Waseda University Institute of Asia-Pacific Studies
早稲田大学 アジア太平洋研究センター

WIAPS Discussion Paper

Series No.2018-E-1

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01/2019

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Abstract: How to design the national innovation system has attracted attention from scholars and policy makers. Firms, universities, and government organizations (including public research institutes) are defined as the three major players of the national innovation system and interactions between the players are considered the key of the national innovation system. However, public research institutes are relatively understudied compared to firms and universities even though their contribution in the national innovation system is not trivial. Aiming at understanding detailed process rather than testing hypotheses, the findings of this paper shed practical information regarding innovation process in public research institutes. Focusing on the National Institute of Advanced Industrial Science and Technology (AIST), Fraunhofer-Gesellschaft (Fraunhofer), and the Industrial Technology Research Institute of Taiwan (ITRI), this paper analyzes and compares innovation processes of public research institutes with their patent data. Based on findings, this study further discusses issues for better management of public research institutes.

Key words: innovation, national innovation system, patent data, public research institute

MSC code: 65

JEL code: O25

1. Introduction

Innovation is to create new value from new ideas with new methods. Innovation is the engine of economic growth. How to design systems to derive innovation at the national level—national innovation systems (Freeman, 1987; Nelson, 1993)—has been an important issue for scholars and policy makers. Firms, universities, and government organizations (including public research institutes) are defined as the three major players of national innovation systems (NIS) and interactions between the players are considered the key of NIS. Their interactions create new value by combining new knowledge and resources and by combining conventional knowledge and resources in new ways. For example, when companies collaborate with universities to develop new technology, their collaboration leads knowledge exchange between the firms and universities.

There is a substantial extant literature focusing on NIS. Since the Organisation for Economic Co-operation and Development (OECD) published a key report (OECD, 1999), research on NIS flourished thereafter. There are three major actors in NIS, but most studies regarding NIS have focused on the collaboration between universities and firms. Public research institutes have received less attention although they are actively involved in innovation and some of them play a key role in the development of industries. Some public research institutes conduct R&D with enormous budgets, leading over industries. In addition, some other public research institutes play a key role in deciding the speed and direction of development of an industry by forming industrial consortia and fora.

This paper investigates how public research institutes contribute to innovation and aims to understand the role of the public research institute in NIS. Accordingly, this paper aims at understanding detailed process rather than testing hypotheses. This paper focuses on three case-studies to illuminate innovation processes therein: the National Institute of Advanced Industrial Science and Technology (AIST), Fraunhofer-Gesellschaft (Fraunhofer), and the Industrial Technology Research Institute (ITRI). The reason why this study chooses AIST, Fraunhofer, and ITRI is they are often considered as amongst the key public research institutes of Japan, Germany, and Taiwan, respectively and as such have garnered attention in the extant literature (Freeman, 1987; Tanaka, 1989; Chen & Sewell, 1996; Beise & Stahl, 1999; Yang et al., 2009; Wong et al., 2015). In addition, as will be seen later in this paper, AIST, Fraunhofer, and ITRI focus on similar research fields and show high correlations in their technological portfolios.

As for contribution, this study adds a missing part to the puzzle that has been overlooked by prior studies. This study focuses on public research institutes whose mission is to conduct R&D. As will be reviewed in the next section, prior studies discussing public research institutes have several limitations such as confusing public research institutes with universities despite the differences and neglecting the evolving roles of public research institutes with changes in surrounding conditions, etc.

The remainder of this paper is organized as follows. Section 2 reviews relevant theories from prior studies in order to define and position this study. Section 3 describes how data were collected and analyzed. Section 4 presents findings and Section 5 discusses these findings along with policy implications. Finally, Section 6 concludes the paper.

2. Literature review

This section reviews some of the prior studies relevant to the current study. By doing so, this section aims to illuminate limitations in existing research in order to facilitate defining and positioning the current study.

2.1. Linkages in National Innovation Systems

The concept of NIS was proposed based on a case study of Japan in the 1980s (Freeman, 1987). Freeman (1987) recognized R&D consortia in Japan and collaborative relationships of government organizations as a national system, and argued that such a system could harness benefits at the same level by Western countries. Then, a group led by Professor Richard Nelson at Columbia University conducted international comparative research regarding NIS (Nelson, 1993). OECD took over the project and proposed innovation polity to its member countries based on the outcomes of its qualitative and quantitative research (OECD, 1999).

As the background of each country is different and heterogeneous in various important respects, application of the NIS concept in practice varies between countries. For example, Bernardes and Albuquerque indicated that the NIS in developed countries operates a different mechanism from developing countries (Bernardes & Albuquerque, 2003; Ribeiro et al., 2006).

However, despite such differences, prior studies on NIS commonly define firms, universities, and governments (including public research institutes) as NIS players. The key to NIS is the linkages between firms, universities, and public research institutes. There are differences in knowledge and capabilities across the players. NIS posits that innovation can be achieved via the exchange of knowledge and capabilities between the players. Accordingly, NIS considers that although the ultimate role of innovation is in firms, research outputs from universities and public research institutes contribute to innovation by firms. Such a tendency is strong especially in high-tech industries like bioengineering.

However, of the three types of linkages, most prior studies have discussed the role of the linkage between universities and firms (Perkmann et al., 2013). Public research institutes have garnered less attention. In addition, prior studies often conflated universities and public research institutes, just because both are publicly funded (Roessner, 1993; Beise & Stahl, 1999; Diez, 2000; van Beers et al., 2008).

But, this paper separates them for the following three reasons. First, public research institute consume all resources for research. On the other hand, although universities also consume a large share of their resources for research, they also consume substantial resources for education, too. Second, there is a difference in research output quality between public research institutes and universities. Although many research projects are run in universities, most of them are carried out by students, especially doctoral students, whose time is mostly spent for learning (Behrens & Gray, 2001). Student researchers in universities are expected to achieve successful research outcomes, but the primary interest for them is to obtain academic degrees through learning and research experience. Meanwhile, most researchers in public research institutes have finished those graduate courses and are expected to deliver appropriate research outputs. Third, the pattern of knowledge flows through the mobility of researchers is different between universities and public research institutes. The majority of student researchers leave their universities after obtaining degrees. Researchers at public research institutes are also mobile, but to a lesser extent than student researchers. Accordingly, tacit knowledge such as know-how is likely to remain and accrue in public research institutes to a greater extent compared to universities. In sum, differences in expected missions, capability of researchers, knowledge flows and accrual serve to suggest differences in innovation processes between universities and public research institutes.

2.2. The role of public research institutes

2.2.1. As a catch up catalyst

Public research institutes aimed at R&D has been contributing to national innovation by upgrading national technological capacity. In the case of Korea, the Electronics and Telecommunications Research Institute (ETRI) played a critical role in Korea's catch-up (Chung & Lee, 1999; Mock, 2005; Yoo et al., 2005). Collaborating with Qualcomm which was trying to commercialize its CDMA technology, ETRI contributed to commercialization and authorization of IS–95 which was the first CDMA-based standard in the mobile communications industry. During the collaboration with Qualcomm, ETRI played a role as a project manager to domestic firms. Similar cases can also be found in other industries in Korea (Kim, 1997; Kim & Lee, 2015). The contributions of public research institutes in terms of catch up can also be found in Taiwan and Thailand (Mazzoleni & Nelson, 2007; Intarakumnerd & Chairatana, 2008). Even in Japan, the effort of the Agency of Industrial Science and Technology (the predecessor of AIST) was considered as one of the determinants that enabled the Japanese semiconductor industry to catch up to the Western level (Freeman, 1987).

However, the role of public research institutes after catch up is not well understood. As technological capability in emerging countries converges towards the level of that in advanced countries, the role of public research institutes in catching up diminishes. Further, the new role after catch up remains under-discussed. One new role is to bridge between universities' basic research and firms' commercialization of that basic research (Cohen et al., 2002). As the speed of technological advancement accelerates and technologies in products and services become more complex, firms are expected to employ open innovation. Although some new roles have been proposed, overall, information is lacking in this respect.

