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A strategic management approach for Korean public research institutes based on bibliometric investigation

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Abstract As a process of knowledge manufacture, research activities are interpretable from the well-known economic perspectives of production and consumption. We therefore aim to investigate the contents of institutes' research portfolio from a knowledge production and consumption perspective. A Hirsch-type-index and mean reference age serve as indicators of knowledge activity. Based on both indicators, we divide research institutes into four categories. This approach is applied to Government-funded Research Institutes (GRIs) in Korea that are dedicated to major disciplines within science and technology. We recognize GRIs' contribution to the development in the characteristic areas. A tailored enhancement strategy is discussed for promising GRIs to improve their knowledge activity. Our results have implications for GRIs' research portfolio management. In terms of R&D portfolio constitution, we reveal that Korean GRIs' research themes concentrate on the strategic research such as chemistry, information and communications technology, and semiconductors. We also point out the possible fragility of the national R&D system, as national leading technologies are reliant on a few giant institutes.

Keywords Research portfolio · Public research institutes · Knowledge production · Knowledge consumption

1 Introduction

Research is a kind of "process of knowledge manufacture", so research activities can be inferred from the well-known economic concepts of production and consumption. Vinkler

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(1987) regarded a citation as one of the products of scientific research and called scientists as "users" of scientific publications. This market metaphor helped to interpret citations as a currency trade—import and export—in previous studies (Stigler 1994; Zhang et al. 2013). Those approaches are attributable to research activities that comprise knowledge production and consumption. To be more specific, knowledge production is the ability to make new discoveries and contribute to scientific advancement. Knowledge consumption relates to the ability to assimilate and adopt new inventions.

In order to estimate research activities at institutional level, effective indicators need to be considered. We deem that knowledge production corresponds to academic performance and that responsiveness to new knowledge substitutes for knowledge consumption. As a result, "*h*-index", introduced by Hirsch (2005), provided an indexical basis for the quality of produced knowledge, while "thought leadership" (Klavans and Boyack 2008) was employed for knowledge consumption in this study. The *h*-index characterizes the combination of productivity and impact (Arencibia-Jorge and Rousseau 2009) and robustness to extremely high citations (Vanclay 2007). The thought leadership designates the average reference age that reveals the freshness level of a knowledge base as evidence for trend following research.

This study aims to discern the state of institutional research activities based on a set of indices for knowledge production and consumption that divides institutes into four Categories. We applied this work to Government-funded Research Institutes (GRIs) in Korea. According to the law in force, the term "GRI" refers to "any government-funded institute whose primary purpose is science and technology research" (MSIP 2013). Since this study tries to investigate research activities on the institutional perspective, the *h*-index and the thought leadership are one of appropriate sets to depict quality of knowledge production and consumption.

In the 1960s and 1970s, to remain in the 'catch up' race with Western countries, the Korean government fostered GRIs in an attempt to pursue developmental strategies (Arnold 1988; Kim 1995, 1992; Cho and Kim 2012; Cho et al. 2007). After the foundation of the nation's first GRI in 1966, the Korea Institute of Science and Technology (KIST), GRIs expanded throughout the 1970s and 1980s. When universities and industries were vulnerable to Research and Development (R&D) in the 1970s, GRIs actually guided scientific improvements (Lee 2002). At that time, GRIs' research covered a wide spectrum in such industrial fields as machinery, metal, electronics, nuclear energy, resources, chemicals, shipbuilding, and marine science.

As Korea enters the post catch up era, an effective system of GRIs has become increasingly essential due to their importance to the economic growth of Korea (Mazzoleni and Nelson 2005; Kim 1995; Seong and Ko 2013; Lee et al. 2012). Korean GRIs are liable for the provision of critical national technologies and GRIs' research takes up a practical problem or public issue tests that are hardly handled by universities and industries now. As of 2011, GRIs accounted for about 40 % of the total government R&D investment.

As recent advances in understanding of the national innovation systems (Lundvall 2007; Sharif 2006) and the "Triple Helix" model of university-industry-government relationships (Leydesdorff 2003; Leydesdorff et al. 2013; Park 2013; Chung and Park 2013), GRI is considered one of the major domains in the system. Those models deal with the knowledge dynamics from the scientific knowledge to the knowledge-based innovation (Lei et al. 2011; Phillips 2014; Gautam et al. 2014). GRIs interact with other actors in the Triple Helix model through research funding, science and technology policy, and collaboration. Korean knowledge dynamics have been also discussed on the Triple Helix perspectives (Park et al. 2005; Park and Leydesdorff 2010; Ye et al. 2013; Kim et al. 2011), and that still require academic attention at variety of levels, from regional scientific excellence (Shapiro and Park 2011; Shapiro 2011) to country wise development (Chung 2013).

This study would determine GRIs which deserve credit for keeping superior research base in terms of quality of outputs and state of the arts in intellectual sources. Even research councils annually conduct a GRI evaluation in Korea, the subject of appraisal inclines to GRIs' management. Otherwise, the collective performance of GRIs is included in the national assessment of academic progress. However, since every GRI carries out mission-oriented research, it needs to measure the contribution in each discipline (or field). Thus to focus on the contents of national strategic research, we take a portfolio approach based on GRIs' scientific publications (Boyack et al. 2014). This study would reveal sterling institutes on research themes where the GRIs have excelled and would enable to inform policymakers about GRIs' research portfolio management and tailored enhancement strategies for promising units.

This paper opens by discussing its motivations and purpose. The remainder of the paper proceeds as follows. Section 2 explains the methods for measurement of institutional research performance and the four Categories created according to knowledge production and consumption. Section 3 describes data collection and processing including discipline categorization. Sections 4 and 5 measure and discuss GRIs' knowledge activity, while Sect. 6 summarizes and concludes.

2 Method

2.1 Institutional research performance: successive h-index

The h-index has received a great deal of attention with the possibility of measuring achievement of from researchers in the whole life span or in a defined period to complete research groups, institutions and groups of authors (Egghe and Rao 2008; Molinari and Molinari 2008b, a). Specifically owing to the simplicity of its calculation and the balances of 'quantity' and 'quality', scholars have evaluated the group of authors via the h-index (Raan 2006; Luz et al. 2008). Conforming to academic interest, Prathap (2006) and Schubert (2007) proposed a successive series of h-indices to evaluate scientific outputs of research groups. The successive h-indices can be applied to universities, research institutes, or other higher levels of aggregation. Several studies rested on the successive h-index (Arencibia-Jorge and Rousseau 2009; Rousseau et al. 2010; Egghe 2008). The successive principle was implemented with other alternatives to h-index (Arencibia-Jorge et al. 2008; Tol 2008), such as g-index (Egghe 2006b, a), A-index (Rousseau 2006; Jin 2006). Other types of indices were also introduced ground on the hierarchical structure (Rousseau et al. 2010; Egghe and Rao 2008; Ruane and Tol 2008).

We embrace the coherent frame for the multi-level assessments of the successive h-index to gauge GRIs' research portfolio. To be more specific, an h_1-index refers to the h-index of every papers within a sub-discipline, and an index h_2 is determined at a discipline level by applying the h-index to decreasing order of h_1: the discipline has an index h_2 if h_2 of its N sub-disciplines have an h_1-index of at least h_2 each, and the other $(N - h_2)$ sub-disciplines have h_1-indices lower than h_2 each. We repeat this calculation for the h-index at the institutional research portfolio level, h_3 . Egghe (2008) reported that the h-indices are generally decreasing as the level increasing. Thus this portfolio based approach is suitable for performance comparison between institutes with distinctive organizational structures.

