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# A Study of RI Clusters Based on Symbiosis Theory

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**Abstract:** Research infrastructure (RI) refers to a large and complex science research facility or system that conducts top-level science activities. In recent years, there has been a tendency toward geographical concentration of RIs and formation of RI clusters. Some of these RI clusters have become engines for regional social and economic development. It turns out that RI clusters present a new stage for RI sustainable development. The present paper tries to study RI clusters based on symbiosis theory in order to build an analytical framework for policy makers' comprehensive understanding of RI clusters. Following the analytical framework, we study the symbiosis system and the symbiosis structures of an RI cluster by analyzing its major characteristics. In order to achieve a balanced symbiotic situation, a competitive model and a symbiosis model are proposed based on the Logistic Model. The analysis is grounded in the samples of China's typical RI clusters and other cases in the world to give a vivid and convincing illustration. During the analysis process, an RI cluster is regarded as a complex ecological system and the organization and management of units in the cluster is the focus of the study. The authors hope that the paper will supplement the existing literature, which mainly focuses on the technological problems and the evaluation of RI's socioeconomic effects, in the sense of a systematical analysis of the management problem of RI.

**Keywords:** RI; RI clusters; symbiosis theory; symbiotic units; competition; cooperation

## 1. Introduction

Research infrastructure, also known as Big Science or large science infrastructure, and RI for short, refers to a large and complex science research facility or system that conducts top-level science activities and is expected to make major breakthroughs at the frontiers of science and technology [1–4]. Currently, with the increasing importance of RI for spearheading science research and as an emerging source of innovation for economic development, RI has become the most cutting-edge scientific research platform due to its incomparable advantages [5–8]. Therefore, the number of RIs keeps increasing and more and more countries are tendingto build new RIs in one city or area to promote synergy between different RIs. RI clusters, as sustainable developing modes for RI, have emerged.

An RI cluster can be defined as an agglomeration of RIs and associated organizations in a well-defined and relatively small geographic area. It includes RIs, universities, research institutes, related companies, etc. Presently, some famous RI clusters in the world are the Paul Scherrer Institute (PSI) in Switzerland, Brookhaven National Lab in the USA, Grenoble in France, Harwell in England, etc. China is also entering a rapid developing period of RI clusters. The Pudong Innovation Campus of Shanghai initially formed an RIs cluster, in which RIs, such as the Shanghai Synchrotron Radiation Facility (SSRF) and the National Center for Protein Science Shanghai (NCPSS), play a key role; related universities, research institutions and industries cooperate together to establish an innovation ecosystem. From the experience of these RI clusters, the concentration of RIs brings new employment, capital, and new technology for start-ups and spin-offs. Through geographical concentration of innovation resources, RI clusters have become engines not only for regional social and economic development, but also for emerging national strategic industries.

As RI clusters present a new stage for the development of RI, some scholars have begun to focus on this phenomenon. However, existing studies mainly focus on the social impact of RI clusters and the measurement of their quantitative performance, and the research on the mechanism of an RI cluster, such as how it works, is relatively inadequate. Scaringella and Chanaron [9] pioneered the study of RI clusters by conducting an empirical study on GIANT model and Grenoble model, which revealed an RI-centered agglomeration phenomenon. This research is significant in the sense that it diversifies the existing researches from technology and efficiency centered research to a broader field such as the organization of an RI cluster.

An RI cluster is a multiple complex system and the units in the system interact with each other through material, knowledge, technology, talents, information and capital exchange. The organization and coordination of these units is vital for the efficiency of a cluster. The more complex the cluster's structure is, the more obvious it is. Therefore, as the scale of RI clusters becomes larger and the network density increases dramatically, the research on the organizational management has to be enhanced. In biology, symbiosis theory is used to explain the mechanism of the close and often long-term interaction between two different biological species. Although this symbiosis theory is based on a natural paradigm, it also can be employed to explain social phenomena. Since the middle of the twentieth century, symbiosis theory has been widely used in the field of economics. It describes how a network of diverse organizations share mutual resources and foster eco-innovation atmosphere to improve their ability and gain profits [10]. The present paper tries to apply the symbiosis theory to the study of RI clusters in order to build an analytical framework for policy makers to comprehensively understand RI clusters, which have already become important technological phenomena in the world and essential modes for RI's sustainable development. The rest of the paper is organized as follows. A literature review is presented in Section 2. In Section 3, we propose an analyticalframework. Following the analytical framework, we demonstrate the symbiosis system and the symbiosis structures of an RI cluster by analyzing its major characteristics and illustrating its features by examples from China, the USA, etc. In this section, symbiotic units and the structures and relationship between units are presented. In Section 4, we study the balanced condition of the symbiotic units based on the Logistic Model. Suggestions and relevant policies are given in the summary. The authors hope that this paper can providea fresh perspective for RI research and promote its sustainable development.