2.2.2. As an innovation seed provider

Consistently through time, public research institutes, whose primary role is R&D, have played a key role by providing innovation seeds. However, such a role has been questioned recently. Historically, public research institutes have indeed provided innovation seeds that later changed the world completely. In particular, public research institutes whose mission was to conduct defense and space research receive substantial budgets for challenging and complex R&D activities, which present opportunities to find new knowledge, new applications and, indeed, paradigm-shifting breakthroughs (Nelson, 1993; Mowery, 2010). For example, the Internet was invented in a research project by the Defense Advanced Research Projects Agency (DARPA) which played a pivotal role in the information revolution in the late 20th century (Mowery & Simcoe, 2002). In addition, substantive knowledge garnered via military robotics research is applied in commercial robotics contexts.

Importantly, the current innovation model is not supporting these types of possibilities. In the past, innovation has been considered as a linear process (Kline, 1985). That is, innovation occurs in one direction as research -> development -> production -> marketing. However, scholars recognized that there is a gap between the linear model and reality. Bearing in mind the complexities inherent in actual, empirical contexts, the innovation process model was further developed as a chain model. The chain model is different from the linear model in several ways. First, the chain model recognizes that there are several paths in the innovation process. In contrast, the linear model has only one path, from research to marketing. Second, as shown in the chain model, there exist feedbacks between organizations and those feedbacks are then reflected in the innovation process. Third, research is not the first step in the chain model. Rather, research is conducted in each step based on necessity. The innovation process that begins from research is also known as the 'technology push' model. Even if the technology push model explains *some* innovations, the 'demand pull' model explains *most.* Lastly, knowledge accrues as shown in the chain model; this is different from the linear model where new knowledge is always employed.

2.3. Conceptual framework: factors that affect the performance of public research institutes

As apparent from the literature review, public research institutes have been assigned various roles for a number of different purposes. Several factors are necessary for them to successfully achieve their assigned roles (Intarakumnerd & Goto, 2016). The availability of such factors tends to influence their success and failure.

The first and most important factor is funding. For example, Fraunhofer receives about one-third of its total budget from the government and the remaining two-thirds from the industry and other revenue sources. Whereas, ITRI receives 65% of its revenue from the government and 35% from the industry, and AIST receives almost its entire total budget from the government. These differences affect the institutes' research and development (R&D) choices.

The second factor is researchers. This is largely influenced by the funding structure. When public research institutes receive stable government block funding, they can hire permanent researchers. An example is AIST. In this situation, the researchers' knowledge remains within the institute, and knowledge accumulation occurs easily. In the absence of such funding, the institutes can only hire fixed-term researchers, as occurs at Fraunhofer and ITRI. In such cases, it is difficult for knowledge to accrue within the organizations.

The third factor is the research agenda. This is also largely influenced by the funding structure. For example, whether the funding comes from the industry or from the government is a critical concern for public research institutes. When they rely heavily on government block funding, it is possible to set a basic research agenda with long-term objectives, although their research agenda must be in the national interest. Meanwhile, if public research institutes rely on industry funding rather than government funding, they must have a commercially-oriented research agenda in order to meet their funders' expectations.

The fourth factor is performance evaluation. Various indicators have been applied to assess the performance of public research institutes such as patents, publications, technology transfers, spin-offs, R&D contract volume, and budget size. However, as the economic outcomes of public research institutes are still difficult to measure, despite these various indicators, measurement of performance remains a concern among policy makers.

The fifth factor is the location of public research institutes. Geographical proximity is important for knowledge transfer and innovation because it increases interactions between researchers from different organizations and the ability to share facilities.

The final factor is governance. This is important to set the overall strategic direction of public research institutes. For example, in order to increase inputs from and interactions with the industry, chief executives are recruited from the industry. Institutes such as AIST and ITRI are some of the examples.

3. Data

3.1. AIST, Fraunhofer, and ITRI

This subsection briefly describes the three public research institutes of interest. All the descriptions in this subsection draw on the webpages and recent annual reports of the three organizations.

This study focuses on AIST, Fraunhofer, and ITRI, amongst others, for several reasons. First, as mentioned in Section 1, these institutes are acknowledged in literature. Second, they focus on common research fields such as ICT, material science, life science, and energy. As will be seen in Section 4.1., they show high correlations in their technological portfolios. Third, they have a large amount of patent data available to conduct patent data analysis. For such reasons, I did not include other public research institutions in other countries; for example, the National Institute of Standards and Technology (NIST) in the United States or the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia (Intarakumnerd & Goto, 2016). These were not chosen for the current study either due to the fact that the focus of their research was different, or because the patent data was insufficient. For example, I did not add NIST due to their mission and lack of patent data. The institute's core competencies are in measurement science, rigorous traceability, and the development and use of standards, where patenting is rare. Additionally, I did not add CSIRO because it had few United States patent applications from which to obtain reliable results

3.1.1. AIST

AIST is one of the largest public research institutes in Japan. AIST is focusing on bridging innovative technologies between basic research and commercialization. It consists of 42 organizations (as of 2014) and they are classified into 7 fields: Energy and environment, life science and biotechnology, information technology and human factors, materials and chemistry, electronics and manufacturing, geological surveys, and national metrology.

2300 researchers are employed by AIST. Additionally, 4800 researchers are conducting research at AIST as visiting researchers from academia and industry. The annual revenue is circa 100 billion yen, around 75% of which consists of subsidies, commissioned research funds, and grants from the government.

3.1.2. Fraunhofer

Fraunhofer is Europe's largest application-oriented research institute. Fraunhofer conducts R&D with others to transform original ideas into innovations that benefit society and strengthen both the German and the European economy. Fraunhofer is specialized in the following seven fields: Defense and security, information and communication technology, life science, light & surfaces, materials and components, microelectronics, and production.

As of 2014, Fraunhofer consists of 66 research institutes and research units within Germany with a workforce of 24000 employees. The annual budget is around 2.1 billion euros, more than 1.7 billion euros of which is from contracted research projects. Defense research provides an important source of income. More than 70% of the contracted research projects are collaborations with the private sector, or publicly funded commissioned research projects. The remainder depend on public funds from governments.

3.1.3. ITRI

ITRI is a Taiwan-based nonprofit R&D organization engaging in applied research and technical services. ITRI has been dedicated to helping industries stay competitive and sustainable. ITRI integrates its six major research areas: Biomedical technology and device, green energy and environment, material and chemical, mechanical and systems, information and communications, and electronics and optoelectronics. Those six research areas are defined in three application domains: Smart Living, Quality Health, and Sustainable Environment.

As of 2014, ITRI has 15 R&D units and 10 service units, with 5800 employees. The annual budget is 20 billion NTD, about half of which derives from competitively won funds from the government and the other half is from contract research projects, service provision, and technology transfer.

3.2. Patent data

Thanks to the rapid advancement of information technology and digitalization in recent decades, data are readily amenable to digitization and storage in databases. In addition, because of the development of computers and software, processing large amounts of data has become easy. As a result, patent data have been used in various academic fields and innovation research is one such field which frequently uses patent data. The patent system grants exclusive ownership over inventions for a certain period of time in the content of inventions which are publicly disclosed and claimed. Accordingly, patent data provide information not only about innovation output but also innovation processes (Jaffe & Trajtenberg, 2002). Concretely, information about people involved (applicants and inventors), timing (filing dates), regions (patent offices, and addresses of applicants and inventors), technological knowledge (inventions and citations), etc. can be retrieved (Kang, 2015; Kang & Tarasconi, 2016). Patent statistics are based on these kinds of information and used in many empirical studies. Patent data analysis has several merits. First, it can remove the biases inherent in subjective survey and interview based methods. Second, effort and cost are lower in terms of collating patent data thanks to well-designed databases.

This paper employs patent statistics (Griliches, 1990; Jaffe & Trajtenberg, 2002) to observe innovation processes of public research institutes. This study employs patent data held by the United States Patent and Trademark Office (USPTO) for three reasons (Nagaoka et al., 2010). The first reason is to minimize 'home office' bias. When a firm files a patent, it tends to file first in the patent office of its own country. Since this study focuses on AIST, Fraunhofer, and ITRI, there are patent filing biases in Japan, Germany, and Taiwan. As a result, the three public research institutes cannot be compared in a fair manner. However, the US market is often considered as the primary market after home countries for many organizations. Therefore, many firms file patents in USPTO after their home offices. Accordingly, using patent data in USPTO helps minimize home biases. The second reason to employ patent data in USPTO concerns the availability of citation data. Since patent citations are used for examining patent applications, applicants have no incentive to add citations. However, in order to file patents in USPTO, one must provide all the information on which the patent application is based (duty of candor). Patent applications which fail to do so will be rejected. As a result, patent data in USPTO tends to provide more citation data than other patent offices (Layne-Farrar, 2011). The third reason is to minimize 'home citation' biases. Patent citations are likely to come from information near the applicants and inventors (Michel & Bettels, 2001). Therefore, it is assumed that AIST, Fraunhofer, and ITRI may be responsible for significant citations of patents which are close to them in spatial terms. By using patent data in USPTO, we may militate against home citation biases. One problem with this method is that there might exist US citation bias, in which a disproportionate number of citations of a patent application come from near the patent examiners. However, since US citation bias will evenly affect the three public research institutes, a fair comparison can be made between AIST, Fraunhofer, and ITRI.