Scholars note that citation practices have very different characteristics across disciplines (Braun et al. 1995a, b; Hargens 2000; Podlubny 2005; Albarrán et al. 2011). It is also known that publication practices are influenced by research fields (Vinkler 1986). Hirsch (2005) even indicated that the h-index cannot be directly applied to compare researchers from different areas. For this reason, bibliometric comparison between research groups should be made only within a discipline (Bornmann et al. 2008) or it should be accompanied by standardization across the disciplines (Alonso et al. 2009; Goodall 2009; Piro et al. 2013). Therefore, several normalization methods for the h-index were introduced (Eck and Waltman 2008; Iglesias and Pecharroman 2007; Batista et al. 2006; Molinari and Molinari 2008b, a; Harzing et al. 2013).

We employ the h_α-index (Eck and Waltman 2008) to correct both differences in publication and citation practices at sub-discipline level. Thus, the index h_1 denotes the normalized h-index derived from the parameter α_k for each sub-discipline k. The sub-disciplinary parameter α_k is determined by the ratio of height to width of the largest rectangle on the decreasing citations for numbered papers, $\alpha_k \in (0, \infty)$. Accordingly, the h_1-indices can show in non-integer values.

2.2 Research activities: knowledge production and consumption

Science may be a different kind of market in which quality drives expansion rather than quantity. Scientists and research institutes produce scientific works, that is, articles or patents. Science autonomously evaluates those works. The achievements are then diffused as citations and the achievers gain academic reputations. This activity forms a part of science in which science systems replicate knowledge exchange, including knowledge production and consumption. Here we employ the h-index and mean reference ages in order to represent the quality of knowledge production and consumption at a discipline level.

We regard the index h_2 of the successive h-index to be disciplinary research performance of each institute. Not just produced knowledge, quality of knowledge consumption also deserve to be considered. There are several possible measures to quantify the knowledge consumption: a number of highly qualified specialists, information quality obtained by diverse partners, relevance to the research theme, or journal prestige that institutes have interested in their references. We choose the freshness of a knowledge base since it is more appropriate to a national context. Recently, there is growing concern that GRIs' research lags behind trends in scholarly publishing since researchers cannot devote to research due to excessive paperwork and an increase of external activities to receive project (Chun et al. 2009). Hence, the mean reference age gauges potential new discoveries because keeping knowledge up-to-date is crucial for scientific breakthroughs. Klavans and Boyack (2008) coined an indicator of this consideration called "thought leadership".

GRIs were placed into following four Categories on the basis of averages:

Category A: High Performance/Fresh Knowledge
Category B: High Performance/Obsolete Knowledge
Category C: Low Performance/Fresh Knowledge
Category D: Low Performance/Obsolete Knowledge

Category A: High Performance/Fresh Knowledge These are the institutes that produce more intellectually influential results than others. They contribute to academic advancement in corresponding areas and deal with recent research trends. The units that belong to this Category are Korean leading research players.

Category B: High Performance/Obsolete Knowledge These are the institutes that hold relatively high academic awareness. However, they utilize knowledge that is far from up-to-date. Although the difference in reference practice for each sub-discipline may be effective, the institutes that belong to this Category are at risk for being one step behind in the world of intellectual advancement.

Category C: Low Performance/Fresh Knowledge These are the institutes that lack the capability to lead research in their relevant discipline yet, they react in a scholarly way to new issues. The policy implication here is that academic leadership can be further enhanced by active support for the accumulation of experience as maintaining the status of their knowledge base.

Category D: Low Performance/Obsolete Knowledge These are the institutes that insufficiently contribute to academic advancement in their corresponding discipline and lack receptivity to intellectual change. The institutes that belong to this Category include unspecialized as well as newly established organizations that suffer from a deficiency of research capability.

3 Data collection and disciplinary classification

We collected bibliographies of GRIs from the Thomson Reuters (formerly ISI) Web of Knowledge. The full names and abbreviations of 27 GRIs were compared with authors' institutional affiliations. The target country was confined to South Korea. We restrict the window size to five years (2008–2012) to reflect current research performance (Price 1970). The World Institute of Kimchi (WiKim) and the National Security Research Institute (NSRI) were excluded from analysis due to a lack of records. In addition, the research area was extracted from the mission, vision, and objectives found on the GRIs' official homepages in English. For the sake of convenience, institutes were designated with abbreviations. To guarantee research continuity, only GRIs that published more than five papers in each discipline were included. Note that the number of publications and citations are not adjusted to the journal quality, amount of pages, or co-authorship. The h-index and the mean reference age are calculated with self-citations here. This study is conducted under the R ver. 3.0.1 environment (R Core Team 2013) and utilized add-on packages for convenience: ggplot2 (Wickham 2009) and treemap (Tennekes 2014).

Descriptive statistics of publications and citations earmarked for each institute are shown in Table 1 in alphabetical order. The search results contained approximately 28,000 documents. The government mostly assigns GRIs' research areas thus, the number of publications is a relevant way to reflect national priorities and scientific objectives (Choung and Hwang 2012). Citations have been a proxy for intellectual output in innumerable researches (Bernstein and Gray 2012; Charlton and Andras 2007; Goodall 2009; Halevi and Moed 2013; Lin et al. 2013). The number of citations measures intellectual contributions and scholarly awareness (Zhang et al. 2013; Bernstein and Gray 2012). The mean is greater than the median, which suggests the shape of distribution of citations is skewed to right.

Identifying the research portfolio (Piro et al. 2013; Shin 2008; Ball et al. 2009) requires information on the structures of science (Klavans and Boyack 2009; Porter and Youtie 2009; Cobo et al. 2011). The UCSD map of science was utilized as a category system at the journal level (Borner et al. 2012). The original UCSD map was created by SciTech Strategies in response to a request by the University of California San Diego (UCSD) in 2007. The updated map, made in 2010, ultimately included 25,258 journals by adding Scopus (2006–2008) and WoS (2005–2010) data. We employed the UCSD map of science for several seasons: it distinguishes not only journal titles indexed in major database—Web of Knowledge and Scopus—but keywords in patents; it is easy to identify disciplinary realm in coordinates and relations between fields since even multi-disciplinary journals have a fraction in figures to each sub-discipline; and it can capture the change of science through updates. The UCSD

Table 1 Government-funded science and technology Research Institutes (GRIs) in Korea

Full name	Abbreviation	Research area	Documents				Citations			
			Sum	Mean year	Mean disciplinary doc.	Variance of disciplinary doc.	Sum	Mean	Variance	Median
Electronics and Telecommunications Research Institute	ETRI	Information telecommunications	2,271	2010.04	205.18	158875.76	10,220	4.33	82.47	2
Korea Atomic Energy Research Institute	KAERI	Nuclear energy	2,982	2009.97	245.75	137575.30	9,964	3.31	55.55	1
Korea Aerospace Research Institute	KARI	Aerospace technology	386	2010.25	34.91	3617.29	843	2.19	15.75	1
Korea Astronomy and Space Science Institute	KASI	Astronomy	543	2010.22	89.67	41235.87	3,733	6.54	126.19	3
Korea Basic Science Institute	KBSI	Analytical science	1,625	2010.34	131.17	27897.79	10,485	6.26	121.57	3
Korea Electrotechnology Research Institute	KERI	Electrical technology	718	2010.04	71.20	11422.62	3,657	4.70	115.19	1

