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Structural efficiency to manipulate public research institution networks

Hyeonchae Yang a, Woo-Sung Jung b,*

a Graduate Program for Technology Innovation & Management, Pohang University of Science and Technology, Pohang 37673, Republic of Korea
b Department of Industrial and Management Engineering & Department of Physics, Pohang University of Science and Technology, Pohang 37673, Republic of Korea

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A B S T R A C T
With the rising use of network analysis in the public sector, researchers have recently begun paying more attention to the management of entities from a network perspective. However, guiding elements in a network is difficult because of their complex and dynamic states. In this study, we address the issues involved in achieving network-wide outcomes, our work here sheds new light on quantifying structural efficiency to control inter-organizational networks maintained by public research institutions. In doing so, we draw attention to the set of subordinates suitable as change initiators to influence the entire research profiles of subordinates from three major public research institutions: the Government-funded Research Institutes (GRIs) in Korea, the Max-Planck-Gesellschaft (MPG) in Germany, and the National Laboratories (NLs) in the United States. Building networks on research similarities in portfolios, we investigate these networks with respect to their structural efficiency and topological properties. According to our estimation, only less than 30% of nodes are sufficient to initiate a cascade of changes throughout the network across institutions. The subunits that drive the network exhibit an inclination neither toward retaining a large number of connections nor toward having a long academic history. Our findings suggest that this structural efficiency indicator helps assess structural development or improvement plans for networks inside a multunit public research institution.

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1. Introduction

Public research more inclines to distribute its findings than commercialize in contrast to industrial research (Geffen and Judd, 2004). In general, institutes conducting public research are largely government funded and target the public domain (Bozeman, 1987). Because of their national orientation and stable funding source, public research institutes do cutting-edge research at least one academic field through long-term plans (greater than three years) (Bozeman, 1987). A public research institution often develops as an association of research institutes rather than a single organization. Research entities with a public research institution enjoy institutional autonomy in choice of subjects notwithstanding the fact that they are under the same umbrella of governance. Naturally, research organizations have different characteristics depending on national circumstances. Some public research institutions, such as the Max Planck Gesellschaft (MPG) in Germany, are faithful to pure research (Philips, 2013), while others have significance within a particular national context: part of the National Laboratories (NLs) in the United States (US) addresses defense-related technologies (Jaffe and Lerner, 2001), and the Government-funded Research Institutes (GRIs) in Korea attempt to assist in the country's economic development by promoting indigenous public research (Mazzoleni and Nelson, 2005; Arnold, 1988; Lee, 2013).

With recent advances in our understanding of network, it is possible to apply novel network knowledge to manage public research institutions in response to internal and external changes. For example, entities in national innovation systems (Freeman, 2004) or the Triple Helix models (Phillips, 2014; Leydesdorff, 2003) can be external factors affecting research of public research institutions. The notion of national innovation systems provides a framework to explain underlying incentive structures for technological development at a national level and international differences in competence from a network perspective of public and private organizations (Patel and Pavitt, 1994). The Triple Helix model considers coevolving academic, industry, and government which provokes techno-economic developments of a country (Leydesdorff et al., 2013). In these systems, public research institutes provide fiscal and technical assistance to other organizations. Kondo (Kondo, 2011) pointed out that public research institutes dedicated to transferring technologies to industry by means of consulting, licensing, and spinning off. By doing so, they contribute to promoting integration and coordination within the system (Provan and Milward, 1995). In order to formulate policies and procedures to steer the entire system, system organizers are able to guide public research institutes properly. In this context, control of those key agencies is important to achieving desirable outcomes.

Moreover, there is a growing need for an efficient implementation throughout public research institutions composed of multiple sub-
organizations in order to deal with internal controls (Yang and Jung, 2014). For example, most public research institutions have undergone transformations in recent years due to modernization, imperatives for efficiency, and the promotion of collaboration with the industry (Buenstorf, 2009; Cohen et al., 2002; Simpson, 2004; Senker, 2001). In unfavorable economic conditions, declining government funding causes the restructuring of research areas (Malakoff, 2013; Izsk et al., 2013) or the government demands more practical outputs from them, such as conducting applied research and setting standards (OECD, 2011). In an attempt to harness technology for socio-economic development, governments often prioritize future research through foresight activities (Priedhorsky and Hill, 2006) and accordingly assign new academic missions to public research institutions. In particular, developing countries have lately been paying more attention to the technology-driven development model under government supervision (Arnold, 1988). At that time, controlling every entity enables the institution to fully guide those internal changes but entails great expense.