4. Findings

4.1. Patent applications

Patent applications to USPTO by the three public research institutes are shown in Figure 1. The case of AIST shows that this organization has been active in filing patent applications to USPTO even before the formation of AIST in 2001. It has been filing patent applications in USPTO since 1975; these increased in the early 2000s before decreasing after 2005. Findings from the case of AIST imply that AIST has considered USPTO to be an important target for patent applications. Meanwhile, Fraunhofer was filing patent applications to an extent less than or similar to AIST until 2005. An interesting fact here is that there were almost no patent applications filed by this organization to USPTO until the 1990s, but patent filing to USPTO has increased since then. This indicates that Fraunhofer started to focus on the US market in the 1990s. Finally, ITRI seems to have a great interest in the US market, more than AIST and Fraunhofer. Until 1985, patent applications to USPTO by ITRI were almost zero, but have boomed since then. Patent applications to USPTO by the three public research institutes decrease after 2010, but this is probably because the most recent data are not reflected in the database.

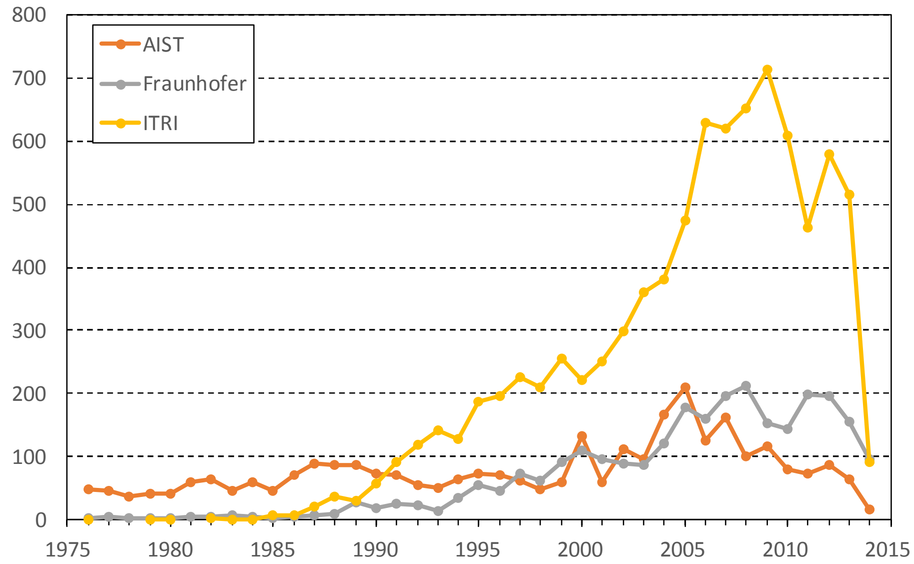


Figure 1. Patent applications to USPTO

Next, the patent portfolio based on patent applications to USPTO is compared between the three public research institutes of interest. This analysis allows us to test if comparing AIST, Fraunhofer, and ITRI is valid. The patent portfolio of each institute was obtained by counting the number of patent applications per the technological classification known as the International Patent Classification. Then, the patent portfolio correlations between AIST, Fraunhofer, and ITRI were calculated. The results are displayed in Table 1. Since correlation levels are high, it is assumed that it is fair to compare AIST, Fraunhofer, and ITRI.

Table 1 Correlation of patent applications by AIST, Fraunhofer, and ITR

	AIST	Fraunhofer	ITRI
AIST	1.000		
Fraunhofer	0.6882	1.000	
ITRI	0.7595	0.7427	1.000

4.2. Co-application analysis

This subsection analyzes the co-application activities of AIST, Fraunhofer, and ITRI. Co-applicants are classified into seven types: 1) domestic firms, 2) foreign firms, 3) domestic universities, 4) foreign universities, 5) domestic research institutes, 6) foreign research institutes, and 7) individuals. The classification results are shown in Figure 2.

First, AIST filed patent applications with 464 organizations. The breakdown of these 464 organizations is as follows: 334 domestic firms, 10 foreign firms, 26 domestic universities, 1 foreign university, 23 domestic research institutes, and 70 individuals. AIST filed a total of 996 patent applications with these 464 organizations, as follows: 758 patent applications with domestic firms, 13 patent applications with foreign firms, 71 patent applications with domestic universities, 1 patent application with a foreign university, 59 patent applications with domestic research institutes, and 94 patent applications with individuals.

AIST's case exhibits three differences from the cases of Fraunhofer and ITRI. First, the numbers of AIST's co-applicants and co-applications are much greater than those of Fraunhofer and ITRI. Second, most of the co-applicants are domestic firms. These two findings indicate that AIST is active in collaborating with other organizations, but their focus is on domestic markets to a greater extent than Fraunhofer and ITRI. Third, collaboration with individuals is significant, rather than marginal. This result may reflect Japanese system protocols to use inventors' names instead of applicants' names. For example, before the Japanese Bayh–Dole Act, universities in Japan were banned from filing patent applications. Instead, inventors in universities used their own names as applicants instead of university names. Accordingly, it is assumed that most of the individuals denoted as AIST's collaborators were probably in universities.

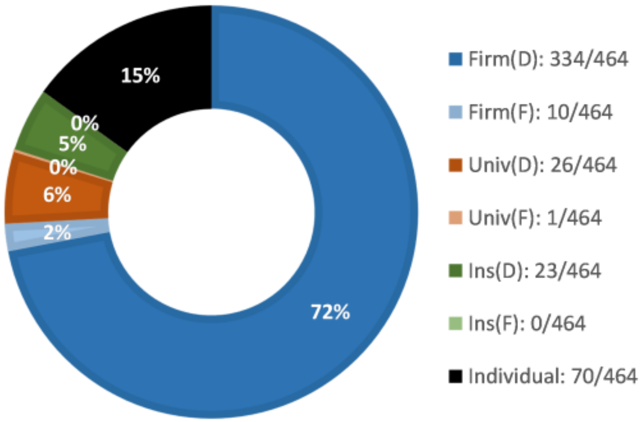
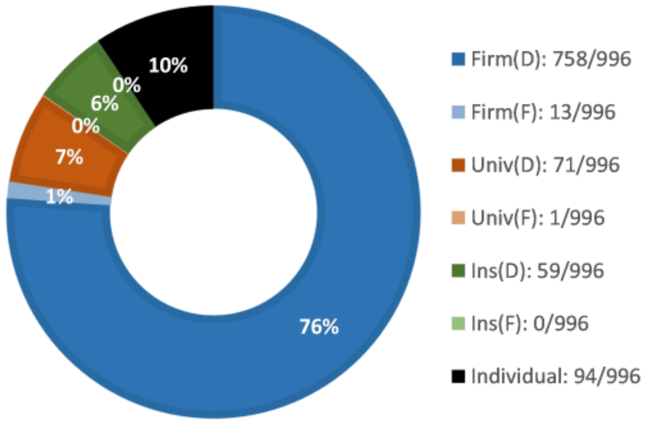
Meanwhile, Fraunhofer filed patent applications with 186 organizations, as follows: 83 domestic firms, 58 foreign firms, 24 domestic universities, 10 foreign universities, 4 domestic research institutes, 5 foreign research institutes, and 2 individuals. Fraunhofer filed a total of 375 patent applications with these 186 organizations. Specifically, Fraunhofer filed 117 patent applications with domestic firms, 127 patent applications with foreign firms, 96 patent applications with domestic universities, 21 patent applications with foreign universities, 6 patent applications with domestic research institutes, 6 patent applications with foreign research institutes, and 2 patent applications with individuals.