## 2. Literature Review

Nowadays, the measurement or assessment of the costs and benefits of RI clusters has received great attention from academic researchers. Different methods of scientometrics are employed to evaluate RI clusters. Hallonsten [6] proposed facility metrics to examine three quantitative performance measurements as technical reliability, competition for access, and publication records and weigh them against the investment on an RI cluster. Data from famous RI complexes, such as European Synchrotron Radiation Facility (ESRF) in Grenoble, France, the Advanced Photon Source (APS) at Argonne National Laboratory in Illinois, United States, and the Super Photon ring-8 GeV (SPring-8) in Harima, Japan were used for demonstration. With the deepening of the research, Hallonsten [11] employed cases of CERN in Geneva, ESRF in France and LCLS at SLAC in the USA, which are famous RI clusters in the world, and concluded that RI is very expensive and it is absurd to use publication counts as performance measurements for RI. The author's self-denial reveals the intrinsic property of RI as a complex system rather than a scientific project. Built on the apparent conflict ideas of pushing facilitymetric assessment of RI on the one hand and the unsuitabilityof simplified publication counts on the other, Heidler and Hallonsten [7] used more complex and nuanced measures such as impact factors, immediacy index and construction citation networks to evaluate the impact of RI clusters. In this research, through the construction of citation networks, both RI's role for promoting multidisciplinary and interdisciplinary research and its clustering effect have been further demonstrated. Florio and Sirtori [12] developed and presented a CBA model to analyze the socioeconomic impact of RI. The model took several factors into account, such as technological output of RI, knowledge creation and diffusion, publications, technological spillovers, human capital formation and cultural effect. Battistoni et al. [13], Evans [14], and Del Bo [15] used different RIs' data to examine the CBA model.

Besides the researches mainly focusing on models for evaluation, some researchers analyze RI clusters from an organizational management perspective. They began to notice the synergy effect between RIs and their surrounding organizations instead of just concentrating on different RIs in a cluster. Scaringella and Chanaron [9] conducted an empirical study on GIANT (including RIs, universities, and engineering and management schools) from aneconomic, social and entrepreneurial perspective. Based on the territorial models proposed by such geographical economists as Porter [16,17], Cooke [18], etc., the authors summarized various Territorial Innovation Models (TIMs): Italian industrial districts, innovative milieus, regional innovation system, new industrial spaces and regional clusters. Under the theoretical background of TIMs, the research compared the long-term investments with the socioeconomic and entrepreneurial returns of RI clusters with respect to budget, employment, and spin-off generation. The conclusion is that the investment in RI clusters is worthwhile and RIs as public resources are recommended to produce a clustering effect. The research also compared the GIANT model with the Grenoble model, which includes a broader range as suppliers and star-ups. This is the first paper that systematically analyzes RIs from aclustering perspective. Qiao [4] conducted an empirical research of nine RIs in China to analyze their scientific effects. Four typical scientific effects have been put forward: the science and technology advancement effect, capability cultivation effect, networking effect and clustering effect. In the analyses of the clustering effect, the authors illustrated the RI cluster ecosystem according to knowledge flow, in which RIs, research institutions, and companies are included. The authors maintained that the Pudong Innovation Campus in Shanghai, an RI cluster, is a relatively new phenomenon in China. How to enhance the interaction and coordination between RIs and organizations in the cluster is both a policy emphasis and research question for further study.

The evolution of the research on RI shows that studies have experienced a transformation from focusing on technology and output (technical reliability, competition for access and publication records) to a deeper and broader range, such as network effect, clustering effect, coordinated development and cultural spillover, etc. This change is the result not only of continuously deepened theoretical research, but also the requirement of RI development. However, on the whole, the extant literature about RI clusters has not been comprehensive, and is at the preliminary stage. Firstly, compared with the research on evaluation of RI clusters' socioeconomic returns, the research on the mechanism of a cluster is insufficient. What are the essential characteristics of RI clusters? How is the cluster organized? What is the key impact factor? Secondly, the existing research tends to treat a cluster as a whole and from a macro, external perspective. A deep, systematical and hierarchical analysis of the cluster from a micro and in-depth perspective is needed. Thirdly, as a newly developing stage for RI, the fostering environment, background and internal structure of an RI cluster are different from traditional industrial clusters as well as general scientific project. Therefore, traditional research theory and method are not enough for a comprehensive interpretation of RI clusters. A new theoretical framework has to be explored. But so far now, there is still a blank.

The present paper regards an RI cluster as an open system and a typical ecosystem. As symbiosis theory has become an emerging and hot issue in the fields of economics and management in recent years, we try to use symbiosis theory from an inner perspective to analyze the symbiosis structure and relationship between symbiotic units in an RI cluster and study the coexistence between symbiotic units in order to solve the problem of resource allocation for the steady development of RI clusters.

## 3. Analysis Framework and a Symbiosis System Analysis

Since the mid-20th century, symbiosis theory has been applied in social science. The application of symbiosis theory in management was initiated in the study of industrial clusters. During the development of RI, the emergence and evolution of RI clusters are similar to that of the industrial clusters. The formation of an RI cluster starts from the selection of a symbiosis development mode. Organizations exist in the cluster as symbiosis units and they cooperate and compete with each other through rational division of different tasks to achieve a synergy effect and co-evolution. This symbiotic evolution process of a cluster can be summarized and demonstrated as per Figure 1. Following this analysis framework, the symbiosis system of an RI cluster will be studied.