From 1935 to 1945, public research institutions engaged in national strategic areas, including exploration of mineral resources, industrial development, and military Research and Development (R&D) (OECD, 2011). After the termination of World War II, the establishment of public research institutions grew in an effort to advance military technology in many countries. Moreover, at that time, public research institutions extended almost all areas with which governments were associated, such as economic and social issues. They continued growing until the 1960s. In the 1970s and 1980s, many countries expressed doubts on their contributions to innovation. However, as deepening the understanding of national innovation systems or the Triple Helix models, public research institutions started to be seen in a new light. In these models, public research institutions have played an indispensable role in preventing systemic failures, which reduce the overall efficiency of R&D (Lundvall, 2007; Sharif, 2006) due to their relations with external collaborators (Klijn and Koppenjan, 2000; McGuire, 2002). Still, the importance of public research institutions is emphasized in particular for scientific innovation (Cabanelas et al., 2014).

In this regard, a network approach is necessary to efficiently implement transformations throughout sub-organizations, and the academic interest also grows for the effective operation of the network (Cabanelas et al., 2014; Jiang, 2014). There is, however, a lack of empirical research on managing public research institutions through a network system. Hence, in this paper, we conceptualize three major public research institutions — the MPG, NLs in the US, and GRIs in Korea — as networks, identify the sub-organizational network structure of each, and examine its structural efficiency. A collaborative research network is one of the most prevalent inter-organizational configurations (Shapiro, 2015). However, we deem that topical similarity between research institutes is suitable to represent a relation between them in research interests. Most transformations involve changes in research areas, and changes in organizational research topics frequently occur when governments prioritize specific research fields or delegate new roles to institute (Wang and Hicks, 2013). Prior studies emphasized the importance of similarity in knowledge content among entities to effectively manage inter-organizational networks as well (Tsai, 2001; Hansen, 2002). For these reasons, a network here is formed by pairs of subunits having the most similar research profiles. With the addition of temporal dynamics to inter-organizational relations, a chain of networks over time allows the description of the structural evolution of public research institutions.

Based on revealed networks, we determined the structural efficiency with which network-wide actions can influence entities for finite time periods. No matter the measure puts in place, all members of network need to adopt it to achieve collective actions. In the early stages of change implementation, network organizers select initiators to change among entities. As the change initiators propagate control actions to the remainder of entities, a public research network can be steered in the desired direction like a car. We can derive a minimum number of suitable initiators from a theory of “structural controllability” (Yuan et al., 2013). In the theory, change initiators refers to injection points of external energy used to steer the network, which are theoretically selected depending on network structure. In this process, structural efficiency is obtained by calculating the share of change initiators in the network: the lower the efficiency value, the smaller the number of entities the network manager is required to handle. Therefore, by comparing efficiencies with structural properties over time, we can estimate network characteristics specific to institutions.

In this study, we divided institutional research portfolios into six time periods based on scientific output over eighteen years (1995–2012), and estimated structural efficiencies of research similarity networks. Considering structural efficiency, we can observe that networks in all three research institutions can be managed with less than 30% of sub-organizations, and the values reflect the changes that have occurred in research institutions. Each research institution has some sub-organizations consistently selected as suitable change initiators over a period of time. Our results primarily highlighted young subordinates as appropriate change initiators, which means that information blockades in network might occur unless the selected units are properly managed. Moreover, the estimated changes initiators tend to have a lower connectivity in network than the rest of nodes. We expect that our work has implications for decision-making bodies and network managers seeking to an efficient way to influence their intention on a network of public research institutes.

The remainder of this paper is structured as follows: in Section 2, we briefly describe the impact of structure on network effectiveness associated with public research institutions based on past research. Section 3 is devoted to an explanation of data sources, network construction processes, and the calculation of structural controllability in a network. We discuss the results of our experiments in Sections 4 and 5, and offer our conclusions in Section 6.

### 2. Research networks around public research institutions

Methods for utilization and development of networks have grown in an attempt to address complex problems that require collective effort. When the purpose of the network is to deliver public services, independent organizations are generally involved in the process, and interdependency between participants facilitates the formation of links (Kickert et al., 1997). By exchanging knowledge through a network, public research organizations attain a higher level of performance, at the same time, create a greater ability to innovate (Morillo et al., 2013). Goldsmith and Eggers (2004) claimed that using a vehicle for networks is favorable to organizations that require flexibility, rapidly changing technology, and diverse skills because actors can exchange goals, information, and resources while interacting with each other. Resources usually refer to units of transposable value, such as money, materials, and customers, and information signifies exchangeable units between agencies, such as reports, discussions, and meetings. With regard to exchanged goods between organizations, van de Ven (van de Ven, 1976) underlined the importance of information and resources as “the basic elements of activity in organized forms of behavior.” In research systems, organizations can take advantage of network participation to have a greater possibility of funding, to broaden their research spectrum, or to reduce the risk of failure (Beaver, 2001). Therefore, networks are beneficial because they can pool resources, permit the mutual exploration of opportunities, and create new knowledge (Priedhorsky and Hill, 2006).