Fraunhofer's case exhibits two differences from the cases of AIST and ITRI. First, Fraunhofer exhibits strong international presence, collaborating with various foreign organizations. Those organizations are not only firms but also universities. A lot of them were from EU member states. Second, collaborations with universities (domestic and foreign universities) are substantial. The reason for this is not known, but since this finding is interesting, some discussion is offered in the following section regarding this point.

Lastly, ITRI filed patent applications with 152 organizations, as follows: 91 domestic firms, 10 foreign firms, 18 domestic universities, 5 foreign universities, 3 domestic research institutes, and 25 individuals. ITRI filed 622 patent applications with these 152 organizations, as follows: 462 patent applications with domestic firms, 22 patent applications with foreign firms, 101 patent applications with domestic universities, 7 patent applications with foreign universities, 4 patent applications with domestic research institutes, and 26 patent applications with individuals.

ITRI's case is similar to that of AIST. That is, their primary collaborator is domestic firms. Although the number of individuals involved in collaborations is noteworthy, actual patent filings with individuals are rare. Meanwhile, universities seem to be important for ITRI as a collaborator. Universities represent 12% of co-applicants and the total number of co-applications with universities is large compared to AIST and Fraunhofer.

How to read	［Co-applicants］ Firm(D): 334/464 ⇒ 334 domestic firms among 464 co-applicants Firm(F): 10/464 ⇒ 10 foreign firms among 464 co-applicants	［Co-applications］ Firm(D): 758/996 ⇒ 758 domestic firms among 996 co-applicants Firm(F): 13/996 ⇒ 13 foreign firms among 996 co-applicants

<table>
<tr><th></th><th>No. of co-applicants</th><th>No. of co-applications</th></tr>
<tr><td>AIST</td><td>
</td><td>
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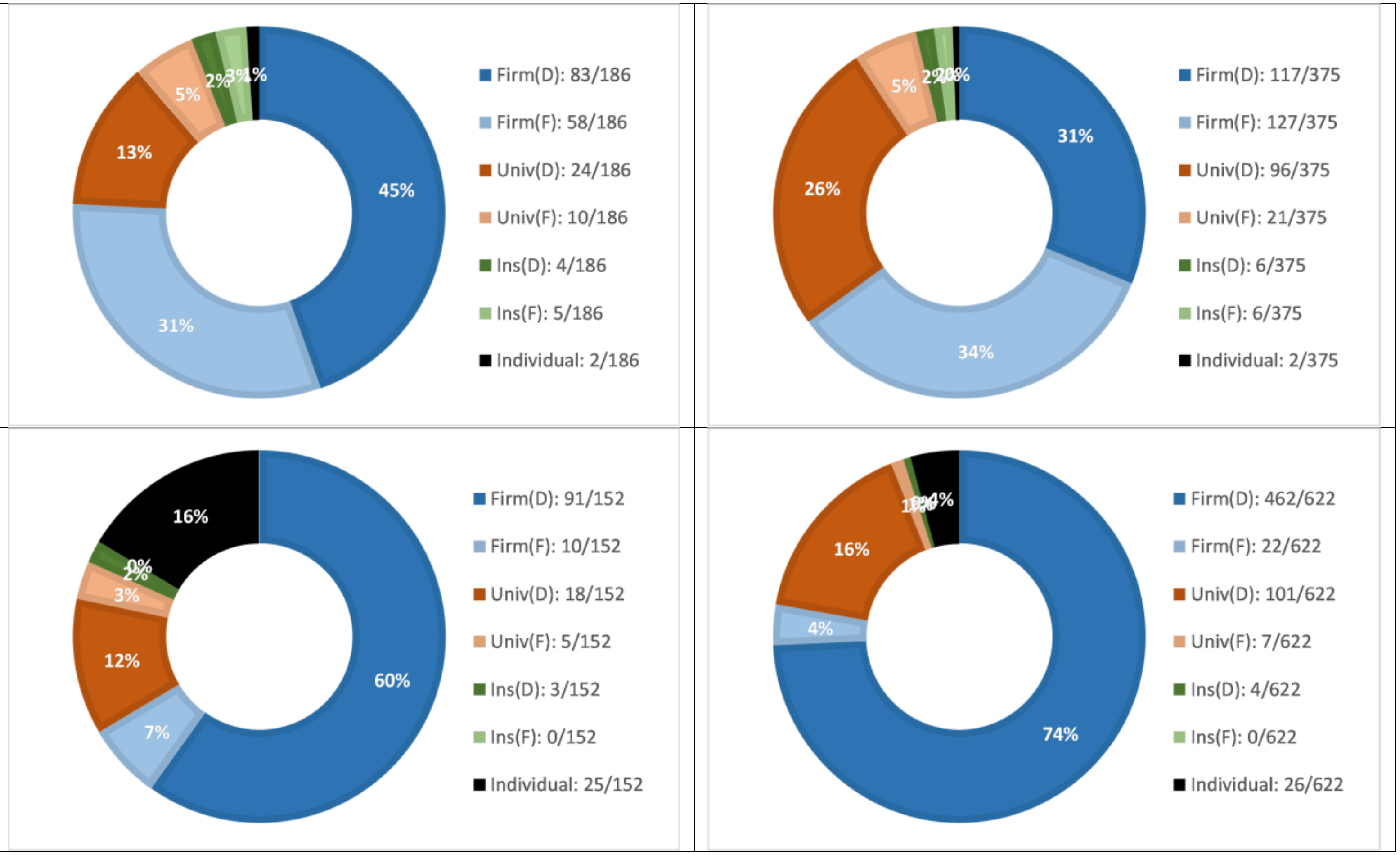
Fraunhofer		
ITRI		

Figure 2. Co-applicants and co-applications of AIST, Fraunhofer, and ITRI

4.3. Patent citation analysis 1: Geographical knowledge origin

Absorptive capacity is a firm's ability to recognize the value of new information, assimilate it, and apply it to commercial ends (Cohen & Levinthal, 1990). Accordingly, Absorptive capacity is considered as a necessary ability to achieve innovation. This subsection shows how widely the three public research institutes of interest search knowledge for their R&D activity from patent data.

If a patent, say A, cites a patent document, say B, we interpret this as a knowledge flow occurring from patent document B to patent A. Based on addresses of applicants, national origins of the applicants are determined. Patent citations have been widely used as a proxy for knowledge flows (Fung & Chow, 2002; Jaffe & Trajtenberg, 2002; Nelson, 2009). Repetition of patent citation analyses, for example analyzing citations of patent citations, allows the estimation of knowledge trajectories (Verspagen, 2007; Fontana, Nuvolari, & Verspagen, 2009; Martinelli, 2011).

Since patent citations are used for examining patent applications, it is the examiner who adds citations in the patent documents in principle. Patent examiners add citations to narrow the protection width claimed in patent applications and to reject patent applications. However, in reality, there is an incentive for applicants and inventors to add patent citations. For example, they add citations to help others understand claims and clarify inventions. (Hedge & Sampat, 2008). In other words, we can interpret that adding patent citations can be considered as an invention process. In addition, applicants must disclose all prior arts on which the proposed inventions are based. Hence, analyzing patent citations allows us to understand knowledge that influenced inventions.

Figure 3 indicates citations in patent applications by national origin, for AIST, Fraunhofer, and ITRI. The results are presented based on a ten-year time-step from 1980 to 2010. The country-level reliance of R&D activity in AIST, Fraunhofer, and ITRI is illustrated. For example, AIST inventions in 1980 were based on the US (71%), Japan (17%) and Europe (10%)[1].

First, AIST relied significantly on US knowledge in 1980. It also relied more on the knowledge of domestic applicants than that of applicants from Europe. Overall, reliance on the US, Japan, and Europe amounts to 98% in total, which clearly indicates that knowledge was concentrated within the so-called triad (Europe, Japan, and US). However, as time passes, the reliance on the knowledge of applicants from the US decreases and AIST relies more on the knowledge of domestic applicants, particularly in 2010. That is, AIST shifted its knowledge reliance from the US to Japan.

Second, Fraunhofer only relied on the knowledge of applicants from Germany and Japan in 1980. Fraunhofer gradually starting filing with the USPTO from the late 1980s. By 1990, Fraunhofer was sourcing 43%, 49%, and 8% of its knowledge from applicants in the US, Europe, and Japan, respectively. Until 2010, Fraunhofer was sourcing 40% and 17% of its knowledge from the US and Japan, respectively. The reliance on the knowledge of applicants from Europe including Germany is seen to decrease whilst the reliance on emerging countries such as Korea and Taiwan increases. This indicates that the technological capabilities of Korea and Taiwan are increasing in relative terms.

