

Brady, T., Davies, A., 2004. Building project capabilities: From exploratory to exploitative learning. Organization Studies 25 (9), 1601-1621.

Brusoni, S., Prencipe, A., 2001. Unpacking the black box of modularity: Technologies, products and organizations. Industrial and Corporate Change 10 (1), 179-205.

Brusoni, S., Prencipe, A., Pavitt, K., 2001. Knowledge specialization, organizational coupling, and the boundaries of the firm: Why do firms know more than they make? Administrative Science Quarterly 46 (4), 597-621.

Carrico, T., 2013. Aerospace: Embraer holds its Own against Global Manufacturers. Financial Times, October, 2013.

Casanova, L., Fraser, M., Hoeber, H., Golstein, A., Molina, R., Arruda, C., Almeida, A., 2009. Multilatinas to Global Latinas: The New Latin American Multinationals. Inter-American Development Bank.

Cassiolato, J. E., Bernardes, R., Lastres, H., 2002. Transfer of technology for successful integration into the global economy: A case Study of Embraer in Brazil. United Nations Conference on Trade and Development, New York.

Chandler, A. D., 1990. Strategy and Structure: Chapters in the History of the American Industrial Enterprise, MIT Press.

Cho, H. D., Lee, J. K., 2003. The developmental path of networking capability of catch-up players in Korea's semiconductor industry. R&D Management 33 (4), 411-423.

Cho, M. C., 2003. Restructuring of Korea's defense aerospace industry: Challenges and opportunities? Bonn International Center for Conversion, Bonn

Choung, J. Y., Hameed, T., Ji, I., 2012. Catch-up in ICT standards: Policy, implementation and standards-setting in South Korea. Technological Forecasting and Social Change 79 (4), 771-788.

Choung, J. Y., Hwang, H. R., 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.

Davies, A., Brady, T., 2000. Organisational capabilities and learning in complex product systems: Towards repeatable solutions. Research Policy 29 (7), 931-953.

Davies, A., Hobday, M., 2005. The Business of Projects: Managing Innovation in Complex Products and Systems, Cambridge University Press, New York.

Delbridge, R., Mariotti, F., 2009. Racing for radical innovation. Advanced Institute of Management Research.

Dittrich, K., Duysters, G., De Man, A. P., 2007. Strategic repositioning by means of alliance networks: The case of IBM. Research Policy 36 (10), 1496-1511.

Dodgson, M., 2009. Asia’s national innovation systems: institutional adaptability and rigidity in the face of global innovation challenges. Asia Pacific Journal of Management 26 (3), 589–609.

DTI., 2006. The top 800 UK & 1250 global companies by R&D investment. The R&D Scoreboard.

Dussauge, P., Garrette, B., 1995. Determinants of success in international strategic alliances: Evidence from the global aerospace industry. Journal of International Business Studies 26 (3), 505-530.

Economist. 2009. Why do Professional Paths to the Top vary So Much? April, 2009.

Etzkowitz, H., Brisolla, S. N., 1999. Failure and success: The fate of industrial policy in Latin America and South East Asia. Research Policy 28 (4), 337-350.

Fisher, D. R., 2004. The impact of foreign weapons and technology on the modernization of China’s People’s Liberation Army. Center for Security Policy. Chicago.

Freeman, C., 1991. Networks of innovators: A synthesis of research issues. Research Policy 20 (5), 499-514.

Frischtak, C. R., 1994. Learning and technical progress in the commuter aircraft industry: An analysis of Embraer's experience. Research Policy 23 (5), 601-612.

Garrette, B., Castaer, X., Dussauge, P., 2009. Horizontal alliances as an alternative to autonomous production: Product expansion mode choice in the worldwide aircraft industry 1945-2000. Strategic Management Journal 30 (8), 885-894.

Gerschenkron, A., 1962. Economic Backwardness in Historical Perspective. Harvard University Press, Cambridge, MA.

Goldstein, A., 2002. Embraer: From national champion to global player. CEPAL Review 77, 97-115.

Goldstein, A., 2002. The political economy of high-tech industries in developing countries: aerospace in Brazil, Indonesia and South Africa. Cambridge Journal of Economics 26 (4), 521-538.

Ham, R.M., Mowery, D.C., 1995. Enduring dilemmas in U.S technology policy. California Management Review 37 (4), 89–107.

Hergert, M., Morris, D., (1988). Trends in international collaborative agreements, in: Contractor, F., Lorange, P. (Eds), Cooperative Strategies in International Business. Lexington Books, MA.