Table 1 continued

Full name	Abbreviation	Research area	Documents				Citations			
			Sum	Mean year	Mean disciplinary doc.	Variance of disciplinary doc.	Sum	Mean	Variance	Median
Korea Food Research Institute	KFRI	Longevity science, functional foods, safe distribution and food processing technology	627	2010.16	53.00	7072.55	3,394	5.44	104.01	2
Korea Institute of Construction Technology	KICT	Construction technology	319	2010.27	34.22	5208.69	871	2.71	26.75	1
Korea Institute of Energy Research	KIER	Energy technology	1,006	2010.43	82.00	26005.27	7,208	7.10	154.56	3
Korea Institute of Geoscience and Mineral Resources	KIGAM	Geoscience and Mineral Resources	920	2010.14	74.08	18870.63	4,070	4.17	45.90	2
Korea & Materials Institute of Machinery	KIMM	Machinery technology	865	2010.03	71.00	14842.36	4,207	4.82	51.15	2
Korea Institute of Material Science	KIMS	Materials technology	1,136	2010.32	94.58	32425.17	5,607	4.91	79.24	2

Table 1 continued

Full name	Abbreviation	Research area	Documents				Citations			
			Sum	Mean year	Mean disciplinary doc.	Variance of disciplinary doc.	Sum	Mean	Variance	Median
Korea Institute of Oriental Medicine	KIOM	Traditional medicine	650	2010.46	54.17	5271.79	2,508	3.86	32.59	2
Korea Institute of Ocean Science and Technology	KIOST	Oceanography	49	2012.00	4.60	12.71	26	0.52	1.32	0
Korea Institute of Science and Technology	KIST	Multi-disciplinary research	4,840	2010.24	392.92	267632.08	36,069	7.27	185.07	3
Korea Institute of Science and Technology Information	KISTI	Information science	541	2010.51	48.82	11120.36	5,837	10.83	405.57	4
Korea Institute of Toxicology	KIT	Clinical contract research	167	2010.09	14.82	203.96	751	4.31	63.46	2
Korea Institute of Industrial Technology	KITECH	Technologies with commercialization potential to support SMEs	945	2010.15	78.33	21184.79	3,403	3.57	37.80	1
Korea Polar Research Institute	KOPRI	Polar research	427	2010.22	44.00	2377.25	1,911	3.99	39.28	2

Table 1 continued

Full name	Abbreviation	Research area	Documents				Citations			
			Sum	Mean year	Mean disciplinary doc.	Variance of disciplinary doc.	Sum	Mean	Variance	Median
Korea Research Institute of Bioscience and Biotechnology	KRIBB	Bioscience and biotechnology	2,659	2010.12	254.40	65301.38	18,657	6.46	143.70	3
Korea Research Institute of Chemical Technology	KRICT	Chemical technology	1,759	2010.03	157.64	97690.05	14,762	7.92	387.29	4
Korea Research Institute of Standards and Science	KRISS	Measurement standards and metrology	1,328	2010.12	108.33	23405.33	7,106	5.30	170.87	2
Korea Railroad Research Institute	KRRI	Railway technology	88	2009.94	14.67	357.87	305	3.47	30.55	1
National Fusion Research Institute	NFRI	Fusion energy	498	2010.38	62.25	22300.21	1,720	3.45	37.32	1

Table 1 continued

Full name	Abbreviation	Research area	Documents				Citations			
			Sum	Mean year	Mean disciplinary doc.	Variance of disciplinary doc.	Sum	Mean	Variance	Median
National Institute for Mathematical Sciences	NIMS	Mathematical science	409	2010.16	33.17	2859.61	2,680	5.76	839.17	2
National Security Research Institute	NSRI	Information protection technology	-	-	-	-	-	-	-	-
World institute of Kimchi	WiKim	Overall R&D related to kimchi	-	-	-	-	-	-	-	-
Total			27,758				159,994			

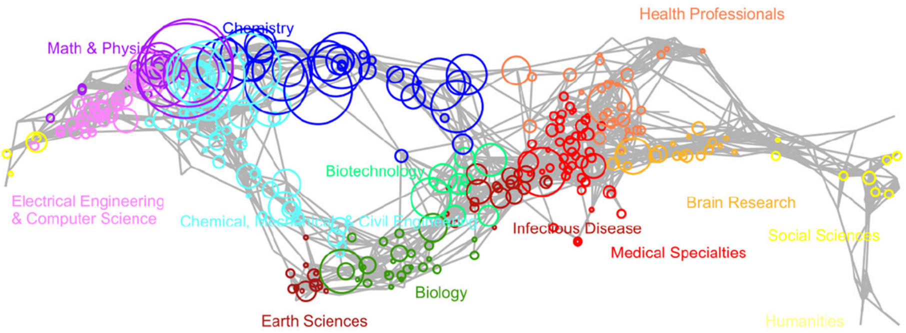

Fig. 1 Thematic categorization of the Korea Institute of Science and Technology (KIST)

map categorizes documents into 554 sub-disciplines belonging to 13 disciplines on the basis of journal titles. Figure 1 shows an example of disciplinary mapping for KIST on Sci2, one of the mapping toolsets for bibliometric study (Sci2 Team 2009).

4 Research activities of Korean GRIs

This section investigates the research activity of the GRIs. First, we identify the GRIs' overall major research areas in order to discern characteristic disciplines. GRI's research performance is measured on their research portfolio through the successive *h*-index. Finally, GRIs' research activity is mapped into four Categories based on knowledge production and consumption at the discipline level.

4.1 Main research areas

GRIs' research spans a number of different disciplines. We estimated (i) disciplinary publications and citations on the overall GRI level, (ii) the composition of the sub-disciplinary publications of each GRI, and (iii) the relative comparison between sub-disciplinary publications and the map of science, to identify major scientific areas. We found 42 sub-disciplines (lower level) belonging to nine main disciplines (upper level) that could be distinguished as GRIs' characteristic research.

Figure 2 shows the share of publications in 13 disciplines, in descending order. The red dotted line averages the fraction of publications (0.077). Disciplines corresponding to Chemistry; Chemical, Mechanical, and Civil Engineering; Math and Physic; and Electrical Engineering and Computer Science are fruitful than the average fraction.

Gini coefficients (Atkinson 1970; Gini 1912) and Lorenz curves (Lorenz 1905) can capture the degree of concentration in scientometric study (Stigler 1994; Buela-Casal et al. 2006; Bornmann et al. 2008; Guan and Ma 2007). Figure 3 depicts Lorenz curves for the cumulative percentage of documents in the x-axis against the cumulative percentage of citations along the y-axis for each disciplines. If all documents get the same number of citations, the perfect equality line, which is the straight diagonal line, would correspond to the Lorenz curve. The Lorenz curve can be summarized by the Gini coefficient that refers to the area between the perfect equality line and the observed Lorenz curve. The Gini coefficient is possible the range of values from 0 = perfect equality to 1 = complete inequality. The citations in Infection Diseases (Gini coefficient = 0.749) are most concentrated around a small number of documents,