Finally, ITRI did not file patents with USPTO until 1980. In case of 1990 when ITRI filed a lot of patents in USPTO, ITRI sourced 46%, 16%, and 35% of its knowledge from applicants in the US, Europe, and Japan, respectively. Together this amounts to 97% of ITRI's knowledge reliance. Reliance on the knowledge of applicants from the US is around 50% in 2000 and 2010 whilst that from Europe is around 10%. The reliance on the knowledge of applicants from Japan decreases, measuring 19% in 2010, which is half of the value observed in 1990. Nevertheless, ITRI's reliance on knowledge from the US, Europe, and Japan is still high.

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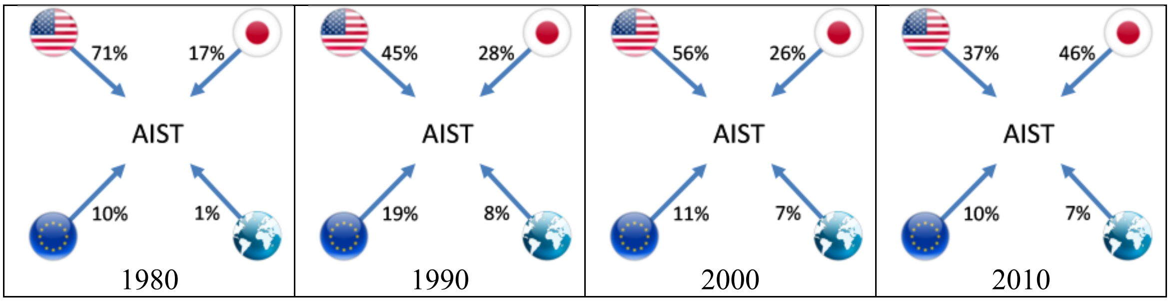
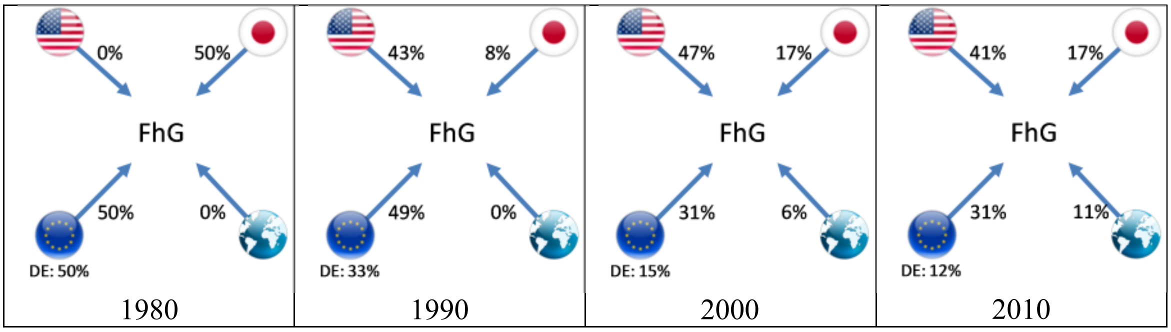
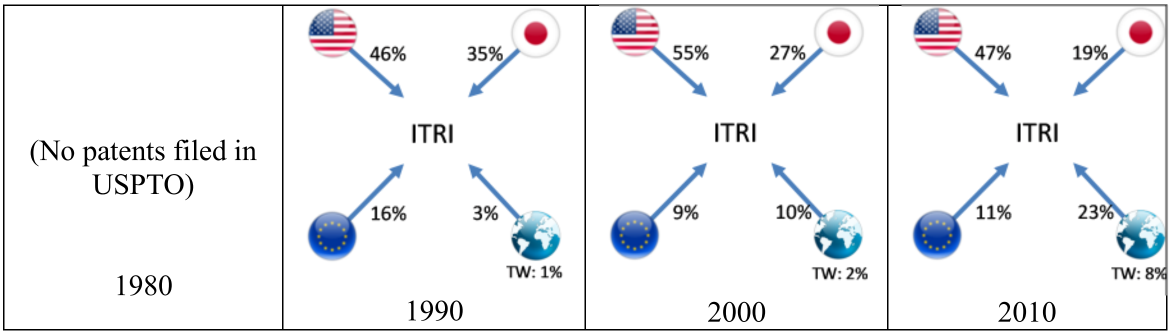
[1] Europe is defined in terms of the 28 EU member states as of 2016.



(a) Case of AIST



(b) Case of Fraunhofer



(a) Case of ITRI

Figure 3 Changing knowledge origins in AIST, Fraunhofer, and ITRI

4.4. Patent citation analysis 2: Self-citation (Knowledge accumulation)

This subsection compares self-citation rates and analyzes knowledge accumulation within AIST, Fraunhofer, and ITRI. Knowledge accumulation can be calculated by counting the number of times that an applicant cites their own patents. So, if knowledge accrues within an organization significantly, the organization tends to cite internal knowledge rather than external knowledge. As a result, self-citation increases with knowledge accumulation. In contrast, if knowledge does not accrue within an organization, the organization has a greater tendency to cite external knowledge. In this case, self-citation rates do not increase, and may remain zero or very low.

The results are shown in Figure 4. The horizontal axis is application year and the vertical axis is the rate of self-citation. Until 1985, in terms of Fraunhofer, there is high trend-variability because the number of patent applications was few and the trends are influenced by small changes. However, with time, this diminishes. There are two key findings in this figure. First, there is some evidence to suggest that the share of AIST's, Fraunhoer's, and ITRI's self-citations increases over time. This indicates increasing knowledge accumulation within each of AIST, Fraunhofer, and ITRI, and hence, they rely on internal knowledge more than external knowledge. Second, AIST's and Fraunhofer's self-citation rates are higher than that of ITRI's. In the analysis above, ITRI filed the largest amount of patent applications to USPTO compared to AIST and Fraunhofer; this is clearly not synonymous with knowledge accrual within the organization.

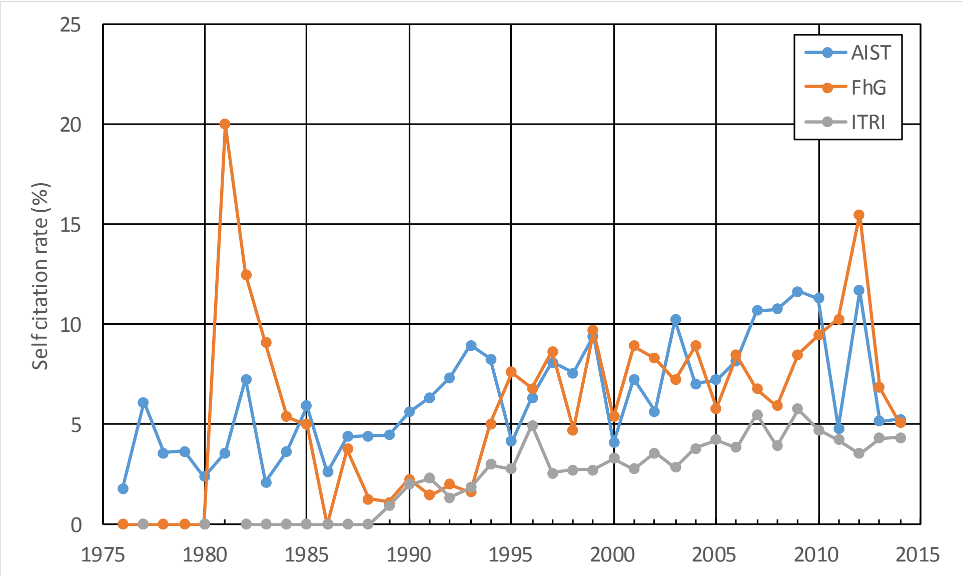


Figure 4 Self-citation rates

4.5. Patent citation analysis 3: Non self-citation (knowledge spillover)

The current subsection analyzes the extent to which inventions by AIST, Fraunhofer, and ITRI affected subsequent inventions by others. That is, knowledge spillover to others. Accordingly, this subsection calculates how many times patents are cited by others (Non self-citation). The analysis is twofold: knowledge spillover to domestic applicants and that to foreign applicants

4.5.1. Knowledge spillover to domestic applicants

The first analysis focuses on knowledge spillover to domestic applicants, i.e., AIST's knowledge spillover to applicants in Japan, Fraunhofer's knowledge spillover to applicants in Germany, and ITRI's knowledge spillover to applicants in Taiwan.