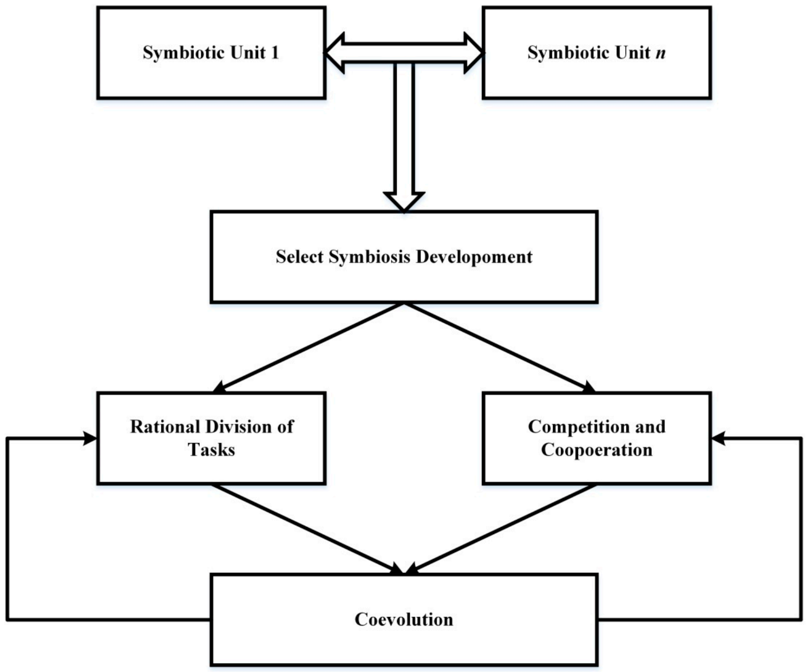


**Figure 1.** Analysis framework.

Although clustering is a developing trend for RIs, it is not a necessary step. Some RIs may evolve in a cluster, while others may not. RIs differ in their functions, existing forms and scientific objectives. Accordingly, they are mainly divided into three types. The first type is called dedicated RIs, such as the Large Collider and the Astronomical Telescope, which have a strong specialty background and serve a single discipline for basic research and applied research. The second type is public experimental RIs. They are platforms for multidisciplinary and interdisciplinary research and support for various kinds of studies. The Radiation Synchrotron, the High Magnetic Field Facility and the Spallation Neutron Source belong to this kind of RI. The third type of RI refers to those RIs aiming at providing scientific data and service for the public and which are thus called public-interest RIs. The Human Genome Project can be categorized as the third type. For these three types of RIs, some of them have a strong specialty and do not fit for clustering development by forming an upstream and downstream relationship with surrounding organizations. For example, the Five-hundred-meter Aperture Spherical Radio Telescope (FAST) is put in use recently in China. FAST has a specific requirement for construction conditions and locations. It is located in Buyi and Miao Autonomous Prefecture of Qiannan in Yunnan Province, a relatively isolated location, because the Karst depression is very suitable for FAST as it is large enough to host the 500-m telescope, deep enough to allow a zenith angle of 40 degrees and let the rain penetrate easily to avoid damage from corrosion. Due to its unique specificity, FAST forms an independent operational system by itself. Therefore, for such RIs, a clustering developing mode does not work.

Aside from such RIs as FAST RIs, for most RIs, especially for public experimental RIs, an RI cluster is a preferable mode. The present paper focuses on those RIs that can evolve in a cluster. They usually have a strong multidisciplinary and interdisciplinary background and can support various scientific research. It is their users from different disciplines that promote the mutual interaction and infiltration between RIs in a cluster, and through regional resource sharing they exert a synergy effect on the development of hightech. Many research institutions with RIs have evolved from the original single discipline into a multidisciplinary research center, from those only engaging in basic science research into both basic and advanced applied research. The change is due to the construction and gathering of RIs, which further develops into an RI cluster. For example, Grenoble in France has RIs such as the neutron reactors in cooperation with Germany in Institute Laue Langevin (ILL) and the European Synchrotron Radiation Facility (ESRF). Both of them can be used as important platforms for the research of structural biology. Therefore, the France Substation of European Molecular Biology Laboratory (EMBL) and Institute of Structural Biology (IBS) together with ESRF and ILL established a localized clustering relationship called PSB (Partnership for Structural Biology). Five enterprises surrounding them also engaged in the cooperation. In essence, it is the typical biological features of the RI cluster that promote those research institutes and enterprises to establish new social ties which have evolved into a symbiotic relationship in order to make breakthroughs in related technology fields and form an innovative industry chain from basic research to consumer products. Therefore, we present the symbiotic units and symbiotic structures of an RI cluster by analyzing features of RI clusters.

### *3.1. Feature-Induced Symbiotic Units*

An RI cluster has conspicuous and unique characteristics of its own. Because RIs which are the main units of a cluster are usually very complex, high-tech systems and have a high integration degree, the construction and running of an RI cluster involve long industrial chain, and require high levels of industrial processing ability and special material production ability for supporting industries. It also needs large investment and a certain scale of supporting team. These features can be divided into three aspects: technology intensive, mental labor intensive and capital intensive. They exert an important influence on the development and management of an RI cluster.