However, strategies are needed to coordinate interactions while managing networks because different actors have different goals and preferences concerning a given problem (Kickert et al., 1997; O’Mahony and Ferraro, 2007). The capability of network management is also necessary to promote innovations (Pittaway et al., 2004), but there remain questions as to how to manage such organizational interactions as Beaver (Beaver, 2001) pointed out. Orchestrating activities
seems unnecessary because of interactions between autonomous organizations, but addressing conflicts keeps agencies cooperative in effort to achieve the goal of the network, thereby facilitating the effective allocation and efficient utilization of network resources. Furthermore, a network sometimes needs to be intentionally formed to boost management by governing parties which would be either an external organization or network participant(s) (Provan and Kenis, 2007). Public research institutions can be said to be governed by external organizations, considering that different entities are in charge of their administration in general, such as ministries, research councils, and other steering bodies. Both the MPG and Korean GRIs are apparently steered by a single entity. The fundamental management policy of the NLs in the US also originates in a federal agency, although several laboratories are operated by contract partners.

By frequently repeating interactions among actors, networks produce certain outcomes. The performance of a network is evaluated according to whether the network effectively attains its goal. The outcome varies depending on governing strategies, and the course of attainment can be enhanced by taking advantage of structural properties of the network (Kickert et al., 1997; Goldsmith and Eggers, 2004). Provan and Milward (2001) argued that the assessment of network effectiveness should involve consideration not only of beneficiaries, but also of administrative entities and the participants of the network. Nevertheless, the literature on networks has paid more attention to the common goal is primarily involved in network-level accomplishment (Provan and Milward, 1995; Möller and Rajala, 2007).

There remain difficulties in determining network effectiveness. The problem primarily resides in the impossibility of quantifying the exact network outcome (Provan and Lemaire, 2012). As Agranoff (2006) claimed, networks are not always directly related to policy adjustments because some interactions are forged by voluntary information exchange or educational service. In the public research institution, researchers engaged in specialized fields have the opportunity to share ideas across administrative boundaries given that they have the goal and intend to generate public knowledge. Outcomes of research networks can be approximated by proxy variables, such as patent and paper citations, innovation counts, new product sales, and productivity growth (Council, 1997). Furthermore, such networks also indirectly affect subsequent movements and policies. Thus, network efficiency needs to be measured for various types of networks, by considering factors beyond collaborations.

In order to increase network effectiveness, structural efficiency in networks is important: since all entities are connected, damage to one part can cause the collapse of the entire system through a cascade of failures. In this regard, considerable research on networks has focused on deliberately building efficiently manageable networks (Cabanelas et al., 2014; Kickert et al., 1997; van de Ven, 1976; Provan and Kenis, 2007). Certain network structures can affect innovation performance by catalyzing knowledge exchange (Valero, 2015). Enemark et al. (2014) argued the importance of the network structure to collective actions via experimental tests that demonstrated structural variations in a network can either improve or degrade network outcomes. However, there is ambiguity in appropriate network structures to achieve effective control. Pittaway et al. (2004) suggested that longitudinal network dynamics need to be taken into account when designing network topologies.

A network is required to change its members or structures in order to adapt to environmental changes. Much of the literature on networks emphasized that instability is an opportunity for transformation (Hicklin, 2004). Although the capability of flexible response is one of the strongest features within a network model, such network dynamics challenge for effectively managing networks. With regard to network size, it is widely known that the greater number of actors involved, the more difficult it becomes for the network to achieve collective cooperation (Kickert et al., 1997). Increasing the number of participants results in more complex network governance because the number of potential interactions also exponentially escalates. However, prior research found that research networks evolved to be more centralized as growing the network (Ferligoj et al., 2015; Hanaki et al., 2010). The growing patterns of research networks imply that adding an entity does not always increase complexity of network management. Theorists rather claimed that the introduction of a new node would improve efficiency to control networks (Klijn and Koppenjan, 2000).

Centralization captures the extent of inequality with which important nodes are distributed across the network, and is often measured in terms of Freeman’s centralities (Freeman et al., 1979). A degree (the number of connections) centralized network is known to readily coordinate across agencies and closely monitor services (Provan and Milward, 1995). In complex networks, a minority of nodes, referred to as hubs, dominates connections while the majority is connected with a small number of points (Barabási and Albert, 1999). Research revealed that complex networks were robust against random attacks (Albert et al., 2000). Hubs in research networks were not only empirically impressive in their performance (Echols and Tsai, 2005; Dhanarag and Parkhe, 2006), but also easy to access new knowledge developed by other entities (Tsai, 2001). Hanaki, Nakajima and Ogura (Hanaki et al., 2010) also found R&D collaboration networks evolved toward more centralized structures because organizations prefer to collaborate with reliable partners based on referrals obtained from former partners. However, a high degree of integration is not always desirable. Provan and Lemaire (2012) proposed that connective intensity between organizations should be appropriately controlled for effective network structure. Cabanelas et al. (2014) also found research networks producing high performance featured nodes with low degree centrality.