The results are shown in Figure 5 which illustrates the number of patent applications from Japan, Germany, and Taiwan that cite AIST's, Fraunhofer's and ITRI's patents, respectively. For example, in 1995, about 210 patent applications from Japanese applicants cited AIST's patents and about 50 patent applications from German and Taiwanese applicants cited Fraunhofer's and ITRI's patents.

It is readily observed that the number of patent applications that cite AIST's, Fraunhofer's and ITRI's patents increases as time goes on. This implies that the influence of AIST, Fraunhofer, and ITRI on domestic applicants is increasing. However, after around 2004, the trends associated with AIST's and Fraunhofer's either decrease of stay constant, whilst ITRI's increases significantly. This may indicate that ITRI's importance to domestic applicants is increasing. In addition, after 2010, all trends exhibit sharp, dramatic decreases. We speculate that this is a function of a database time lag: it takes time for patent documents to be published, and patent databases can add data only after those documents are published.

It is worthwhile to conduct individual analysis, too. AIST is cited the most out of the three public research institutes of interest. The number of Japanese applicants that cite AIST's patents increases rapidly between 1984 and 1989. There is a moderate increase from 1990 to

2000 because this time period covers when the bubble economy in Japan collapsed and firms started to strategically file patents with select and concentration strategy. Besides, on January 1st 1988, patent law in Japan was amended from "one patent = one claim" to "one patent = multiple claims." Accordingly, it is easy to conceive how and why the number of patent applications would drop after this policy change. However, the AIST trend is upwards from 1998 until 2005. To explain, R&D investment in Japan had been increasing since 1994[2] and as a result, a lot of patents had been filed since then (Japan Patent Office, 2007).

Second, the number of patent applications that cite Fraunhofer's patents continues to increase until 2003, However, subsequently it is characterized by plateau and decline. We assume that the macroeconomic context is being reflected here: the German economy between 2002 and 2003 was as unfavorable as it was during the onset of the financial crisis in 2008 which was characterized by the fall of Lehman Brothers amongst many others.

Lastly, ITRI shows a remarkable increase over time, excepting a blip in 2000. That is, the number of patent applications that cite ITRI's patents is ever increasing.

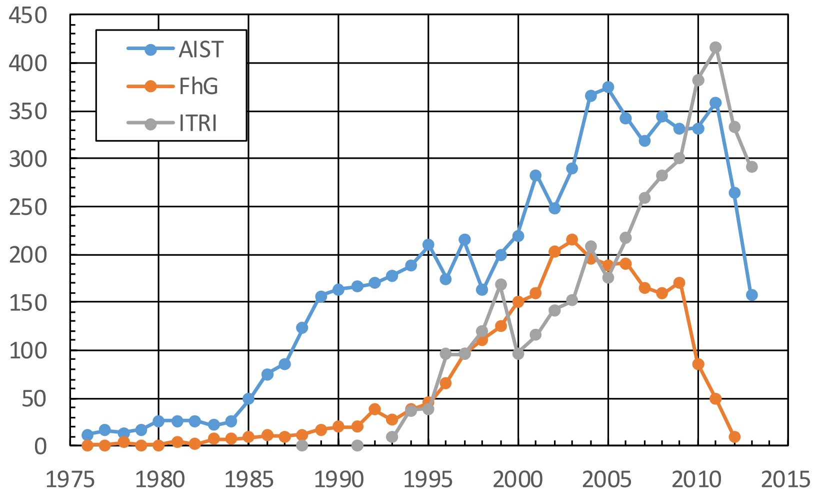


Figure 5. Patent applications by domestic applicants that cite patent documents by each of AIST, Fraunhofer, and ITRI

Figure 6 shows the value obtained by dividing the values in Figure 5 with the number of citable patents by AIST, Fraunhofer, and ITRI. In other words, Figure 6 shows the ratio of actually cited patents to all existing patents by AIST, Fraunhofer, and ITRI. One limitation of Figure 5 is that if an applicant files many patents, the applicant's patents have a greater chance of being cited compared to an applicant with one or few patents. Figure 6 removes this bias and compares AIST, Fraunhofer, and ITRI in a fair manner. For example, until 1995, a patent application by AIST was likely to be cited by 0.16 patent applications by applicants from Japan while a patent application by Fraunhofer and ITRI was cited by 0.12 and 0.5 by applicants in Germany and Taiwan, respectively.

First, the AIST and Fraunhofer trends are similar after 1985, remaining in the region of 0.1–0.2 even though the variability in the Fraunhofer trend is more pronounced. This implies that their impact on domestic players was reasonably consistent. However, after 2005, both trends are downwards. One reason is the number of patent applications by AIST and Fraunhofer increased much more than citing patents. Another reason is, as seen in Figure 5, the number of patent applications by domestic applicants that cite AIST's and Fraunhofer's patent applications decreases. However, it is not clear if the decrease is Japan and Germany specific or if the decrease is common globally. Thus whether, why and how AIST's and Fraunhofer's impacts is

[2] http://www.jpo.go.jp/shiryou/toushin/nenji/nenpou2007/honpen/2-1.pdf

domestic applicants are changing, warrants future study.

Moving on, ITRI's trend remains in the region of 0.05 after 2000. Accordingly, ITRI's impact on domestic applicants is reasonably consistent. This indicates that the number of patent applications by domestic applicants that cite ITRI's patent documents is increasing as much as ITRI increases its patent filings (as seen in Figure 1).

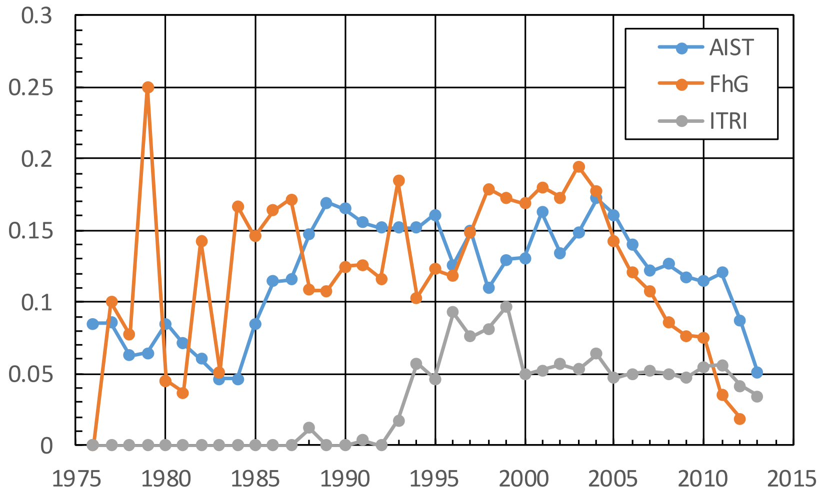


Figure 6 Ratio of actually cited patents by domestic applicants to all existing patents by AIST, Fraunhofer, and ITRI

4.5.2. Overseas firms

This analysis focuses on knowledge spillovers to overseas applicants, i.e., AIST's knowledge spillover to applicants outside Japan, Fraunhofer's knowledge spillover to applicants outside Germany, and ITRI's knowledge spillover to applicants outside Taiwan.

The results are shown in Figure 7 in terms of the number of patent applications outside Japan, Germany, and Taiwan that cite AIST's, Fraunhofer's and ITRI's patents, respectively. For example, in 2005, about 2300 patent applications from non-Japanese applicants cited AIST's patents and 1100 and 800 patent applications from non-German and non-Taiwanese applicants cited Fraunhofer's and ITRI's patents.

What is readily observed from the three public research institutes of interest is the number of patent applications that cited AIST's, Fraunhofer's and ITRI's patent documents is increasing as times goes. Thus, their impacts outside of their home countries are increasing. However, AIST's and Fraunhofer's trends are relatively stable after 2002 and 2004, respectively. Meanwhile, ITRI's trend exhibits a remarkable increase: because ITRI files a lot of patents to USPTO, there are many ITRI's patents to cite compared to AIST and Fraunhofer. In addition, as seen in Figure 5, the number of patent applications that cite AIST's, Fraunhofer's, and ITRI's patent documents is decreasing due to the incompleteness of the patent databases.