(1) Technology-intensive

The technology-intensive aspect is embodied in concentration on a number of advanced scientific and technological achievements in an RI cluster. As the construction, maintenance and upgrading of RIs have been continuously carried out, an RI cluster is a system of highly integrated technology, with a wide range of industrial relevance. An "integrated manufacturing model", which promotes a decentralized specialization production process guided by "intermediate product", is generally adopted by RIs in a cluster. Technology division in such a process is obvious, and as a result, the split and outsourcing of the non-core business is very common. For example, the construction of SSRF, a representative RIs in the Pudong Innovation Campus of Shanghai, includes many integrated systems that stimulate the development of modern high performance accelerators, advanced electrical technology, ultra-high vacuum technology, high precision machining, X-ray optics, fast electronics, automatic control technology of large systems and high stable construction technology. Most of these technologies become new directions of the market and industry in China. The micro fabrication technology based on the third generation synchrotron radiation source has become the main supporting technology for the development of micro-electronic mechanical industry. To some extent, the construction and running of an RI cluster is a high-tech integrated process and makes the RI cluster into the innovation source of modern industry.

The technology intensive of an RI cluster is also reflected in its technology spillover effect. Relying on RIs in the cluster, important scientific discoveries continue to emerge, with the revolutionary technology innovation produced, many of which have been transferred to industry. Take SSRF as an example; it has become an irreplaceable and comprehensive research platform for a large amount of research on life science, material science, environmental science, earth science, physics, chemistry, information science, as well as an important means of development of microelectronics, pharmaceutical, new materials, biological engineering and fine petrochemical industry. For the past decade, there has been a few medicine and new materials enterprises built around the SSRF with high technical threshold. Thus, the symbiotic units of an RI cluster should include a supply system consisting of a series of institutes and enterprises which provide raw materials and "intermediate products" and an application system consisting of technology-derivative enterprises.

(2) Mental labor-intensive

When constructing and operating such a complex, giant system as an RI cluster, a personnel team of a certain scale must be organized. They have to conduct long-term research and reach a large number of breakthroughs to reduce the technical risks and formulate the scheme. In particular, the construction and operation of RIs in the cluster need a batch of versatile talents such as scientists and those who have skills in management. It also needs an engineering team covering extensive fields and possessing key problem tackling ability. The institutes and universities are major sources of these talents. The Brook Brookhaven National Laboratory (BNL) of United States has more than 4000 visiting personnel a year. Some of RIs are even directly run by the surrounding universities. Among the U.S. Department of Energy's 17 National Laboratories, 8 are managed or co-managed by first-class universities. For instance, Argonne National Laboratory is managed by the University of Chicago, and Laurence Berkeley National Laboratory by University of California, Berkeley. Thus, an RI cluster has a highlighted characteristic of being mental labor-intensive. Universities and research institutes have become an important source of various professional talents, and finally form a symbiotic relationship through the exchange of knowledge, technology, human resources and information with the whole system.

(3) Capital-intensive

The capital-intensive aspect of an RI cluster is manifested in such issues as one-time investment in fixed assets, long construction cycle (generally about 10 years) and the long investment recovery period. The core mission of an RI cluster is to enhance the national basic scientific research and original innovation ability through major breakthroughs in science principles and core technology; the purpose is to satisfy the significant demand of the long-term development target of the country, and its organization system fully reflects the layout of the national innovation strategy system. These properties determine that the main source of funding for an RI cluster is government. Since the end of the last century, the United States, Britain, Germany and other major advanced country have had a tendency toward abundant and stable investment in RIs. Taking the United States as an example, Table 1 shows the input of the Department of Energy (DOE), the National Science Foundation (NSF) and the National Institute of Health (NIH) from 2004 to 2007. The data are from American Association for the Advancement of Science, the annual budget request report of DOE and NSF. These three departments' investment in RIs accounted for 1.86% of the total R&D investment of the government, and accounted for 1.84/10,000 of GDP.

In addition to government support, social forces are also involved in the construction and operation of an RI cluster. Taking synchrotron radiation source as an example, PSI, Spring8 and SSRF all have beam line stations financed by companies. Britain's Harwell campus has constructed a few RIs through the government, non-government, international financing and other approaches. The British government announced $1.9 billion's investment in the development of a number of major RIs in 2010. Britain's famous synchrotron radiation source Diamond also receives 14% of the investment from charitable donations. As a result, government agencies, non-governmental organizations, financial institutions and other investment agencies can be deemed to be the promoting system of an RI cluster.

**Table 1.** Investment in RIs by the US government (billions of dollars).

| | 2004 | 2005 | 2006 | 2007 (Budget) |
|---|---|---|---|---|
| R&D investment of government [19] (GDP%) | 126.32 (1.08) | 131.29 (1.06) | 134.47 (1.04) | 136.89 (1.02) |
| DOE's investment in RIs [20,21] | 1.424 | 1.496 | 1.480 | 1.868 |
| NSF's investment in RIs [22,23] | 0.872 | 0.753 | 0.829 | 0.900 |
| NIH's investment in RIs [24] | 0.119 | 0.179 | 0.030 | 0.025 |
| Total | 2.415 | 2.428 | 2.339 | 2.793 |
| Total/R&D investment of government | 0.191 | 0.185 | 0.175 | 0.204 |
| Total/GDP | 2.06/10,000 | 1.96/10,000 | 1.82/10,000 | 2.08/10,000 |

Note: DOE's investment data only involve the RIs managed by the Office of Science, excluding national security and energy related research infrastructures.