No matter the types of networks that develop out of interactions, the goal achievement is possible only when the relevant information spreads throughout the network to encourage actors to conform. In recent years for public research institutions, the controllability of organizational portfolios has been seen as constitutive of dynamic capabilities, which means the “ability to integrate, build, and reconfigure internal and external competencies to address rapidly changing environments” (Teece et al., 1997; Floricel and Ibaneescu, 2008). In this sense, estimating efforts to control entities of public research institutions is related to assessing the feasibility of research reorganization over networks. At the same time, the number of key points in information flow within a network affects burden on the network administration. Although earlier work emphasized that selectively activating critical actors is more effective to integration than full activation, the system must secure the capability to exercise influence across agencies (Kickert et al., 1997; Provan and Lemaire, 2012). Furthermore, the efficiency with which network structure can be manipulated would be a suitable criterion to evaluate the built structure.

3. Data and methods

This section is devoted to describing methods of network construction based on collected bibliographies and analytical methods. We describe a quantification method for structural efficiency given structure to control the whole network, and explain structural properties to explore their relation with structural efficiency. In the process of efficiency calculation, we extract suitable organizations to initiate transformation. This investigation was conducted in the R ver. 3.1.2 environment (R Core Team, 2015), and used the following add-on packages for convenience: ggplot2 (Wickham, 2009) and igraph (Csardi and Nepusz, 2006).

3.1. Data collection and research portfolio identification

We identified research portfolios based on scientific output, and gathered bibliographic data regarding NLs, MPG, and GRIs from the Thomson Reuters Web of Knowledge. Academic output over eighteen
years (1995–2012) was compiled according to institutional names and abbreviations of authors’ affiliations. We only used affiliations in English for this study. Subordinate research institutes listed in official websites were considered, and their portfolios were tracked using at least twenty papers for each.

All disciplines, which are the constituent elements of a portfolio, need to be identified using the same classification system for ease of institutional comparison. We utilize the University of California-San Diego’s (UCSD) map of science (Borner et al., 2012) as a journal-level classification system. The map classified documents into 554 sub-disciplines belonging to 13 disciplines on the basis of journal titles. Naturally, a research portfolio has two levels of classification: discipline and sub-discipline. Particularly, a discipline refers to the aggregate level of sub-disciplines in the hierarchical structure in this study. Fig. 1 shows an example of disciplinary mapping using Sci2 (Sci2 Team, 2009) for the Lawrence Berkeley National Laboratory (LBNL), one of the national laboratories of the US Department of Energy (DOE). Our investigation ultimately included 337,417 scientific articles from 104 institutes — 59,333 articles from 26 GRIs in Korea, 85,540 articles from 61 subordinate institutes of the MPG, and 192,544 articles from 17 NLs in the US.

In order to analyze the thematic evolution of network over time, we split the portfolios into time intervals. With regard to an adequate duration of assessment period to represent scientific output being measured, Abramo et al. (2012) claimed that a three-year period is adequate to assess scientific outputs. By accepting their recommendations, we observed the development of institutional portfolios for six consecutive time slices.

3.2. Organizational thematic network

As a well-known analytical method, a complex network is suitable for exploring dynamic topology changes (Strogatz, 2001). Here, an inter-organizational network is formed between subordinate institutes building similar research profiles. Representing sub-organizations, nodes are connected by a link when two sub-organization have similar research portfolios. In order to measure similarities, we used “inverse frequency factors” for weighting system and “second-order cosine similarities” (García et al., 2012). The inverse frequency factor borrows from a term discrimination method for text retrieval (Salton and Yang, 1973; Salton and Buckley, 1988). The factors weight each sub-discipline in the research portfolio. The weight of sub-discipline \( m \) for research institute \( i \) is determined by \( w_{mi} = f_{mi} \times \log(\frac{n_{m}}{n_{i}}) \), where \( f \) denotes the number of articles; and \( \log(\frac{n_{m}}{n_{i}}) \) implies the inverse frequency factor to file out prevalent research (Jones, 1972). The logarithmic frequency factor is calculated inversely from the ratio number of subunits \( n_{m} \) that publish their achievements in sub-discipline \( m \) to the total number \( N \) of research institutes. As a result, the set of weights generates a 554 sub-disciplines-by-institute matrix.

3.3. Quantification of network-wide structural efficiency

In order that the network structure can efficiently elicit the desired response from its elements, a certain amount of energy needs to be injected into the network to change the behavior of actors. Thus, the selection of several agencies to initiate changes depending on network structure is inevitable. At the same time, it is important to minimize the number of injection points due to management cost. Studies on complex networks consider that nodes can dynamically make decisions or can dynamically change their states by responding to information received through links between nodes. As individual actors, nodes on research networks can be researchers or research institutions, and the nodal states can be represented by individual research interests or disciplinary composition. Here, we estimate the capability that controls the behavior of such nodes in complex networks with the minimum involvement of intervention adopting the notion of structural controllability.