AIST receives more citations than Fraunhofer until 2003, following which the former takes the lead. This implies that their global impacts could have exhibited similar trends and changes.

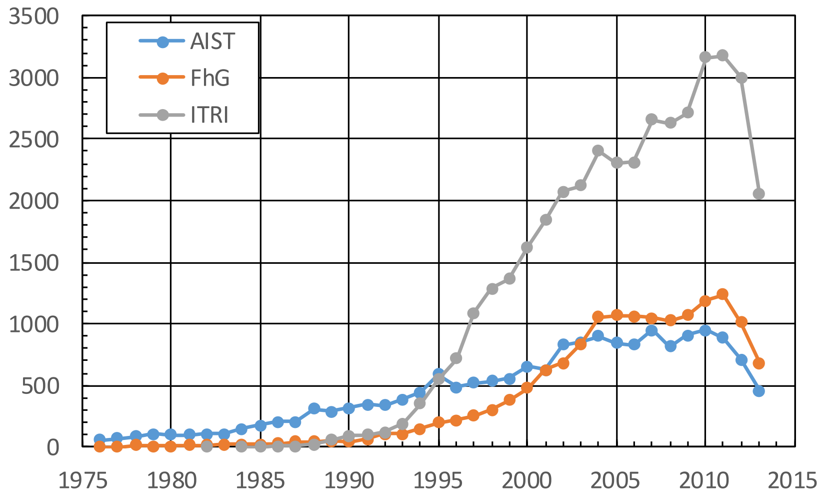


Figure 7 Patent applications by foreign applicants that cite patent documents by each of AIST, Fraunhofer, and ITRI

Figure 8 shows the value obtained by dividing the values in Figure 7 with the number of citable patents by AIST, Fraunhofer, and ITRI. In other words, Figure 8 shows the ratio of actually cited patents to all existing patents by AIST, Fraunhofer, and ITRI. One limitation of Figure 7 is that if an applicant files many patents, the applicant's patents have more chances of being cited compared to an applicant with zero or few patents. Figure 8 removes such bias and compares AIST, Fraunhofer, and ITRI in a fair manner. For example, until 2005, a patent application by AIST, Fraunhofer, and ITRI is likely to be cited by 0.4, 0.9, and 0.6 patent applications by foreign applicants, respectively.

A common tendency is for the trends to slope downwards after 2005. This is because the number of patent applications by AIST, Fraunhofer, and ITRI increased much larger than that of citing patents.

AIST's trend is subordinate, but consistent, over the period of interest. That is, AIST had the least impact on foreign applicants compared to Fraunhofer and ITRI.

Fraunhofer's trend dominates over the period of interest. That is, Fraunhofer had the largest impact to foreign applicants. However, the variation in this trend is large, so Fraunhofer's performance is affected significantly by applied research tendencies in each era.

Lastly, ITRI's trend presents the largest increase from the 1980s to 2000, winning over Fraunhofer between 1996 and 2001.

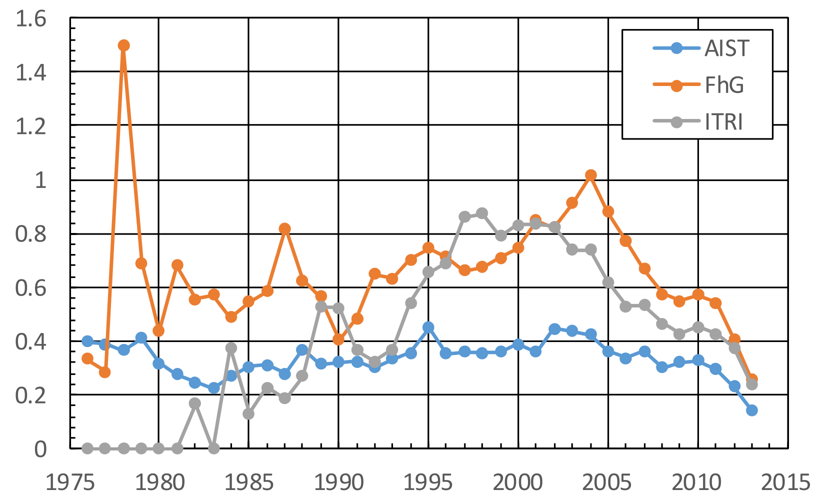


Figure 8 Ratio of actually cited patents by foreign applicants to all existing patents by AIST, Fraunhofer, and ITRI

4.6. Patent citation analysis 4: technological fields - generality versus originality

This subsection analyzes the generality and originality of AIST's, Fraunhofer's, and ITRI's inventions. Trajtenberg et al. (1997) defined generality in terms of how subsequent inventions spread across different technological fields, and originality in terms of how back-up inventions spread across different technological fields. If generality (originality) is substantial, the technical advances (roots) of the originating invention are broad (concentrated). The Herfindahl index operationalizes these concepts as follows:

$$\text{Generality:}\quad Gen_i = 1 - \sum_{k=1}^{N_{g,i}} \left(\frac{N_{citing,i}(k)}{N_{Citing,i}} \right)^2$$

$$\text{Originality:}\quad Org_i = 1 - \sum_{k=1}^{N_{o,i}} \left(\frac{N_{cited,i}(k)}{N_{Cited,i}} \right)^2$$

where k, N_g, N_{citing}, N_o, and N_{cited} are patent class indices: the number of different classes to which the citing patents belongs, the number of citing patents, the number of different classes to which the cited patents belong, and the number of cited patents, respectively.

First, generality of the inventions by AIST, Fraunhofer, and ITRI is compared. In this analysis, average organizational generality is calculated per application year (Figure 9).

Different tendencies are observed before and after 2000. First, until 2000, of the three public research institute of interest, the highest generality value is associated with Fraunhofer. Then, AIST and ITRI follow. After 2000, the generality of the inventions by all three organizations falls. It seems that thy are shifting towards more applied research, rather than basic research.

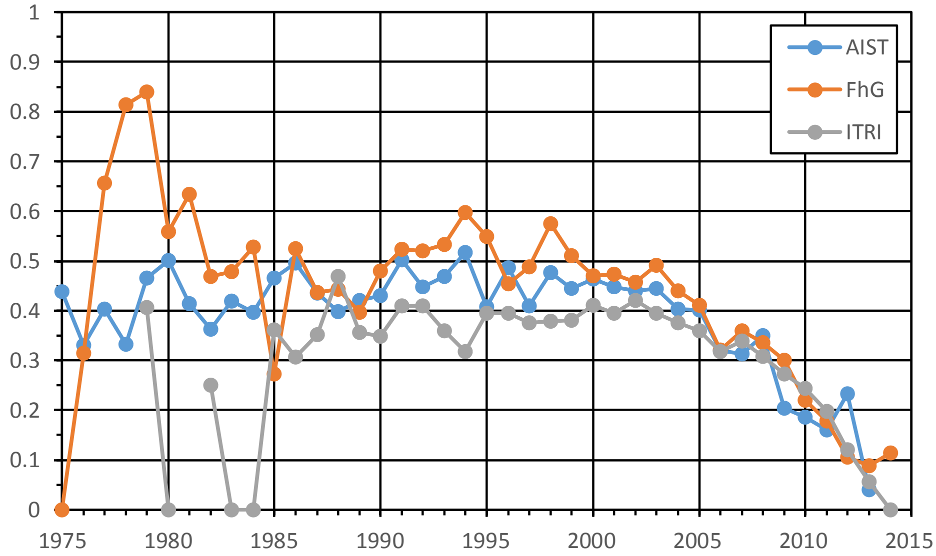


Figure 9. Generality of inventions by AIST, Fraunhofer, and ITRI

Second, originality of the inventions of AIST, Fraunhofer, and ITRI is compared. As was the generality analysis, the average organizational originality is calculated per application year (Figure 10).

Different tendencies are again observed before and after 2000. Originality of AIST's, Fraunhofer's and ITRI's inventions stayed a constant level until 2000. There is no big gap among them. However, after 2000, their inventions commonly increase originality after 2000. Fraunhofer's case shows sudden increase in the early 2000s and ITRI's case shows a constant increase every year. Even though the increase amount is smaller than Fraunhofer and ITRI, AIST's inventions also increase its originality every year. The primary reason is probably that technological fields in which AIST, Fraunhofer, and ITRI heavily file patent applications are in the ICT industry. Those technological fields occur active convergence between technologies (Gambardella & Torrisi, 1998). Technological convergence is one method in applied research which achieves innovation by applying conventional methods to new technologies.