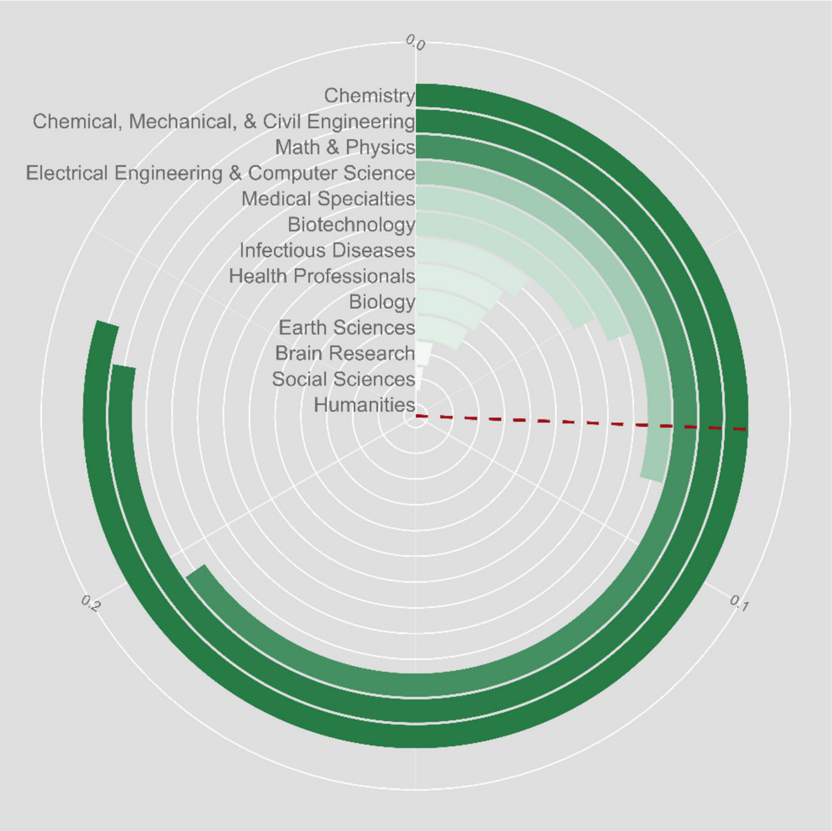

Fig. 2 Proportion of total publications by disciplines

whereas relatively most documents are equally cited in Biotechnology (Gini coefficient = 0.618) than others. The difference in the concentration may be affected by disciplinary practices or a small number of 'big hits' (Raan 2006). The different Gini coefficients indicate that the number of citations need to be normalized in each field.

The treemap in Fig. 4 shows institutional research portfolios at the sub-discipline level. A set of nested rectangles indicates top-ten sub-disciplines according to publications for individual GRIs. Each tile's rectangle has an area proportional to the publication ratio and the color represents the ranking. Mutually interesting areas also are distinguishable based on co-occurrences. Surface Science, which occurred 13 times within Math and Physics, is the most prevalent subject among GRIs' research. Ceramics, Material Science -part of Chemical, Mechanical, and Civil Engineering-, Nanotechnology- subordinate to Chemistry-, and Semiconducting Materials-within Math and Physics- are the second most appearances in 11 times.

We examined the relative significances of the fraction of national publications and the node size of the UCSD map at the sub-discipline levels. The size of the map's nodes is proportional to the average number of papers per year. By comparing the proportions of the publications and the node size, this test determined whether GRIs' R&D was committed to further efforts than international attention to each sub-discipline (Harzing and Giroud 2014).

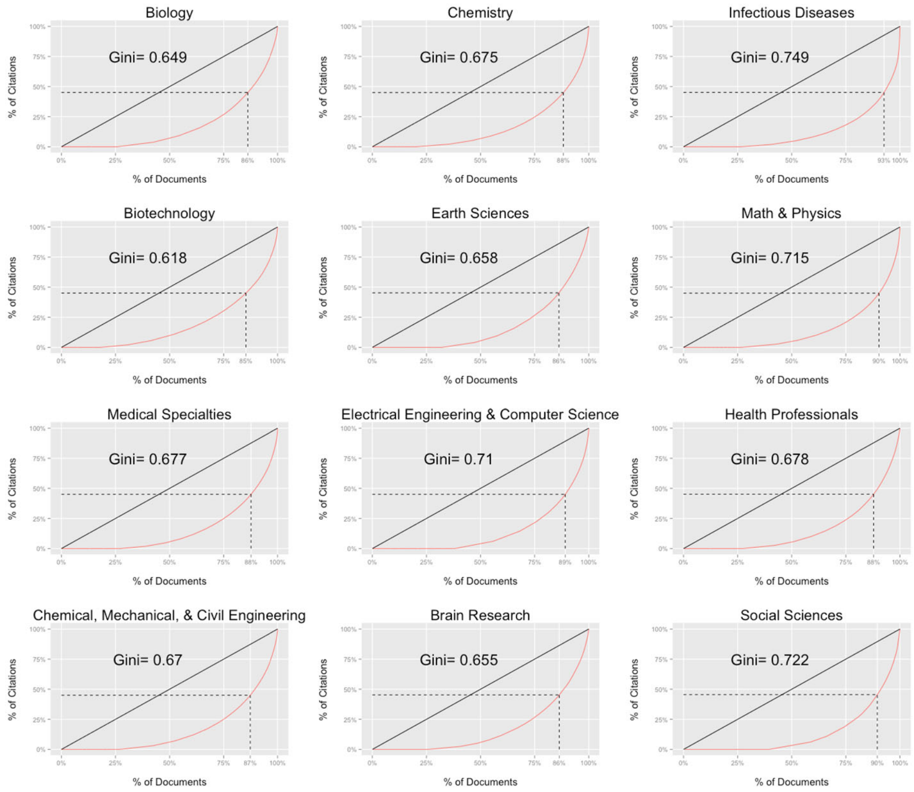

Fig. 3 Gini coefficients and Lorentz curves for each discipline

The one-tailed z-test was adopted to statistically compare the two proportions (Leydesdorff and Bornmann 2012; Bornmann et al. 2012). Hypotheses constitute a one-tailed test at the 5 and 1 % significance levels (p value < 0.05 and p value < 0.01, respectively). Consequentially, the GRIs' focus areas were ferreted out by this investigation.

The results in Table 2 show the fourty-two sub-disciplines of the publications that are greater than the node sizes of the UCSD map, with a proportion statistical significance of 5 %. Thirty-four sub-disciplines are significant at the 1 % level. The majority of sub-disciplines appear within the field of Chemistry; and Chemical, Mechanical, and Civil Engineering. Math and Physics comes next, followed by Biotechnology; and Electrical Engineering and Computer Science with three sub-disciplines each.

4.2 Measuring GRI's research performance

Tables 3 and 4 contain GRIs' sub-discipline ranking according to the h_1-index. The highest number of citations ($\max_c$) was used to handle the sub-disciplines with the same h_1 value. Interestingly, top five sub-disciplines are related to superconductors and semiconductors, which are the materials that allow for the flow of electricity through it to be controlled. Electrochemistry and Material Sciences comprise the great part of Chemical, Mechanical, and Civil Engineering. Chemistry, the most productive discipline, places only one subordinate—Pharmaceutical Design—in the list. All sub-disciplines related to Electrical Engineering