### *3.2. The Symbiosis System of an RI Cluster Based on Cooperation and Division of Labor*

According to the characteristics of an RI cluster, a core system and four auxiliary systems form symbiotic units in the symbiosis system of an RI cluster (see Figure 2). The core system includes various RIs; through the internal division of labor and cooperation, these RIs become innovation sources of each system. The enterprises and other suppliers which produce raw materials and intermediate products constitute a supply system. They often provide a lot of high-tech service. The application system consists of technology-derivative companies, start-ups and spin-off companies which directly or indirectly use the scientific and technological achievements of RIs in the core system of a cluster. Universities, research institutes and transfer platforms form a cooperation and support system that is most closely linked to the core system. They are not only the source of talents, but also major users. R&D and transformation platform is an important intermediary for the transformation of scientific and technological achievements produced by RIs in the core system. Government agencies, non-governmental organizations and financial institutions become the promotion system, which ensures the funding and policy of an RI cluster.

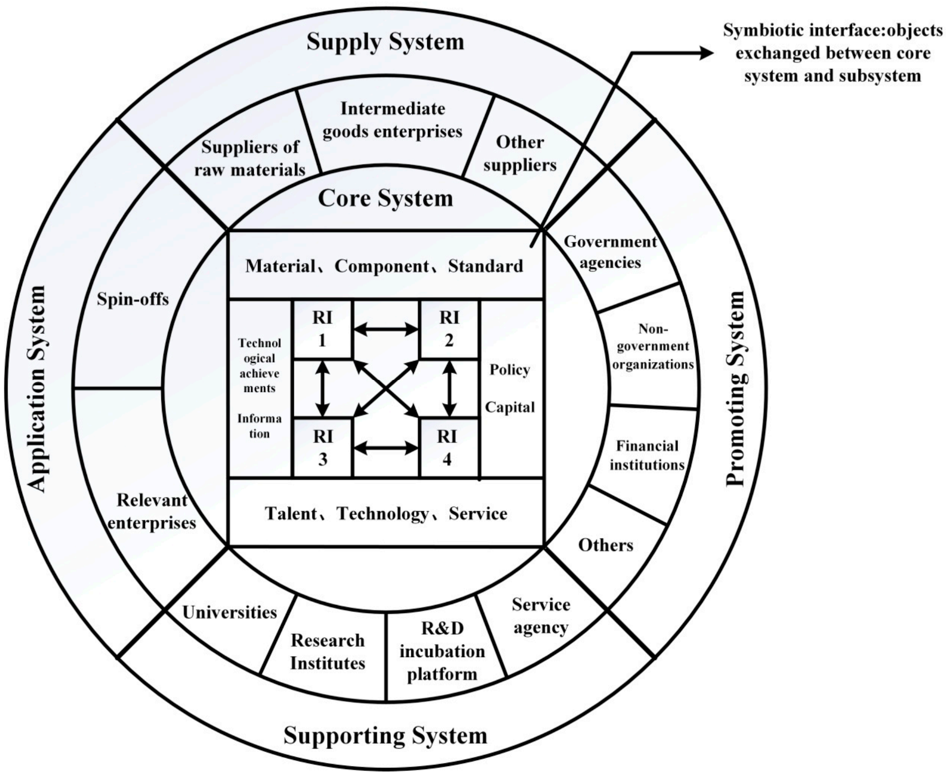


**Figure 2.** Symbiosis system of an RI cluster.

In an RI cluster, the exchange objects between core system and each subsystem include materials, components, "intermediates", standards, policy, capital, talent, technology, service, technology, information and so on. They form an interaction interface in the exchange process. Through the interface, symbiotic units in the system follow the interdependent organizational principle aiming at the maximum benefits of the whole symbiosis system. The most important thing for an RI cluster is not each symbiotic unit, but the cooperation relations between individuals. The various systems in Figure 2 have a dialectical relationship of competition and cooperation, being independent from each other and interdependent upon each other. Although cooperation is the first significant feature of this symbiosis system in Figure 2, the competition also exists in the system objectively. However, the competition is not a substitution, rejection of symbiotic units for each other, or disappearance of the characteristics of symbiotic units, but a supplement to and promoting force for symbiotic units, and an inheritance of its own characteristics. This is also the focus of the next section.

## 4. Symbiosis Equilibrium for a Co-Existing Competition and Cooperation RI Cluster

The symbiosis system of an RI cluster is similar to that of an ecosystem. The members in a cluster depend on each other and compete and co-evolve with each other. Although cooperation is one of the main common characteristics of the symbiosis system, competitive relations still occupy an important position inside a symbiotic unit, between different symbiotic units, and even between heterogeneous symbiotic units. This co-existing cooperation and competition relationship is most obvious in the core system. RIs with different disciplinary backgrounds cooperate with each other for interdisciplinary and multidisciplinary achievements, but they also compete with each other for common resources. As shown in Figure 2, RIs in the core system share the same subsystems. They may have the same material or component supplier, the same university or research institute as main user, and even the same source of funding. They compete for the limited resources of capital, talents, etc. In the core system in Figure 2, the arrows show the cooperation and competition relationship between RIs. As the core system is the most important part in the whole cluster and the innovation source of this symbiosis system, the stability of the core system matters the whole. In addition, the relationship between units in the core system is representative and can be popularized for other units. Therefore, in this section, we focus on the competition and cooperation relationship of the core system.We intend to explore how to allocate resources to maximize RIs' impact on the one hand, and on other hand, how to achieve a state of symbiosis equilibrium between symbiotic units. The Logistic Model is employed to illustrate competition and symbiotic state of the members in the core system by assuming that in a certain period, resources in the environment are limited and exclusive.