In recent years, a number of studies have focused on driving networks to a predefined state by combining control theory and network science (Liu et al., 2011; Wang et al., 2012; Lombardi and Hörnquist, 2007; Gu et al., 2014). According to network controllability, if a network system is controllable by imposing external signals on a subset of its nodes, called driver nodes, the system can be effectively driven from any initial state to the desired final state in finite time (Kalman, 1963; Kalman, 1964; Lin and Varaiya, 2005; Li et al., 2016).

![Fig. 1. Thematic categorization of the Lawrence Berkeley National Laboratory (LBNL).](image-url)
Lin, 1974). Thus, network controllability depends on the number and the placement of the control inputs. For this reason, structural efficiency refers to the share of the driver nodes. In this study, agencies found using structural controllability are key locations to steer the entire inter-organizational research network.

We applied the structural controllability for undirected networks, introduced by Yuan et al. (2013), to matrix representation of our temporal MSTs. Each temporal matrix $G(A)$ was considered a linear time-invariant model $\dot{x}(t) = Ax(t)$, where the vector $x \in \mathbb{R}^N$ represents the state of the nodes at time $t$, $A \in \mathbb{R}^{N \times N}$ denotes the research similarity matrix of MST, such that the value $a_{ij}$ is the portfolio similarity between institutes $i$ and $j$ ($a_{ij} = a_{ji}$). The controlled network $G(A,B)$ corresponds to adding $m$ controllers using ordinary differential equations $\dot{x}(t) = Ax(t) + Bu(t)$, where vector $u(t) \in \mathbb{R}^m$ is the controller and $B \in \mathbb{R}^{N \times m}$ is a control matrix. The problem of finding the driver nodes of the system is solved by the exact controllability theory following the Popov–Belevitch–Hautus (PBH) rank condition (Hautus, 1969). To ensure complete control, the control matrix $B$ should satisfy $\text{rank}[\lambda^{\text{MIN}} \text{I}_N - A, B] = N$, where $\text{I}_N$ is the identity matrix of dimension $N$, and $\lambda^{\text{MIN}}$ denotes the maximum geometric multiplicity $\mu(\lambda_l)$ ($= \text{N-rank}(\lambda_l \text{I}_N - A)$) for the distinct eigenvalues $\lambda_l$ of $A$. Therefore, from a theoretical perspective, changes initiated from the drivers are likely to affect the entire structure. Hence, driver institutes are crucial to the functioning of networks for public research institutes. In this paper, we regard the share of drivers in all agencies as an efficiency indicator in that the number of drivers is important for efficient control.

Network properties have been utilized by a considerable amount of literature in the area to better understand structural features of networks (Newman, 2003; Albert and Barabasi, 2002; Woo-young and Park, 2012). In order to understand the relation between efficiency and the inter-organizational research network, we extracted major features across institutions based on some structural properties, such as network size and connectivity. The number of participants represents network size associated with network volume. Centrality is one of the most studied indicators in network analysis, and measure the influence of a node in a network using degree centrality (Freeman et al., 1979; Borgatti et al., 2009; Freeman, 1978). We examine the degree feature of driver nodes. As a nodal attribute, we assign research experience in time periods to nodes to characterize driver nodes.

4. Results

This section contains the major results of our investigation of the structural features of the inter-organizational networks. To form our desired skeletal network, we extracted pairs of academically close institutes based on portfolio similarities among their participants using the construction algorithm of the Maximum Spanning Tree (MST). The results obtained from the backbone networks are related to structural controllability.

In order to address the evolution of inter-organizational research, we assessed the structural features of temporal MSTs. Figs. 2–4 show tree-like structures of institutions over time. Each node represents a sub-organization, and its size is proportional to the total number of documents published. The colors filling the nodes were determined by the discipline in which the institute was found to be most productive. The portfolio similarities between pairs of linked institutes represented the weight on the network, and these weights affected the width of links as well.

The descriptive statistics of portfolio similarity summarize and describe the distribution of the skeletal relationships between
subordinates, as listed in Table 1. For all institutions, we found that the distributions were biased toward high similarities between research portfolios. For the NLs networks in the US, the overall greater averages and smaller standard deviations of portfolio similarities than the other two institutions indicated that most research units were seen as connected, with the smallest difference in their research areas. On the other hand, in case of the GRIs, the lowest values of average similarity signified that each unit had a distinct research portfolio. The largest standard deviation and the low values of kurtosis for most time periods also showed that their research similarities were the most widely distributed.

In order to represent the dynamic characteristics of MSTs, their structural properties are listed in Table 2. The number of nodes $N$ increased and, accordingly, the number of links increased to $N - 1$ following the definition of an MST in the context of a connected network. In spite of sparsity of the network, nodes having a relatively large number of links could be found in some institutions, in particular the Oak Ridge National Laboratory (ORNL) within the NLs, which was connected to approximately a quarter of the other organizations for four time periods, and the Korea Research Institute of Standards and Science (KRISS) and the Korea Institute of Science and Technology (KIST), which appeared as a maximally connected node in each half of the dataset. However, there was stiff competition among institutes with the maximum number of connections in the MPG. We noted that network density $(2/N)$ could be obtained from the number of nodes, and the transitivity always reduced to zero because MST rules out cycles.