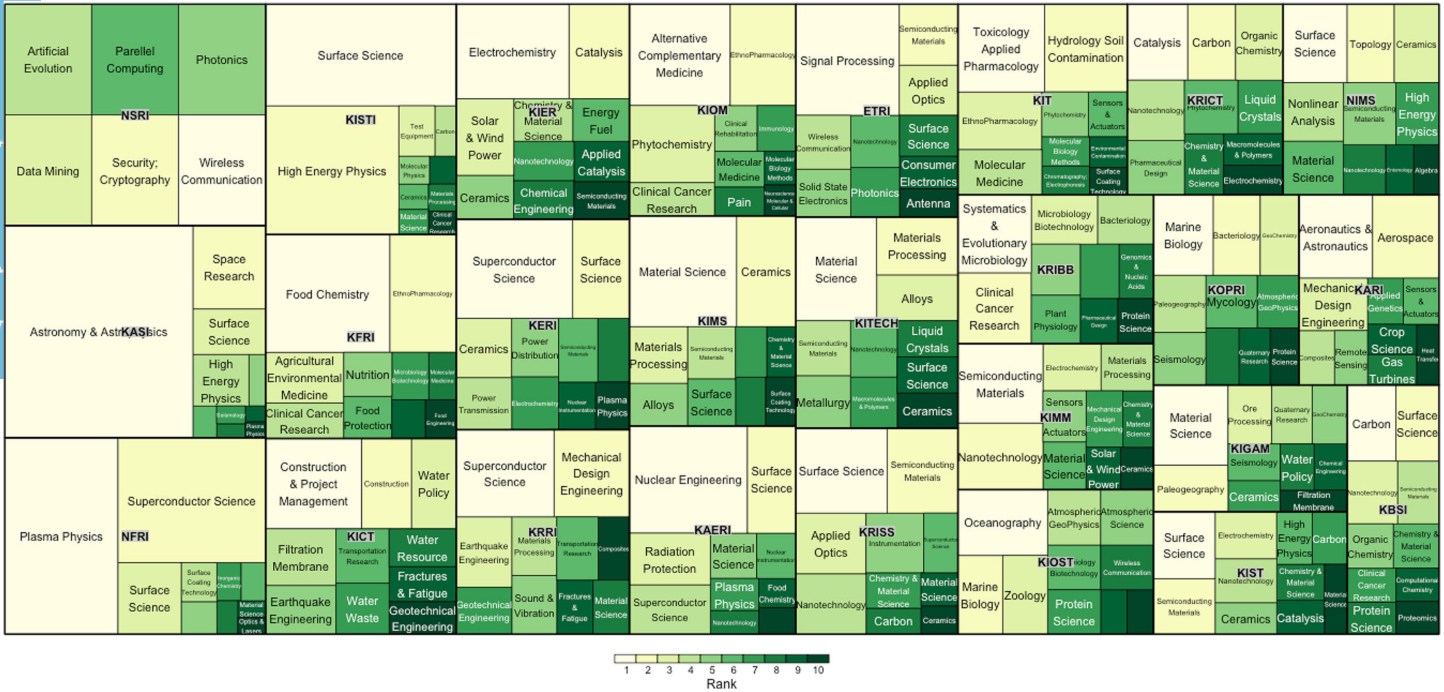

Fig. 4 Publication importance of sub-disciplines for each GRI

Table 2 Fourty-two concentrated research areas of twenty-five Korean Government-funded Research Institutes in science and technology (GRIs) from the one-tailed test for the proportion of sub-disciplinary publications at 0.05 significance level

Discipline	Sub-discipline	Publications[†]	*z* statistic	95 % Confidence interval
Biology	Plant Physiology	192.36 (0.69)	3.0292	(0.003, 0.0069)
BioTechnology	Enzyme Microbiological Techniques *	177 (0.64)	5.4969	(0.0014, 0.0064)
	Microbiology Biotechnology *	294.12 (1.06)	11.8893	(0.0015, 0.0106)
	Systematics & Evolutionary Microbiology *	321 (1.16)	12.196	(0.0019, 0.0116)
Medical Specialties	Clinical Cancer Research *	503.14 (1.81)	6.7388	(0.0091, 0.0181)
	Radiation Protection *	272.28 (0.98)	10.5481	(0.0015, 0.0098)
Chemical, Mechanical, & Civil Engineering	Material Science *	845.12 (3.04)	37.072	(0.0041, 0.0304)
	Nuclear Engineering *	679 (2.45)	32.7523	(0.0022, 0.0245)
	Ceramics *	644 (2.32)	24.9132	(0.0041, 0.0232)
	Alloys *	289 (1.04)	7.0076	(0.0034, 0.0104)
	Mechanical Design Engineering	154 (0.55)	3.1941	(0.0019, 0.0055)
	Filtration Membrane *	183 (0.66)	5.8104	(0.0014, 0.0066)
	Electrochemistry *	813 (2.93)	39.8788	(0.0025,0.0293)
	Hydrology Soil Contamination	99 (0.36)	2.7515	(0.0008, 0.0036)
	Materials Processing *	308 (1.11)	12.5384	(0.0015, 0.0111)
	Solar & Wind Power	240 (0.86)	3.5297	(0.004, 0.0086)
	Sensors & Actuators *	243 (0.88)	5.4318	(0.003, 0.0088)
Chemistry	Food Chemistry *	352 (1.27)	11.5367	(0.0029, 0.0127)
	Pharmaceutical Design *	321.36 (1.16)	10.0218	(0.0028, 0.0116)
	Phytochemistry *	388 (1.4)	15.0006	(0.0023, 0.014)
	Nanotechnology *	969.28 (3.49)	49.9419	(0.0023, 0.0349)
	Catalysis *	515 (1.85)	21.0267	(0.0028, 0.0185)
	EthnoPharmacology *	395 (1.42)	17.4445	(0.0016, 0.0142)
	Applied Catalysis *	233 (0.84)	9.6411	(0.001, 0.0084)
	Chemistry & Material Science *	566.28 (2.04)	26.1401	(0.0021, 0.0204)
	Surfactants	170.12 (0.61)	4.0771	(0.0019, 0.0061)
	Liquid Crystals *	324 (1.17)	9.9446	(0.0029, 0.0117)
	Carbon *	586 (2.11)	26.0830	(0.0025, 0.0211)
	Applied Optics *	351.28 (1.27)	6.4308	(0.0052, 0.0127)
	Solid State Electronics *	305 (1.1)	10.8801	(0.0021, 0.011)

Table 2 continued

Discipline	Sub-discipline	Publications†	z statistic	95 % Confidence interval
Electrical Engineering & Computer Science	Signal Processing *	480 (1.73)	9.9529	(0.0067, 0.0173)
	Biomaterials *	234 (0.84)	6.7262	(0.0022, 0.0084)
Infectious Diseases	Bacteriology	210 (0.76)	3.7262	(0.0031, 0.0076)
Health Professionals	Alternative Complementary Medicine	135(0.49)	3.7664	(0.0012, 0.0049)
Math & Physics	Surface Science *	1502.86 (5.41)	58.9868	(0.0104, 0.0541)
	Semiconducting Materials *	1038 (3.74)	32.4038	(0.0101, 0.0374)
	Astronomy & Astrophysics *	397.28 (1.43)	9.2995	(0.0049, 0.0143)
	High Energy Physics *	381.28 (1.37)	8.9672	(0.0047, 0.0137)
	Photonics	170 (0.61)	3.7169	(0.002, 0.0061)
	Plasma Physics *	353 (1.27)	12.1964	(0.0026, 0.0127)
	Surface Coating Technology *	292 (1.05)	9.3015	(0.0024, 0.0105)
	Superconductor Science *	722 (2.6)	30.4739	(0.0038, 0.026)

† Values are extracted from the number of documents (%)
* Statistical significance at 1 % (p value <0.01)

and Computer Science are conducted by the Electronics and Telecommunications Research Institute (ETRI). Half of GRIs putting their names on Table 3 can be distinguished,

Table 5 exhibits the GRIs' discipline ranking, according to h_2. In order to resolve ties, the highest value of h_1 ($\max_{h1}$) was utilized. Most top 20 disciplines, except the twelfth place, are from Chemistry; and Chemical, Mechanical, and Civil Engineering. This h_2-index classifies the institutional research activity as a performance criterion in Sect. 4.3. Table 6 describes the ranking of GRIs' research performance from the overall portfolio level. KIST and the Korea Basic Science Institute (KBSI), the representative multi-disciplinary institutes, hold the top two spots in rankings for the overall research performance. In addition, h_4, which is the h-index of GRIs' h-indices has 5.