The Logistic Model expressed as below is a classical population evolution model based on exclusive resource consumption.

$$\frac{dN}{dt} = aN_t$$

### 4.1. A Competitive Model

In a cluster, suppose there are n RIs. $S_i$ is a specific RI. $S_i$ and $S_j$ share some resources, and have some common users and suppliers. Resource utilization ratio of $S_i$ is $P_{ir}$. $S_i$ and $S_j$'s niche overlap value is assumedto be $\alpha_{ij}$.

$$\alpha_{ij} = \frac{\sum_{r=1}^{R} P_{ir} P_{jr}}{\sqrt{\left(\sum_{r=1}^{R} P_{ir}\right)^2 \left(\sum_{r=1}^{R} P_{jr}\right)^2}} \tag{1}$$

Niche overlap value $\alpha_{ij} \in [0,1]$. If $\alpha_{ij} = 0$, it means that $S_i$'s ecological niche are completely separate from $S_j$. If $\alpha_{ij} = 1$, two RIs ecological niches overlap completely. $0 < \alpha_{ij} < 1$ means that niches are not completely separate, and there is some overlap in resource use. $\alpha_{ij}$ is proportional to the competition intensity of RIs in a cluster, and it reflects the competition pressure brought by niche overlap.

We suppose there are two RIs, $S_1$ and $S_2$ in the core system of a local cluster. The niche width of $S_1$ and that of $S_2$ at time t are respectively $N_1(t)$ and $N_2(t)$. The natural growth rate of $S_i$'s niche width is $r_i$. There is a niche saturation value $K_i$. The competition model between $S_1$ and $S_2$ is as follows:

$$\begin{cases} \frac{dN_1(t)}{dt} = r_1 N_1(t)\left[1 - \frac{N_1(t)}{K_1} - \alpha\frac{N_2(t)}{K_2}\right] \\ \frac{dN_2(t)}{dt} = r_2 N_2(t)\left[1 - \frac{N_2(t)}{K_2} - \alpha\frac{N_1(t)}{K_1}\right] \end{cases} \tag{2}$$

When RIs in a cluster reach a steady state, the change rate of their niche width is zero.

$$\begin{cases} \frac{dN_1(t)}{dt} = r_1 N_1(t)\left[1 - \frac{N_1(t)}{K_1} - \alpha\frac{N_2(t)}{K_2}\right] = 0 \\ \frac{dN_2(t)}{dt} = r_2 N_2(t)\left[1 - \frac{N_2(t)}{K_2} - \alpha\frac{N_1(t)}{K_1}\right] = 0 \end{cases} \tag{3}$$

Solving the above equations, points of equilibrium of the RIs niche width are (0, 0), ($K_1$, 0), (0, $K_2$) and $\left(\frac{K_1}{1+\alpha}, \frac{K_2}{1+\alpha}\right)$.

If $\alpha_{ij}$ = 0, the equilibrium points are (0, 0), ($K_1$, 0), (0, $K_2$) and ($K_1$, $K_2$). At those points, $S_1$'s ecological niche separates completely with $S_2$. There is no overlap between their niches and the competitive relationship does not exist between them. RIs in a cluster separately possess their own niche width and development environment. Their evolution processes respectively follow the law of their own until they fully utilize their regional ecological resources and their niche widths reach saturation value ($K_1$, $K_2$). At these points, the niche width of RIs in a cluster achieves relative balance. RIs use different resources and are able to coexist with each other.

When $0 < \alpha \leq 1$, the niche widths of $S_1$ and $S_2$ have some overlapping area. By solving Equation (3), we get the equilibrium points as (0, 0), ($K_1$, 0), (0, $K_2$) and $\left(\frac{K_1}{1+\alpha}, \frac{K_2}{1+\alpha}\right)$. At these points, competitive relationship exists between these RIs. They own some common resources and the evolution of their niche widths depends on their ability to compete with each other. RI, which has competitive advantages, will exclude the less competitive one from niche space and finally reach a stable state. If the competitive ability difference betweenthe two RIs is very prominent, one of them will occupy the entire niche space and the other will disappear from the niche space. Their niche widths tend to be ($K_1$, 0) or (0, $K_2$). If RIs' competitive ability is comparable, they will divide the regional resources equally and the niche width tends to be $\left(\frac{K_1}{1+\alpha}, \frac{K_2}{1+\alpha}\right)$.