Heymann Jr, H., 1975. China's approach to technology acquisition. RAND, Santa Monica, CA.

Hobday, M., 1995. East Asian latecomer firms: Learning the technology of electronics. World Development 23

(7), 1171-1193.

Hobday, M., 1995. Innovation in East Asia: The Challenge to Japan. Edward Elgar Publishing.

Hobday, M., Davies, A., Prencipe, A., 2005. Systems integration: A core capability of the modern corporation. Industrial and Corporate Change 14 (6), 1109-1143.

Hobday, M., Rush, H., Tidd, J. 2000. Innovation in complex products and systems. Research Policy 29 (7), 793-804.

Hullmann, A., Meyer, M., 2003. Publications and patents in nanotechnology. Scientometrics, 58(3), 507-527.

Jun, Y., 2011. Technological catching-up and isolation avoidance: The case of the mobile communications industry in Korea and Japan. Asian Journal of Technology Innovation 19 (1), 149-168.

Jung, S., Imm, K. Y., 2002. The patent activities of Korea and Taiwan: a comparative case study of patent statistics. World Patent Information 24(4), 303-311.

Kim, L., 1997. Imitation to Innovation: The Dynamics of Korea’s Technological Learning. Harvard Business School Press, Boston, MA.

Kim, L., 1998. Technology policies and strategies for developing countries: Lessons from the Korean experience. Technology Analysis & Strategic Management 10 (3), 311-324.

Kim, L., 1999. Building technological capability for industrialization: Analytical frameworks and Korea’s experience. Industrial and Corporate Change 8 (1), 111–136.

Kim, L., Lim, Y., 1988. Environment, generic strategies, and performance in a rapidly developing country: A taxonomic approach. Academy of Management Journal 31 (4), 802-827.

King, D. R., Nowack, M. L., 2003. The impact of government policy on technology transfer: An aircraft industry case study. Journal of Engineering and Technology Management 20 (4), 303-318.

Lall, S., 1993. Technological development, technology impacts and industrial strategy: A review of the issues. Industry and Development 34, 1-36.

Lee, J. J., 2008. Legal analysis of Sea launch license: National security and environmental concerns. Space Policy 24 (2), 104-112.

Lee, J. J., Chung, S., 2011. Space policy for latecomer countries: A case study of South Korea. Space Policy 27 (4), 227-233.

Lee, J., Baek, J., Nam, M., 2009. A study on strategic R&D governance for defense sector. Journal of Technology Innovation 17, 149-177.

Li, P. P., 2010. Toward a learning-based view of internationalization: The accelerated trajectories of cross-border learning for latecomers. Journal of International Management 16 (1), 43-59.

Liu, X., White, S., 2001. Comparing innovation systems: A framework and application to China’s transitional context. Research Policy 30 (7), 1091-1114.

Luo, Y., Tung, R. L., 2007. International expansion of emerging market enterprises: A springboard perspective. Journal of International Business Studies 38 (4), 481-498.

Maculan, A. M., 2013. Embraer and the growth of the Brazilian aircraft industry. International Journal of Technology and Globalisation 7 (1), 41-59.

Magnusson, T., Tell, F., Watson, J., 2005. From CoPS to mass production? Capabilities and innovation in power generation equipment manufacturing. Industrial and Corporate Change 14 (1), 1-26.

Mathews, J.A., Cho, D.S., 2000. Tiger Technology: The Creation of the Semiconductor Industry in East Asia. Cambridge University Press, Cambridge.

McGregor, J., 2010. China’s drive for ‘Indigenous Innovation’. U.S. Chamber of Commerce.

Miller, R., Hobday, M., Leroux-Demers, T., Olleros, X., 1995. Innovation in complex systems industries: The case of fighter simulation, Industrial and Corporate Change 4 (2), 363-400.

Mowery, D. C., 1987. Alliance politics and economics: Multinational joint ventures in commercial aircraft, Ballinger Publishing Company.

Moxon, R. W., 1987. International competition in high technology: The Brazilian aircraft industry. International Marketing Review 4 (2), 7-20.

Nelson, R.R., 1993. National Innovation Systems. Oxford University Press.

Nelson, R.R., 1995. Why should managers be thinking about technology policy? Strategic Management Journal 16 (8), 581–588.

Neto, R., 1991. The role of transnational companies in the Brazilian Defense Tripod. Journal of Latin American Studies 23 (3), 573-597.

Niosi, J., Zhegu, M., 2005. Aerospace clusters: Local or global knowledge spillovers? Industry & Innovation 12 (1), 5-29.