4.3 Mapping GRIs' research activities

Figure 5 shows the four Categories according to GRIs' research activities in each discipline. The index h_2 and the average reference age are plotted along the y-axis and the x-axis, individually. The red dotted lines on the graphs that divide the four Categories denote the averages of h_2-indices and reference ages. The area in the upper right graph falls within the ambit of Category A: High Performance/Fresh Knowledge. This is followed clockwise by Category C: Low Performance/Fresh Knowledge, Category D: Low Performance/Obsolete Knowledge, and Category B: High Performance/Obsolete Knowledge.

Chemistry was found to be most recognized for academic excellence in terms of averages on the h_2-indices with 9.4 and the biggest capability gaps between GRIs. Electrical Engineering and Computer Science have a youngest knowledge bases with 2001.89. KIST, which is a typical multi-disciplinary research institutes as well as the most experienced, appears most frequently as a high achiever in Category A. A large number of institutes participate in Chemical, Mechanical, and Civil Engineering. Medical Specialties; Brain Research; and

Table 3 Top 20 sub-disciplines of the h_1-index list during the period 2008-2012

Rank	Sub-discipline	Discipline	GRI	h_1-index	max_C
1	Superconductor Science	Math & Physics	**KAERI**	1236.67	30
2	Superconductor Science	Math & Physics	**KERI**	795.00	20
3	Superconductor Science	Math & Physics	**NFRI**	706.67	30
4	Semiconducting Materials	Math & Physics	**ETRI**	649.11	82
5	Semiconducting Materials	Math & Physics	**KIST**	564.44	84
6	Signal Processing	Electrical Engineering & Computer Science	**ETRI**	531.67	30
7	Superconductor Science	Math & Physics	**KBSI**	530.00	20
7	Electrochemistry	Chemical, Mechanical, & Civil Engineering	**KIST**	517.22	76
9	Electrochemistry	Chemical, Mechanical, & Civil Engineering	**KIER**	517.22	73
10	Nuclear Engineering	Chemical, Mechanical, & Civil Engineering	**KAERI**	513.33	18
11	Material Science	Chemical, Mechanical, & Civil Engineering	**KIST**	512.50	63
12	Material Science	Chemical, Mechanical, & Civil Engineering	**KIMS**	512.50	49
13	Astronomy & Astrophysics	Math & Physics	**KASI**	460.00	120
14	Superconductor Science	Math & Physics	**KIMS**	441.67	11
15	Ceramics	Chemical, Mechanical, & Civil Engineering	**KIST**	429.00	93
16	Material Science	Chemical, Mechanical, & Civil Engineering	**KITECH**	375.83	43
17	Semiconducting Materials	Math & Physics	**KRISS**	366.89	68
18	Semiconducting Materials	Math & Physics	**KBSI**	366.89	40
19	Pharmaceutical Design	Chemistry	**KIST**	360.00	30
20	Solid State Electronics	Electrical Engineering & ComputerScience	**ETRI**	353.33	36

Social Sciences have a low participate rate in research activities. The Category A in Earth Sciences even remains unoccupied.

5 Discussions

This study investigates the GRIs' academic achievement in each field grounded on their scientific outputs (articles and conference proceedings). Even fundamental sciences cannot directly reflect industrial needs, it is well recognized that academic research proffers engines of economic growth in a roundabout way (Narin et al. 1997; Merrifield 1989). Previous studies found a linear or exponential correlation between the econometric (GDP or GDP per capita) and scientific publications (Moya-Anegón and Herrero-Solana 1999; Schubert and Braun 1992; King 2004; Jaffe 2005). Since scientific knowledge is prone to transfer to technological innovation (Narin et al. 1997; Sorenson and Fleming 2004), Vinkler (2007) emphasized the importance of fundamental research to countries with high GDP for further development. Moreover, Jaffe et al. (2013) used academic productivity to make predictions

Table 4 Top 3 sub-disciplines for each Government-funded science and technology Research Institute (GRI)

GRI	Sub-discipline	Discipline	h_1-index
ETRI	Semiconducting Materials	Math & Physics	649.11
	Signal Processing	Electrical Engineering & Computer Science	531.67
	Solid State Electronics	Electrical Engineering & Computer Science	353.33
KAERI	Superconductor Science	Math & Physics	1236.67
	Nuclear Engineering	Chemical, Mechanical, & Civil Engineering	513.33
	Radiation Protection	Medical Specialties	315.00
KARI	Superconductor Science	Math & Physics	88.33
	Material Science	Chemical, Mechanical, & Civil Engineering	68.33
	Materials Processing	Chemical, Mechanical, & Civil Engineering	67.33
KASI	Astronomy & Astrophysics	Math & Physics	460.00
	High Energy Physics	Math & Physics	106.56
	Signal Processing	Electrical Engineering & Computer Science	48.33
KBSI	Superconductor Science	Math & Physics	530.00
	Semiconducting Materials	Math & Physics	366.89
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	217.78
KERI	Superconductor Science	Math & Physics	795.00
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	299.44
	Semiconducting Materials	Math & Physics	169.33
KFRI	Food Chemistry	Chemistry	242.40
	EthnoPharmacology	Chemistry	204.00
	Microbiology Biotechnology	Biotechnology	172.50
KICT	Nuclear Engineering	Chemical, Mechanical, & Civil Engineering	51.33
	Solar & Wind Power	Chemical, Mechanical, & Civil Engineering	50.29
	Filtration Membrane	Chemical, Mechanical, & Civil Engineering	44.33
KIER	Electrochemistry	Chemical, Mechanical, & Civil Engineering	517.22
	Semiconducting Materials	Math & Physics	254.00
	Catalysis	Chemistry	223.89
KIGAM	Material Science	Chemical, Mechanical, & Civil Engineering	239.17
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	190.56
	Ceramics	Chemical, Mechanical, & Civil Engineering	132.00
KIMM	Superconductor Science	Math & Physics	353.33
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	326.67
	Semiconducting Materials	Math & Physics	310.44
KIMS	Material Science	Chemical, Mechanical, & Civil Engineering	512.50
	Superconductor Science	Math & Physics	441.67
	Ceramics	Chemical, Mechanical, & Civil Engineering	330.00
KIOM	Phytochemistry	Chemistry	201.00
	EthnoPharmacology	Chemistry	183.60
	Clinical Cancer Research	Medical Specialties	131.56

Table 4 continued

GRI	Sub-discipline	Discipline	h_1-index
KIOST	Phytochemistry	Chemistry	22.33
	Protein Science	Biotechnology	12.00
	Molecular Medicine	Health Professionals	11.67
KIST	Semiconducting Materials	Math & Physics	564.44
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	517.22
	Material Science	Chemical, Mechanical, & Civil Engineering	512.50
KISTI	High Energy Physics	Math & Physics	319.67
	Surface Science	Math & Physics	244.48
	Ceramics	Chemical, Mechanical, & Civil Engineering	99.00
KIT	EthnoPharmacology	Chemistry	61.20
	Microbiology Biotechnology	Biotechnology	57.50
	Semiconducting Materials	Math & Physics	56.44
KITECH	Material Science	Chemical, Mechanical, & Civil Engineering	375.83
	Superconductor Science	Math & Physics	265.00
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	245.00
KOPRI	Systematics & Evolutionary Microbiology	Biotechnology	98.40
	Microbiology Biotechnology	Biotechnology	86.25
	Electrochemistry	Chemical, Mechanical, & Civil Engineering	54.44
KRIBB	Clinical Cancer Research	Medical Specialties	345.33
	Microbiology Biotechnology	Biotechnology	316.25
	Pharmaceutical Design	Chemistry	312.00
KRICT	Electrochemistry	Chemical, Mechanical, & Civil Engineering	326.67
	Catalysis	Chemistry	310.00
	Semiconducting Materials	Math & Physics	282.22
KRISS	Semiconducting Materials	Math & Physics	366.89
	Superconductor Science	Math & Physics	353.33
	Ceramics	Chemical, Mechanical, & Civil Engineering	297.00
KRRI	Superconductor Science	Math & Physics	353.33
	Materials Processing	Chemical, Mechanical, & Civil Engineering	101.00
	Material Science	Chemical, Mechanical, & Civil Engineering	68.33
NFRI	Superconductor Science	Math & Physics	706.67
	Plasma Physics	Math & Physics	258.00
	Nuclear Engineering	Chemical, Mechanical, & Civil Engineering	154.00
NIMS	Semiconducting Materials	Math & Physics	254.00
	Material Science	Chemical, Mechanical, & Civil Engineering	205.00
	Superconductor Science	Math & Physics	176.67

for the future economic growth. In case of Korea, academic research takes about eight years to influence on the economic growth (Lee et al. 2011).