### *4.2. A Symbiosis Model*

The above model describes the competitive relationship between RIs in a cluster. It can be used to allocate resources for RIs in order to reach a balanced condition in the core system and eventually enhance the stability of an RI cluster. But besides competition, we also want RIs to cooperate with each other to generate more outcomes and interdisciplinary achievements. Therefore, we also develop a symbiosis model to study the cooperation relationship of RIs. $E_i$ (t) is the output effect of an individual RI. $\frac{dE_i(t)}{dt}$ is the changing rate of $S_i$'s output effect at time t. There is a natural growth rate for the output effect for RI and it is assumed to be $\gamma_i$. Saturation value is $Q_i$. If $S_i$ can promote the outcome of $S_j$, there is an influence coefficient $\beta_{ij}$ ($0 \leq \beta_{ij} < 1$). The symbiosis model between two RIs, $S_1$ and $S_2$, is as follows:

$$\begin{cases} \frac{dE_1(t)}{dt} = \gamma_1 E_1(t)\left[1 - \frac{E_1(t)}{Q_1} + \beta_{12}\frac{E_2(t)}{Q_2}\right] \\ \frac{dE_2(t)}{dt} = \gamma_2 E_2(t)\left[1 - \frac{E_2(t)}{Q_2} + \beta_{21}\frac{E_1(t)}{Q_1}\right] \end{cases} \tag{4}$$

If RIs in the core system reach a steady state, their outputs increase at a fixed rate and the change rate of output effect is zero.

$$\begin{cases} \frac{dE_1(t)}{dt} = \gamma_1 E_1(t)\left[1 - \frac{E_1(t)}{Q_1} + \beta_{12}\frac{E_2(t)}{Q_2}\right] = 0 \\ \frac{dE_2(t)}{dt} = \gamma_2 E_2(t)\left[1 - \frac{E_2(t)}{Q_2} + \beta_{21}\frac{E_1(t)}{Q_1}\right] = 0 \end{cases} \tag{5}$$

Solving the above equations, points of equilibrium of the RIs output effect are (0, 0), ($Q_1$, 0), (0, $Q_2$), $\left(\frac{1+\beta_{12}}{1-\beta_{12}\beta_{21}}Q_1, \frac{1+\beta_{21}}{1-\beta_{12}\beta_{21}}Q_2\right)$.

If $\beta_{12} = 0$, $\beta_{21} = 0$, the equilibrium points are (0, 0), ($Q_1$, 0), (0, $Q_2$) and ($Q_1$, $Q_2$). Like the situation in the competitive model, at those points, $S_1$'s ecological niche is completely separate from that of $S_2$. There is no symbiotic relationship. RIs in a cluster produce their output respectively and evolve according to a law of their own until their output effects reach saturation value ($Q_1$, $Q_2$). That is to say, there is no interaction between RIs and if they are located separately, the output will be the same.

If $\beta_{ij} = 0$, $0 < \beta_{ji} < 1$, there is an asymmetrical symbiotic relationship between $S_i$ and $S_j$. $S_j$ benefits from $S_i$, but $S_i$ gets neither benefits nor harm. By solving the Equation (5), equilibrium points are (0, 0), ($Q_1$, 0), (0, $Q_2$) and ($Q_i$, $(1 + \beta_{ji})Q_j$). The output of $S_i$ and $S_j$ tends to be ($Q_i$, $(1 + \beta_{ji})Q_j$), and it depends on saturation value of each RI and the influence coefficient of $S_i$ on $S_j$.

When $0 < \beta_{ij} < 1$, $0 < \beta_{ji} < 1$, $S_i$ and $S_j$ benefit from each other. The output of $S_i$ and $S_j$ tends to be $\left(\frac{1+\beta_{12}}{1-\beta_{12}\beta_{21}}Q_1, \frac{1+\beta_{21}}{1-\beta_{12}\beta_{21}}Q_2\right)$ and there is a mutual benefit symbiotic relationship between them. RIs contribute to the output of each other. The cooperation relationship improves the productivity of individual RI and eventually symbiosis equilibrium can be achieved.

### *4.3. Empirical Analysis*

Based on the above models, we take an RI cluster in Hefei of China as an example to make a symbiotic analysis. Hefei is another emerging city with an RI cluster like Shanghai. It has an RI-intensive region, where RIs such as the Experimental Advanced Superconducting Tokamak (EAST), the Hefei Synchrotron Radiation Facility (HSRF) and the Steady High Magnetic Field Facility (SHMFF) are located. HSRF and SHMFF are chosen as two symbiotic units because both of them are public experimental RIs which as described in Section 3 are most likely to form a cluster and they share some resources and some common users and suppliers. Data come from the Chinese Academy of Sciences Large Research Infrastructures Annual Report 2012 and 2015. The data in 2013 and 2014 are not included, because the HSRF was shut down for maintenance and reconstruction in 2013 and 2014.

In order to simplify the model, we suppose that the influence coefficient $\beta_{ij}$ between HSRF and SHMFF are the same, that is $\beta_{HSRF-SHMFF} = \beta_{SHMFF-HSRF} = \beta$. The formula for estimation of β is as follows:

$$\beta = \frac{\sum_{r=1}^{R} P_{ir}P_{jr}}{\sqrt{\left(\sum_{r=1}^{R} P_{ir}\right)^2 \left(\sum_{r=1}^{R} P_{jr}\right)^2}} \tag{6}$$

Output ratio of $S_i$ is $P_{ir}$.

The data of Table 2 are used in Formula (6). $\beta^{2012} = 0.84$, $\beta^{2015} = 0.80$. Solving the Equation (5), the points of equilibrium of the RIs' output in 2012 are (0, 0), ($Q_1$, 0), (0, $Q_2$), ($6.25Q_1$, $6.25Q_2$) and in 2015, they are (0, 0), ($Q_1$, 0), (0, $Q_2$), ($5Q_1$, $5Q_2$).