We calculated a periodical change of structural efficiency, and then examined the relations between network efficiency and structural properties. Following this, we investigated the features of estimated driver nodes in terms of degree and period of appearance. Note that although the number of driver nodes is theoretically fixed in a network, there can be multiple sets of drivers (Jia and Barabasi, 2013). We randomly selected a set where multiple driver sets existed. As an indicator of network efficiency obtained from structural controllability, Fig. 5 denotes the share of driver nodes over time. According to the graph in the figure, the proportion of drivers varied, but institutions did not have to consider all their agencies for network-wide transformation. Less than 30% of nodes were selected as suitable points at which to inject external information in all three institutions because the maximum value of structural efficiency in the entire datasets was about 30% at the second period (1998–2000) in the GRIs. In particular, the NLs could be influenced with a relatively small share of drivers among the institutions at all times, which was except for the period 2004–2006, wherein the GRIs, the largest portion of nodes mostly needed to initiate changes. The efficiency fluctuation of the MPG was more stable than other two institutions over time periods.

An understating of drivers enables administrators to take preemptive action to prevent information isolation, like the knowledge of the relation between the share of drivers and network efficiency can help plan structural development. The total number of driver appearances for the entire period corresponded to 13, 25, and 53 for the NLs, the GRIs, and MPG, respectively but 6, 15, and 31 agencies were selected as drivers. This was an evidence for the existence of memory in the drivers. Moreover, Figs. 6 and 7 capture some features of the drivers. Fig. 6 compares the average number of links between drivers and the entire nodes over different periods. Despite the common knowledge that nodes possessing large connectivity are influential, our results showed that drivers with low connectivity tended to determine collective agreement on the network. Fig. 7 shows the average durations of appearance by institutional drivers. We see that the driver nodes were
the ones newly entered to the network based on the average durations. Of the institutions, the research units of the NLs showed a wide difference between drivers and non-drivers.

5. Discussion

Public research has contributed to major innovations by improving competitiveness among existing industries and developing new ones. As prominent contributors to public research, governments have implemented a variety of support policies and programs for higher efficiency and excellence. Among the actors involved in public research, public research institutions aim to disseminate their knowledge, by providing various functions: priority-driven research to address national and academic agendas or blue skies research engaging large-scale research facilities to complement university research (Pot and Reale, 2000). To maintain such diversity, public research institutions seek to coordinate elements with varying specializations and missions in adapting to dynamic technological environments. As a part of the effort, institutions occasionally attempt to restructure research portfolios or modify organizational placements in relation with other research units. In

| Group | Statistics | Time span | 1995–1997 | 1998–2000 | 2001–2003 | 2004–2006 | 2007–2009 | 2010–2012 |
|-------|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| GRI   | Mean       |           | 0.505     | 0.531     | 0.618     | 0.621     | 0.628     | 0.658     |
|       | Median     |           | 0.507     | 0.551     | 0.623     | 0.551     | 0.59      | 0.663     |
|       | Standard deviation | | 0.271     | 0.229     | 0.227     | 0.258     | 0.223     | 0.181     |
|       | Skewness   |           | −0.256    | −0.439    | −0.171    | −0.556    | −0.284    | −0.298    |
|       | Kurtosis   |           | 1.836     | 2.538     | 1.713     | 2.663     | 1.962     | 2.195     |
| MPG   | Mean       |           | 0.608     | 0.68      | 0.65      | 0.698     | 0.706     | 0.774     |
|       | Median     |           | 0.577     | 0.768     | 0.679     | 0.735     | 0.749     | 0.846     |
|       | Standard deviation | | 0.269     | 0.268     | 0.26      | 0.209     | 0.221     | 0.183     |
|       | Skewness   |           | −0.04     | −0.56     | −0.59     | −1.132    | −1.12     | −1.111    |
|       | Kurtosis   |           | 1.975     | 2.173     | 2.336     | 4.351     | 3.907     | 3.932     |
| NL    | Mean       |           | 0.836     | 0.825     | 0.817     | 0.816     | 0.874     | 0.879     |
|       | Median     |           | 0.848     | 0.877     | 0.844     | 0.867     | 0.876     | 0.9       |
|       | Standard deviation | | 0.134     | 0.156     | 0.18      | 0.13      | 0.109     | 0.101     |
|       | Skewness   |           | −1.492    | −2.399    | −0.81     | −0.812    | −1.414    | −1.082    |
|       | Kurtosis   |           | 4.917     | 7.7       | 2.251     | 2.452     | 4.164     | 3.024     |
order to assess the development of public research institutions, we examined structural evolution derived from research similarities in the context of networked organizations in this paper.