Moya-Anegon and Herrero-Solana (2010) classified Korea as being as strong in chemistry, engineering, material science, and physics as China and Russia. The top 3 disciplines by the share of publications—Chemistry; and Chemical, Mechanical, and Civil Engineering; and Math and Physics—showed the similar results. Accordingly, the predominance of such

Table 5 Top 20 disciplines of the h_2-index list during the period 2008–2012

Rank	Discipline	GRI	h_2-index	$\max_{h1}$
1	Chemistry	**KIST**	18	360.00
2	Chemistry	**KRICT**	17	310.00
3	Chemical, Mechanical, & Civil Engineering	**KIST**	16	517.22
4	Chemistry	**KBSI**	16	175.00
5	Chemistry	**KRIBB**	14	312.00
6	Chemistry	**KAERI**	14	192.00
7	Chemical, Mechanical, & Civil Engineering	**KIER**	12	517.22
8	Chemical, Mechanical, & Civil Engineering	**KAERI**	12	513.33
9	Chemical, Mechanical, & Civil Engineering	**KIGAM**	12	239.17
10	Chemistry	**KIER**	12	223.89
11	Chemistry	**KRISS**	12	155.00
12	Electrical Engineering & Computer Science	**ETRI**	11	531.67
13	Chemical, Mechanical, & Civil Engineering	**KIMM**	11	326.67
14	Chemistry	**KITECH**	11	160.00
15	Chemistry	**KIMS**	11	125.00
16	Chemical, Mechanical, & Civil Engineering	**KIMS**	10	512.50
17	Chemical, Mechanical, & Civil Engineering	**KITECH**	10	375.83
18	Chemical, Mechanical, & Civil Engineering	**KRICT**	10	326.67
19	Chemical, Mechanical, & Civil Engineering	**KRISS**	10	297.00
20	Chemistry	**ETRI**	10	144.00

academic fields is quite possibly due to essential or fundamental researches from a national R&D viewpoint. In contrast, sub-disciplines within Earth Science, Brain Research, and Social Sciences are omitted from the main research. This may be due to a less concentrated or shorter history of research.

The quantity in discipline level has tendency to match the quality, which mostly stems from a small number of sub-disciplines. The biggest examples are Superconductor Science and Semiconducting Materials in Math and Physics. According to the h_1 values, Math and Physics appears as the main discipline, whereas Chemistry; and Chemical, Mechanical, and Civil Engineering occupied high ranks at h_2. Most players in Math and Physics are involved in only two sub-disciplines — Semiconducting Materials and Superconductor Science. Therefore, the concentrated sub-disciplines and the performances in Math and Physics reveal that the industrial development and the applied science is more emphasized than the fundamental science.

The superiority of Chemistry and Chemical, Mechanical, and Civil Engineering also comes from a part of sub-disciplines. In the 1970s, GRIs' research in chemistry developed to correct the underbelly of heavy and chemical industry. At the time, most of GRIs pursued organic chemistry, inorganic chemistry, polymer chemistry, and chemical engineering. GRI's chemistry research evolved into fine chemistry, novel materials, and petrochemistry in the 1980s. The research in chemistry matured over time, and GRI made their mark in Material Science, Ceramics, and Pharmaceutical Design. Most GRIs are mutually committed to those sub-disciplines as well.

In addition, we found that only fragmentary sub-disciplines rank among the prolific research areas. As research capacity in universities and industries increases, GRIs recently

Table 6 Ranking of Government-funded science and technology Research Institutes (GRIs) according to h_3 value during the period 2008-2012

Rank	GRI	h_3-index	$\max_{h2}$	$\max_{h2}$ Discipline
1	**KIST**	5	18	Chemistry
2	**KBSI**	5	16	Chemistry
3	**KAERI**	5	14	Chemistry
3	**KRIBB**	5	14	Chemistry
5	**KIGAM**	5	12	Chemical, Mechanical, & Civil Engineering
6	**KERI**	5	9	Chemical, Mechanical, & Civil Engineering; Electrical Engineering & Computer Science
7	**KRICT**	4	17	Chemistry
8	**KIER**	4	12	Chemical, Mechanical, & Civil Engineering; Chemistry
8	**KRISS**	4	12	Chemistry
10	**ETRI**	4	11	Electrical Engineering & Computer Science
10	**KIMM**	4	11	Chemical, Mechanical, & Civil Engineering
10	**KIMS**	4	11	Chemistry
10	**KITECH**	4	11	Chemistry
14	**KFRI**	4	9	Chemistry
15	**KARI**	4	8	Chemical, Mechanical, & Civil Engineering
15	**KIOM**	4	8	Chemistry
15	**NIMS**	4	8	Chemistry
18	**KISTI**	4	7	Chemistry
18	**KOPRI**	4	7	Earth Sciences
18	**NFRI**	4	7	Chemical, Mechanical, & Civil Engineering; Math & Physics
21	**KICT**	3	9	Chemical, Mechanical, & Civil Engineering
22	**KIT**	3	8	Chemistry
23	**KRRI**	3	5	Chemical, Mechanical, & Civil Engineering
24	**KIOST**	3	2	Chemistry
25	**KASI**	2	5	Math & Physics

focus on the large-scale research to complement R&D in universities and industries. Thus such researches as Solar and Wind Power; and Nuclear Engineering are conducted by designated institutes. On the other hand, GRIs' specialties would influence to the performance of Radiation Protection; and Systematics and Evolutionary Microbiology.

Although the academic missions of KIST and the Korea Research Institute of Bioscience and technology (KRIBB) are originally assigned to the basic science, both institutions obtain excellent results in the applied research as well. KIST has prospered with the economic growth of Korea coming from the heavy chemical engineering and exceptionally contributes to advancement in Chemistry; and Chemical, Mechanical, and Civil Engineering: 56.41 % of its publications are in both disciplines. KRIBB leaves other GRIs far behind in Biology; Infectious Diseases; Medical Specialties; and Health Professionals. However, KRIBB should rejuvenate their knowledge base in Biotechnology. ETRI is the only player in Electrical Engineering and Computer Science within Category A. Moreover, all major sub-disciplines in Electrical Engineering and Computer Science are on ETRI's top sub-discipline list as