From the above results, we could see that NSRF and SHMFF benefited from each other in both 2012 and 2015 and there is a mutually beneficial symbiotic relationship between them. That is to say, they contribute to the output of each other and the productivity of individual RI has been improved by the cooperation and eventually form a balanced symbiotic situation. But their symbiotic relationship is changing all the time. The best equilibrium points of the RIs output tends to be ($6.25Q_1$, $6.25Q_2$)

in 2012, but ($5Q_1$, $5Q_2$) in 2015. The reason may be that some changes have taken place in their symbiotic structures.

**Table 2.** RI-related output ratio.

| Year | RI | Ratio of Completed Research Grants | Ratio of SCI Indexed Papers | Ratio of Academic Papers | Ratio of Staff | Ratio of Students |
|---|---|---|---|---|---|---|
| 2012 | HSRF | 37% | 59% | 63% | 55% | 82% |
| | SHMFF | 63% | 41% | 37% | 45% | 18% |
| 2015 | HSRF | 36% | 47% | 21% | 50% | 71% |
| | SHMFF | 64% | 53% | 79% | 50% | 29% |

Source: Chinese Academy of Sciences Large Research Infrastructures Annual Report 2012 and 2015, through the authors' calculation. Note: the authors consider the output of HSRE plus that of SHMFF to be 100%.

Therefore, through the application of the symbiotic model, we found that the symbiosis system of an RI cluster is always changing. By calculating the influence coefficient and solving the equations, equilibrium points can be acquired. This not only helps policy makers and operators of RI clusters to seek a stable symbiotic condition for RIs in a cluster, but also demonstrates the change of the symbiotic relationship between symbiotic units and provides a path for further exploration of the symbiotic structure changes which will result in symbiotic benefits. Because the running budget for an RI cluster is now mainly from government funding, the competitive relationship between symbiotic units in an RI cluster is not significant. Thus, only the symbiotic model is examined in the empirical analysis, but the authors believe that with the development of RI clusters and with the already existing trend of diversified investment for RIs cluster, competition will be increasingly apparent. In this paper, the models are meant to provide a research method and research perspectives.

## 5. Conclusions

Our research contributes to the existing literature by using symbiosis theory to study the organization and management of an RI cluster. Firstly, the paper gives a fresh perspective on the research into RI by focusing on the organizational management of RI clusters. The characteristics of RI clusters show that clustering development is the inevitable trend for most RIs, especially for public experimental RIs. In this process, the organizational structure within a cluster and the relationship between the internal and external systems not only become the important factors influencing the socioeconomic returns of an RI cluster, but also serve as important components for the cluster. That is to say, the operational process and the management of an RI cluster are as important as the technical aspect of RIs and cannot be separated and ignored. In addition, due to RIs' widespread adoption of an "integrated construction mode", an RI cluster has a high integration degree, a long related industrial chain and a high level of asset specificity. Therefore, compared with other scientific and technological projects or industrial projects, the socioeconomic effect of an RI cluster will be maximized if a corresponding management system and reasonable organizational structure are applied to coordinate the units in the cluster to a state of symbiosis.

Secondly, based on symbiosis theory, the paper probes the structures of an RI cluster and studies the relationship between symbiotic units. A symbiosis system of an RI cluster is provided. It is a complex ecosystem with a core system and four sub-systems. Five systems as symbiotic units cooperate and compete with each other. RIs constitute the core system of an RI cluster. The supply system includes enterprise and suppliers of raw materials and "intermediate goods". Universities, research institutes, and an R&D incubation platform form a supporting system. The system of application consists of start-ups, spin-offs and relevant enterprises. Last but not least, an important system is the promotion system composed of government agencies, non-government organizations and financial institutions, etc.

Thirdly, the present paper studies the governance of symbiotic units. Materials, components, technology, talents, capital, etc. are exchanged between symbiotic units in the core system and subsystems, and even inside the subsystem, and form a symbiotic interface. Following the principle of autonomous organization, the symbiotic units develop a co-existing competitive-while-cooperative, independent-while-interdependent relationship. This relationship is in a state of constant change. As the mutually beneficial relationship between symbiotic units in a cluster justifies the essence of an RI cluster, we proposed a competitive model and a symbiosis model based on the Logistic Model and obtained stable symbiotic conditions for RIs in the core system of a cluster to achieve a state of symbiotic equilibrium. Because the relationship between RIs in the core system is representative and can be popularized for other units, the models we proposed can be applied to the whole system.

From a policy perspective, this study may suggest several implications for RI planning. Firstly, promoting a more sustainable pattern of RI development is crucial for maximizing the socioeconomic effect of RIs. At present, the construction of RI clusters has become an important way for countries to cultivate innovation capacity and increase competitiveness. RI clusters' operational process and management deserve great attention. Secondly, when the layout of an RI cluster has been considered, the characteristics of RIs, the coordination between RIs, industry, education, financial institutions, and the symbiosis relationship between different units have to be taken into account in advance. As policymakers decide how many resources are allocated for each unit in the cluster, the problem of excessive competition has to be avoided and cooperation between units in an RI cluster has to be enhanced to achieve a state of symbiotic equilibrium.

This paper has theoretical and realistic significance in enriching the mechanism of RI study, expanding these research fields and promoting sustainable development of RI. In future research, more empirical evidence and more data could be utilized, through which RI clusters could be better understood.

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