More precisely, this study focused on public research institutions composed of several specialized research units, and extracted a network from similarities between sub-organizational research portfolios over eighteen years. A pair of connected agencies would be most influenced by the same type of exertion on a specific research area. In addition, sub-organizations connected to each other can be potential partners to collaborate because they share similar academic backgrounds. For example, the similarity networks of the GRIs give implications for inter-disciplinary research groups operated by the Research Council. In the research group, researchers working at different GRIs seek a solution together to technological difficulties and research similarities can indicate proper GRIs to resolve the difficulties. Moreover, offering the advantage of predictable network controllability, network modeling helps to understand the system's entire dynamics, which could be guided in finite time by controlling the initiators (Liu et al., 2011). As a result of the modeling, we can measure the efficiency of the network, where network efficiency implied the proportion of elements required as initiators to change the states of the entire agencies. The lower the proportion, the greater the network efficiency because the initiators are injection points for external information. We also revealed the structural properties of estimated initiators.

Our research here is different from other studies concerning network effectiveness in that it quantitatively estimated the effort required to control an entire inter-organizational network based on its structure. Naturally, if we send control signals to every single node, the network is operated with high controllability but involves significant cost. Thus, by employing the concept of structural controllability, we can theoretically detect the initial spreaders of information that need to be properly treated. Otherwise, they would have produced barriers to the exertion of authority; in extreme cases, the information blockades could have caused network failure (Klijn and Koppenjan, 2000). However, handling these elements incurs extra cost, because of which it is important to build networks with the minimum possible number of initiators to reduce enforcement costs incurred for complete control (Egerstedt, 2011). Common structural features of estimated initiators can direct network management of public research institutions. We generated results to provide a clear idea of how structural efficiency of research network is related to structural properties, such as size and nodal degree. Previous work on network governance structures has provided recommendations on how to build and design inter-organizational networks for innovation acceleration. For example, related to the number of participants, it is natural to expect that the share of drivers would also increase owing to a higher risk of insularity in information due to increasing structural complexity. However, our findings suggest not necessarily complying with the idea. Each of the institutions considered by us was different in size from others: the MPG was the largest-scale organization, whereas the NLs formed the smallest group in terms of number. However, according to our results, the size of the network did not seem to meaningfully affect

![Graph showing changing share of drivers over periods](image)

**Fig. 5.** Changing the share of drivers.
the proportion of drivers in public research institutions. Despite being a medium-sized institution, the networks of the GRIs were more likely to be inefficient than those of the MPG and the NLs. We think this was because an institution more experienced with managing such a union has built more effective structures. Even we found that the GRIs took advantage of the structural reorganization of the network because additions improved their network efficiency. In this regard, Kickert et al. (1997) claimed that the introduction of new actors can be a strategy to accomplish a mutual adjustment, since the new institute would cause structural changes within the network.

Proposition 1. A subset of nodes positioned in structurally important locations will have ability to steer a whole network of public research institution.

Our findings indicated that control actions applied to only less than half of the research units can lead to changes of an entire system, and the units repeatedly appear over time. We suspect the reason that public research institutions are designed to be a cost effective and resilient, as do their infrastructure networks. However, as national research structures can be affected by government policies (Hossain et al., 2011), the network efficiency also changes over time. The drastic fluctuation in the share of drivers would be related to changes in the relevant institution’s strategy or operation. For example, the GRIs underwent a restructuring to remove redundancy, and began operating under the research councils after 1999. We can capture drastic changes at the same time in our results because their structural efficiency significantly increased between the second and third periods between 1998 and 2003. The results would imply that the organizational rearrangements in the GRIs worked well. Besides, the research subjects of the NLs were revamped in the 2001–2006 period due to several events, i.e. the September 11 attacks and the outbreak of the Severe Acute Respiratory Syndrome (SARS). Since the terrorist attacks of September 11, 2001, the NLs have made greater efforts to reinforce national security by working on nuclear weapons or intelligent detection of potentially dangerous events. Moreover, a sudden epidemic of SARS accelerated multidisciplinary research in the NLs on vaccines, therapeutics, bioinformatics, or bioterrorism. We also find that the structural efficiency of the NLs were severely affected during the readjustment period. These changes in portfolio composition would cause temporary disarray in the structure of the networks. On the other hand, the property of stable
fluctuations in the MPG would be attributable to internal transitions for scientific advances rather than external impact. The MPG makes an expansion of research topics by mostly spinning off units because each unit has its own research area.

**Proposition 2.** Variations in structural efficiency of research networks will reflect structural changes in research composition.

Another difference between past research and our work here is that degree centralization is not invariably recommendable. Policy makers and network scientists have hitherto paid attention to highly connected institutes because hubs are regarded as network facilitators. However, our findings indicated that most key elements were apt to have low degrees. Our study focused on revealing the injection points to infect their nearest neighbors with energy regardless of the amount of energy required, and the nodes impart directions to connected neighbors at a time rather than exuding control forces over their adjacencies simultaneously. Obviously, the energy-entering hub can effectively reach agencies within its orbit, but there is a diffusion range. Thus, our observations suggest that network-wide influence was dependent upon nodes with a low connectivity. In this context, a network with moderately distributed focal points can be more effective to influence all organizations than a thoroughly concentrated one.