Noailly, J., Batrakova, S., 2010. Stimulating energy-efficient innovations in the Dutch building sector: Empirical evidence from patent counts and policy lessons. Energy Policy 38(12), 7803-7817.

Nolan, P., Zhang, J., 2002. The challenge of globalization for large Chinese firms. World Development 30 (12), 2089-2107.

Pack, H., Westphal, L. E., 1986. Industrial strategy and technological change: Theory versus reality. Journal of Development Economics 22(1), 87-128.

Park, T. Y., 2012. How a latecomer succeeded in a complex product system industry: Three case studies in the Korean telecommunication systems. Industrial and Corporate Change 22 (2), 363-396.

Pavitt, K., 1984. Sectoral patterns of technology change: Toward a taxonomy and theory. Research Policy 13 (6), 343–372.

Phillips, F., Su, Y. S., 2009. Advances in evolution and genetics: Implications for technology strategy. Technological Forecasting and Social Change 76(5), 597-607.

Powell, W. W., White, D. R., Koput, K. W., Owen-Smith, J., 2005. Network dynamics and field evolution: The growth of interorganizational collaboration in the life sciences. American Journal of Sociology 110 (4), 1132-1205.

Prencipe, A., (2013). Aircraft and the third industrial revolution, in: Dosi, G., Galambos, L. (Eds), The Third Industrial Revolution in Global Business. Cambridge University Press.

Prencipe, A., Tell, F., 2001. Inter-project learning: processes and outcomes of knowledge codification in project-based firms. Research Policy 30 (9), 1373-1394.

Ramamurti, R., 1985. High technology exports by state enterprises in LDCs: the Brazilian aircraft industry. The Developing Economies 23 (3), 254-280.

Rodengen, J. L., 2009. The History of Embraer, Write Stuff Enterprises.

Rotman, D., 2012. Can we build tomorrow's breakthroughs? Technology Review 115 (1), 36-45.

Saunders, P. C., Wiseman, J. K., (2011). China's quest for advanced aviation technologies, in: Hallion, R. P., Cliff, R. (Eds), The Chinese Air Force: Evolving Concepts, Roles, and Capabilities. National Defense University Press.

Skocpol, T., 1979. States and social revolutions: A comparative analysis of France, Russia and China. Cambridge University Press.

Sikkink. K., 1991. Ideas and Institutions: Developmentalism in Brazil and Argentina, Cornell University Press, Ithaca.

Smith, D. J., Tranfield, D., 2005. Talented suppliers? Strategic change and innovation in the UK aerospace industry. R&D Management 35 (1), 37-49.

Stewart, T. P., Drake, E. J., 2011. China's support programs for high-technology industries under the 12th five-year plan. Law Offices of Stewart and Stewart, Washington, DC.

Su, Y. S., Hung, L. C., 2009. Spontaneous vs. policy-driven: The origin and evolution of the biotechnology cluster. Technological Forecasting and Social Change 76(5), 608-619.

Teece, D.J., Pisano, G., Shuen, A., 1997. Dynamic capability and strategic management. Strategic Management Journal 18 (7), 509–533.

Tirpak, J., 2009. The sixth generation fighter. Air Force Magazine 92, 38-42.

U.S. Congress. 1990. Arming Our Allies: Cooperation and Competition in Defense Technology. Washington D.C.

Vernon, R., 1966. International investments and international trade in the product cycle. Quarterly Journal of Economics 80 (2), 190-207.

Vertesy, D., Szirmai, A., 2010. Interrupted innovation: Innovation system dynamics in latecomer aerospace industries, Maastricht Economic and Social Research and Training Centre on Innovation and Technology, UNU-MERIT.

Viotti, E. B., 2002. National learning systems: A new approach on technological change in late industrializing economies and evidences from the cases of Brazil and South Korea. Technological Forecasting and Social Change 69 (7), 653-680.

Vogel, D.J., 1996. The study of business and politics. California Management Review 38 (3), 146–165.

Winthrop, M. F., Deckro, R. F., Kloeber Jr, J. M., 2002. Government R&D expenditures and US technology advancement in the aerospace industry: A case study. Journal of Engineering and Technology Management 19(3), 287-305.

World Economic Forum. 2013. Manufacturing value chains driving growth. World Economic Forum Report in collaboration with Deloitte Touche Tohmatsu.

Yoon, H., Lee, J. J., 2013. Entrepreneurship education and research commercialization of engineering-oriented universities: An assessment and monitoring of recent development in Korea. International Journal of Engineering Education 29(5), 1068-1079.