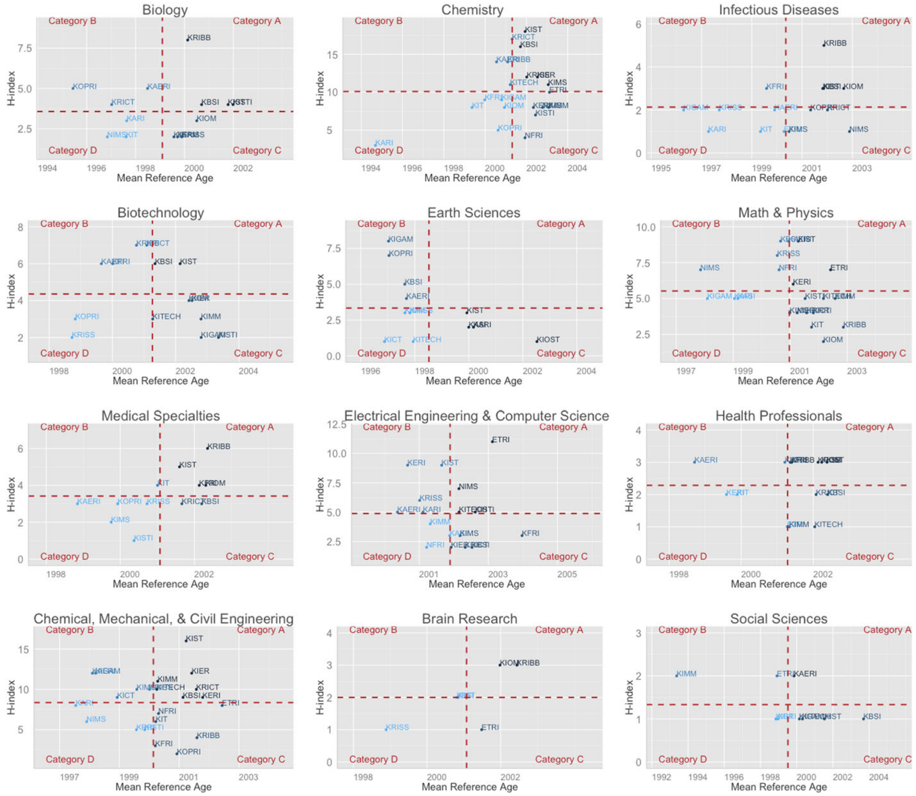

Fig. 5 GRIs' knowledge production and consumption

shown in Fig. 4. In terms of the balance of the national research system, this implies that ICT one of the nation's leading technologies is reliant on one giant institute.

Our findings have important implications for science and technology in terms of (i) a rigid R&D portfolio, (ii) giant institutes in some areas, and (iii) development plans for each Category. In the 1970s and 1980s, GRIs took an active part in the whole field of national scientific and technological development. Now, GRIs' research area contracts due to improvement of research capacity in universities and industries. A majority of the GRIs pursue the top 3 prolific disciplines—Chemistry; Chemical, Mechanical, and Civil Engineering; and Math and Physics-, despite the one-sided view of these sciences. The excessive concentration on those disciplines stems from the national industry development. On the other hand, the results are implicit in the thematic rigidity of R&D portfolios as well. In case of chemistry and related disciplines, GRIs adhere to the development style in the heavy chemical industry of the 1960s. The attention to Math and Physics would be indebted to the development of semiconductor industries. In consequently, GRIs have neglected the fundamental researches and their portfolios require flexibility for further development (Vinkler 2007).

In contrast to the engrossment in some areas, we are concerned about research isolation from other GRIs. Notable examples are KRIBB in Biology and ETRI in Electrical Engineering and Computer Science. These GRIs conduct incomparable scientific research in both basic and applied sciences. However, the elitism could hinder the balanced development between GRIs since government resources and opportunities are exclusively assigned to the giant institutes. The practical effects that originate in research collaboration cannot be counted on, including equipment sharing and reduction in expense. The existence of exclusive institutes also implies that the national R&D might be susceptible to research failure.

Another implications of this study is the suggestion of development plans for GRIs. First, the gap between knowledge production and consumption is present, especially, among GRIs in Categories B and C. These institutes have to narrow their level of inactivity based on institutional objectives, expertise, and capacity. To achieve entrance into Category A, the GRIs are required to further develop remedies for imperfections, such as funding for remarkable scientific accomplishments or refurbishment of knowledge bases. More to the point, these institutes should develop the capacity for professional research or look for research collaborators to amplify their synergy.

There are intractable problems in dealing with Category D. Most GRIs affiliated with Category D are at a premature capacity for accomplishing their academic purpose, with the exception of non-expert institutes. For example, the National Institute for Mathematical Sciences (NIMS), established in 2005, has a chance to be a leading intellectual institute despite its relatively short history. To promote these under-represented institutes, efforts to improve performance and government support are essential, but it takes a long time to develop expertise and to accumulate experience is extremely huge, as great discoveries are always attended by more perseverance than “eureka” moments.

6 Conclusions

This paper interpreted GRIs’ research portfolios regarding to national strategies from the perspective of knowledge production and consumption. In particular, we focalized on GRIs’ pivotal role and academic contribution to the economic development in Korea. We investigated research themes where the research was committed to further efforts than international attention, thereby identifying characteristic research. The performance of the characteristic research was evaluated, and the state of research activity was determined. We adopted the successive h-index and mean reference age as indices. To correct the citation and publication practices cross the disciplines, the h_α-index (Eck and Waltman 2008) measured research performance instead of the original$h$-index in the successive h-index (Prathap 2006; Schubert 2007).

We applied this approach to Korean GRIs, and identified the leading GRIs that are currently contributing to Korean scientific advancement during the five years (2008–2012). GRIs’ characteristic research areas were revealed to be Chemistry; Chemical, Mechanical, and Civil Engineering; Electrical Engineering and Computer Science; and Math and Physics. Even we attended to the basic sciences through scientific outputs, the themes, GRIs engaged in, are closely related to strategic industries. The superb disciplines are closely related to industrial capabilities of Korean chemical industry, ICT, and semiconductor industry. Although GRIs recently expanded their research interest to Nanotechnology in Chemistry and Brain Research adapting to technological change, they need to enhance the research performance. Key players in each disciplines were also found in Category A. KIST and KBSI, multi-disciplinary research institutes, are superior to other GRIs. Moreover, ETRI can be considered as another multi-disciplinary research institute based on their broad research portfolio, especially in Electrical Engineering and Computer Science; Chemistry; Chemical, Mechanical, and Civil Engineering; and Math and Physics.

As limitations of this paper we would like to point out the following. Even the original formulation of h-index included self-citations, recently academic community pays attention to the possible influence of self-citations. Several authors recommended to exclude self-citations for a fairer indicator (Raan 2006; Schreiber 2007). The number of self-citations is rather small to apply statistics theory since the self-citations appear less than ten times per institute. Although the effect on self-citations would be imperceptible, other factors could additionally provoke changes when it comes to applying the index to institutional level. In particular,Vinkler (1986) considered "indoor" citations that refer to citations made by any articles whose authors working at the same institute published. Problems related to multi-authorship counts would be addressed (Rousseau et al. 2010), as well because a full credit, which is given to each co-author, can inflated the performance. To assess the scientific achievement of institutional level, it would be essential to understand the effect of those factors on the performance.

Although Korean GRIs particularly take the lead in the fundamental sciences, research on their scientific activities has paid little attention. Enhancing research capacity in universities and industries, Korean GRIs need to be assigned a new role in the national R&D. As an introductory study of GRIs' contribution, we dealt with GRIs' academic outputs and research performances in domestic context of national R&D strategies and economic development. This study would serve supplementary information to provide research themes, which GRIs are in charge of. Considering the domestic situation is crucial, but balancing that with global trends is necessary as well. We must emphasize the importance of national R&D competitiveness in the knowledge-driven global economy. In comparison to other countries, we would like to analyze and determine any superiorities or differences as a sequel.

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