Furthermore, emergent sub-organizations show a tendency to have greater effect on structural efficiency than sub-organizations with a long research experience. We suspect that this is why a new research institute is often derived from a larger unit in public research institutions, holds low research similarity with other units than its parent, and takes position at the border, beyond any energy ranges. Another possible is that a newly-established research institute has unstable research portfolios, as Braam and van den Besselaar (2014) pointed out. The instability that a new research institute has in its research areas can increase uncertainty about the consequences of network-wide changes. Therefore, network managers may have the need to monitor the degree of acceptance of a network-wide action especially among emerging sub-organizations. This result is also consistent with recent observations, whereby driver nodes in real-world networks tend to be reluctant to link with high-degree nodes (Liu et al., 2011).

**Proposition 3.** Other things being equal, a possibility to control the whole research network will increase when control actions work properly at nodes with a low connectivity and a short research history.

We consider the differences in network effectiveness between existing studies and our findings originate from: whether the complete functioning of all elements was considered. Previous studies regarding the maximization of network effectiveness implicitly presupposed the complete performance of all entities a priori despite conflicts between participants, but at least network managers need to ensure complete operation of their network. For the full functioning of a network, all elements are required to be within the sphere of influence of the network manager for network-wide control. We deal with a possibility to manage the network behavior in public research institutions by quantifying the effort required to implement maneuvers. In order to avoid control blockades, we showed the importance of the elements, *inter alia*, with low connectivity and brief experience in academia.

This study provided theoretical results for structural controllability assuming some ideal situations, such as that measures were implemented on network skeleton without redundant connectivity, sufficient resources were provided to change the network, all institutes respected the administrator's intention, and there were no conflicts between a pair of connected institutes. The success or failure of such measures can be determined once the processes are completely implemented because a network's dynamic nature in inter-organizational network raises difficulties in coordination. Nevertheless, estimating the completion of network-wide objectives is still critical to network planning and design. Our theoretical calculations here can assist decision making for structural improvement plans. Moreover, the common features of the selected initiators are sufficient to suggest elements significant to attaining a synchronized response across and institutional network to reorganize research portfolio.

### 6. Conclusions

Public research institutions continue to gain prominence in the development national agendas of science and technology. Institutions have their own strategies according to their values and interests in research trends to a greater or lesser extent. Governments and research councils significantly affect these institutes through policies, programs, funding, and financial support in an effort to better coordinate their research agencies (Rammer, 2006). Therefore, guiding the subunits of these institutes in a network is important to efficiently deliver managerial control. In doing so, administrators should be concerned with improving network structure to enhance its outcomes. However, manipulating network structure is difficult because of complex and dynamic states of the sub-organizations. In this study, we quantified network structural efficiency to maneuver a set of spontaneous elements into network-wide goals by using the theory of structural controllability (Yuan et al., 2013), and tracked the efficiency of networks of these public research institutions: the GRIs in Korea, the NLs in the US, and the MPG. For the relevant calculations, we extracted a hidden network structure from each institution based on similarities between the profiles of their subordinate organizations. The results of structural efficiency enabled the assessment of the operational strategies of each institution for eighteen years.

The elements selected by structural controllability implied suitable points to inject external energy for governing networks. Revealing the injection points was important to prevent information blockages that hinder collective action. Apparently, the greater number of injection points required, the lesser the efficiency of network due to the increased burden of management. Our findings indicate that structural efficiencies reflect changes in research interests of an institution. In this sense, research institutions have the necessity to track the structural controllability to assess their structural changes, such as portfolio adjustments on all of sub-organizations. The structural controllability can also provide the suitable spots for an intervention by a network manager (ministries, research councils, or steering bodies) as driver nodes with regard to structural changes. According to our results, the proper intervention points tend to be with a low connectivity as well as young sub-organizations.

In spite of these implications for managing strategies of inter-organizational networks, this study has shortcomings that limit the generalizability of our findings. Scientific articles represent only part of an institute's capacity for research. Major scientific outputs are classified into two types: scientific articles and patents. Depending on the major research types, some institutes concentrate on patents instead of publications. As a result, research portfolios derived from richer data sources than were used would more precisely depict institutional research capacity. Another limitation of this study is that network properties other than those considered here, such as network density, clustering coefficient, and betweenness centrality, might affect structural efficiency like. Furthermore, our findings raised several questions that suggest directions for future research. These include exploring the range of drivers' influence on structural efficiency, determining the optimal network structure to steer, and investigating diverse network properties with other types of players in innovation systems, e.g., academia and industries.

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Hyeonchae Yang is a Ph.D. candidate of the Graduate Program for Technology and Innovation Management at Pohang University of Science and Technology, Republic of Korea.

Woo-Sung Jung is an associate professor of the Department of Industrial and Management Engineering and Department of Physics at Pohang University of Science and Technology, Republic of Korea.