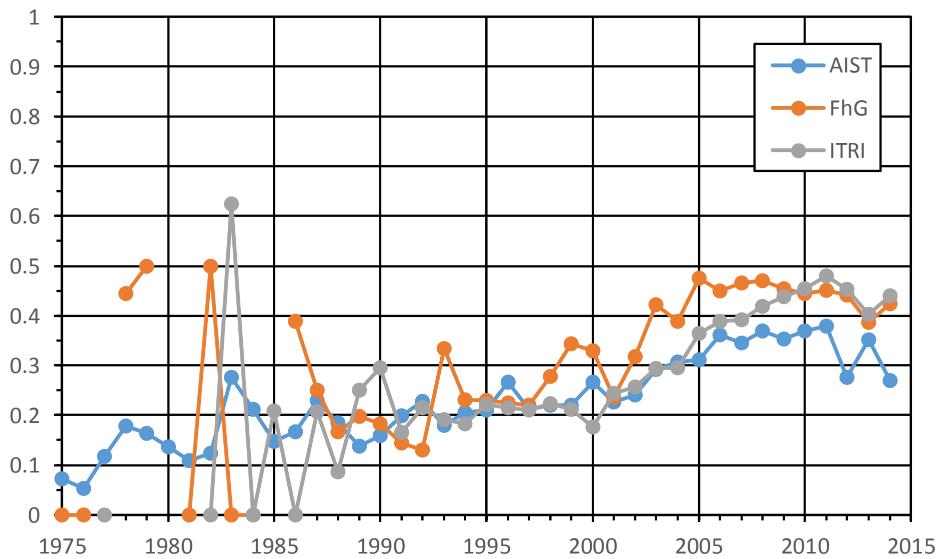


Figure 10. Originality of inventions by AIST, Fraunhofer, and ITRI

5. Discussion

Table 2 summarizes the findings in the previous section. Some findings are worth further discussion. We must note that generalization of our findings and discussion is difficult because the background of each country is different and public research institutes are heterogeneous in various important respects. Understanding this limitation, we discuss the findings that are relevant to the conceptual framework explained in Section 2.3.

Table 2 Summary of findings

Indicator	AIST	Fraunhofer	ITRI
Patent applications to USPTO	Consistent over time	Increasing after 1990	Rapidly increasing after 1990
No. of co-applicants	464	186	152
No. of co-applications	996	375	622
Characteristics of co-applications	Often collaborations with domestic firms	・Often collaborations with domestic firms ・Many collaborations with foreign institutes and universities	・Often collaborations with domestic firms ・Many collaborations with institutes and universities
Knowledge origin	・Shifted from US to domestic sources	・Shifted from Europe, especially Germany, to abroad	・Increasing reliance on domestic sources ・High reliance on US, Europe, and Japan
Knowledge accumulation	・High accumulation	・High accumulation	・Low accumulation, but increasing
Knowledge spillover	・Concentrated to domestic firms ・Recently, citations per application drops	・Total citations by domestic and foreign inventions increase ・Recently, citations per application drops	・Total citations by domestic and foreign inventions increase ・Recently, citations per application drops
Generality of inventions	Decreasing	Decreasing	Decreasing
Originality of inventions	Increasing	Increasing	Decreasing

5.1. Contribution to domestic and international firms through collaboration

As Figure 2 indicates, almost all of AIST's and ITRI's collaborators are domestic organizations, while Fraunhofer works equally with both domestic and foreign organizations. I attribute their choice of collaborator to the funding system of each institute. Since AIST and ITRI rely on national funds, their primary focus is on domestic needs, as expected by government organizations. Accordingly, it is natural for AIST and ITRI to work primarily with domestic organizations. On the other hand, Fraunhofer receives the largest proportion of its funding from the industry. Accordingly, it is natural for Fraunhofer to work with any organizations, irrespective of whether the collaborators are from Germany.

However, in the future, if government endowment declines further, AIST and ITRI will need to find not only domestic but also foreign partners. Working with foreign organizations is more difficult than working with domestic organizations due to the geographical distance, lack of shared knowledge about institutional conditions, lack of shared language and work culture, and weak personnel-level networks. Both AIST and ITRI need to prepare for working with foreign partners when seeking diverse external sources of revenue.

5.2. Knowledge accumulation and spillover

As Figure 4 indicates, knowledge accumulation in AIST is better than in Fraunhofer and ITRI. Due to the hiring conditions of those institutes, this result is to be expected. The conceptual framework in Section 2.3 identified researchers as a determinant for the success of public research institutes, and that their hiring conditions affect knowledge accumulation. Most researchers in AIST are tenured, while those in Fraunhofer and ITRI are fixed-term. Therefore, it is natural to expect knowledge accumulation to be better in AIST than in Fraunhofer and ITRI.

However, knowledge accumulation is not the only role of public research institutes. Knowledge transfer is also important. This can occur through the mobility of researchers, licensing technologies, and interacting with industries. Therefore, it is important find a balance between knowledge accumulation and knowledge transfer based on the mission and resources of public research institutes.

5.3. Research direction

One similarity among the three institutes is the characteristics of their patent outcomes. As seen in Figure 9, their R&D outcomes now have less generality than before. The figure indicates that AIST, Fraunhofer, and ITRI have also conducted notable basic research, but after 2000 their focus moved increasingly toward applied research. That implies that they placed emphasis on outcomes targeted to special technological purposes.

Emphasis on applied research should not result in the undermining of basic research. There is a concern that following a move toward a market-based mechanism, investment in basic research is decreasing (Nelson, 2004). This can be observed in many countries including Germany, Japan, and Taiwan, and is largely due to the decline in government investment in the scientific community stemming from financial pressure. However, scientific progress has long been considered to be a key contributor to a nation's prosperity (Bush, 1945). Scientific knowledge produced from basic research is the foundation of applied research, and is can be beneficial to the whole of society for a very long time. Since private organizations have little incentive to conduct basic research, they can only be supported by public research institutes. Accordingly, an environment in which to conduct basic research must be provided to public research institutes.

6. Conclusions

This study investigates how public research institutes contribute innovation in NIS using case-studies of AIST, Fraunhofer, and ITRI. Using patent data, this paper analyzed innovation processes of AIST, Fraunhofer, and ITRI. Some findings are unique to each institute; others are common to all of them. Based on the conceptual framework, the findings are discussed three points: 1) Contribution to domestic and international firms through collaboration, 2) knowledge accumulation and spillover, and 3) research direction. Policy implications are derived to better utilize public research institutes for NIS.

Before closing, we would like to indicate limitations of this study. First, this study uses only patent data to analyze the performance of public research institutes. Patent data have merits such as providing raw data regarding innovation process at a low cost. However, patent documents are only one type of research output that emanates from public research institutes. As mentioned in Section 2.3, how to assess the performance of public research institutes has been a concern among policy makers. Accordingly, proper indicators to undertake such an assessment must be studied in the future.

Second, of all patent data, this study uses only those filed to USPTO. The reason to do so is to make an international comparison without having home biases. The US is one of the most important markets for firms doing international business. In this sense, using patents to USPTO is a fair choice. On the other hand, as a tradeoff, patents to USPTO represent only a part of all the patent applications to all patent offices. If further detailed analysis is needed in terms of AIST, Fraunhofer, and ITRI, then focusing on their home patent offices may be pertinent.

Third, this study is limited to analysis at the applicant level. However, sometimes analyzing at the inventor level can provide further insights to understand innovation processes. For example, analyzing inventor networks will allow determination of "star inventors" who lead R&D projects, understand his/her involvement in innovation processes, mobility of personnel between organizations, etc. Those analyses, again, remain as a future research agenda.

Lastly, there is also a limitation to the use of citation data. It takes a great deal of time (up to 10 years) for a patent document to be cited by subsequent inventions. However, there is no way to overcome this issue, except to wait for another decade to pass until more citations are added. Reproducing the current study with more reliable data also remains on the future research agenda.

Acknowledgement

The author would like to thank two anonymous reviewers for their comments. All remaining errors are on my own.

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