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Assessing the Dual Innovation Capability of National Innovation System: Empirical Evidence from 65 Countries

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Abstract: Open innovation has drawn significant attention over the years, and there is a growing body of literature that highlights the importance of considering this phenomenon at the national level. Less appreciated, however, is the radiative capability of national innovation systems (NIS) and the linking inbound and outbound processes. We provide a measurement of the dual innovation capability (DIC) of NISs based on process-oriented concepts by using a multi-indicator approach, which provides a more comprehensive picture of sectoral NISs compared to currently used metrics. To assess the DIC of NISs, a composite weighting method was used to obtain the score of our selection of 65 countries. The results show the spatio-temporal evolution of DIC from 2010 to 2018 and explore the interactions among sub-elements within the framework. The 65 countries were grouped into 4 categories based on the sub-dimension scores, and we provided 3 possible paths that can be chosen to improve DIC. The index provides a powerful tool to enrich research on innovation systems, guide national positioning, and optimize policies.

Keywords: dual innovation capability; process-oriented; open innovation; national innovation system; composite indicator

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1. Introduction

With the increasing competition of global science and technology, more countries are enhancing their innovation performance to achieve high-quality economic development [1]. Cooperation among different innovation actors of various countries and regions has effectively improved innovation efficiency [2]. A variety of innovation indexes have been proposed to evaluate innovation capability and the effectiveness of governments' interventions in the field of innovation at national or regional scales [3–5]. However, the evaluation framework is worth considering in terms of different innovation stages and its internal structure. With the introduction of the national innovation system (NIS) in the late 1980s [6], a systematic perspective for measuring national innovation capability was provided [7–10], which was initially proposed as a concept for explaining the technological, economic, social and institutional dimensions of innovation in the context of advanced countries [11]. The factors that drive the improvement of innovation capabilities come from the inside and outside of the NISs and play different roles at different development stages of innovation. Academics and policymakers continue to seek better methods for evaluating national innovation capability.

Deepening economic globalization affects the development of NISs, making them more collaborative and open [12], and strengthens the interaction between different countries [13]. The profound changes that have taken place in the international system have created a novel scenario with new rules, trends, patterns and a global structure [14]. Many existing innovation evaluation indexes [15,16] are not fully adequate for measuring national innovation capability because they cannot simultaneously reflect the internal development capability (IDC) and external exploitation capability (EEC) of a NIS. The improvement of national innovation capability depends not only on the capability of a NIS to create and commercialize knowledge and technology within a country, but also on its capability to absorb and radiate knowledge and technology through a global innovation network [17]. The literature usually assumes that a country's innovation capability relies solely on internal factors while neglecting external sources of supplementary internal knowledge [18–20]. In order to remain invincible for a long time, innovation systems must carry out two kinds of innovation activities at the same time (i.e., dual innovation) [21].

Duality theory [22] introduces the exploitation and exploration of two innovation modes into the research on enterprise innovation capability [23]. Exploitation innovation uses existing resources for adaptive adjustment, and innovation and innovation effects have certain limits. Exploration innovation achieves continuous iterative renewal of products and technologies but can easily result in errors [24]. Due to the limited resources and techniques of most countries, dual innovation needs to be embedded in open innovation to stimulate its effectiveness. From the perspective of open innovation, scholars began to pay attention to the externality of dual innovation, and the exploration and exploitation, as well as the concept and connotation of DI, continued to evolve and expand.

The openness perspective has revealed a different way of thinking about innovation and provides a new scenario of thinking about NISs as participants in the global innovation network. Successful innovation today is considered more the product of a network of actors than individuals or organizations alone [18,25]. Although the concept of open innovation provides a basis for the NIS to capture EEC, empirical studies on the evaluation of open innovation are currently insufficient. As AB Santos [26] points out, most literature focuses on this issue at the micro-level (e.g., enterprises or sectors) rather than from a national perspective [27–29]. Such literature evaluates open innovation capability from the perspective of external absorption of the innovation system [30].

The two approaches of knowledge and technology acquisition and external acquisition and internal integration have positively affected the development of exploration innovation and exploitative innovation, respectively, to different degrees [21]. The absorptive capability and radiative capability of a NIS are two aspects of EEC, which promote each other in the dual innovation process. The knowledge and technology flow of the inward-oriented (absorptive) capability and outward-oriented (radiative) capability constitute a complete process of innovation in a NIS. The EEC has become a powerful tool for acquiring new ideas and technologies, which, in turn, serve as the basis for the value creation process applied in a local country [30,31], and researchers have paid increasing attention to this process. However, existing studies ignore the interactive process of the two aspects of innovation elements, leading to incomplete and inaccurate evaluation of NISs.

In addition, an increasing number of studies (e.g., National innovation systems-analytical concept and development tool; What we should know about regional systems of innovation; Modeling the relative efficiency of national innovation systems) shows that it is more meaningful to explore trajectories of innovation within a system framework. Prior studies [32] have shown that the regional heterogeneity of innovation capability is closely related to the change in the regional innovation environment. Since innovation is a multi-stage process including a collective interaction of multiple actors, the evaluation of national innovation capability should consider the innovation environments in the different stages. However, most of the innovation evaluation studies use a "black-box" framework, which is not consistent with the theory that innovation is a multi-stage sequential process [31]. Through proactive behaviours such as knowledge acquisition and knowledge integration, the innovation system transfers valuable innovative knowledge to the knowledge creation link. After completing the "chemical reaction" in this process, the knowledge is used for dual innovation [21]. Most studies give less consideration to the complexity of innovation elements in the transformation process of knowledge to revenue in a NIS. An integrated approach to managing the innovation process is required to better understand the interaction between a NIS's activities.

As mentioned above, an abundance of research has been carried out on national innovation systems and dual innovation, but there are still many areas worth exploring that need further in-depth research. First, most of the dual innovation studies originate from enterprises, and there is not enough research on dual innovation at other levels, especially at the level of NISs. Second, the openness perspective has revealed fresh insights about innovation, while existing studies of dual innovation mainly focus on inward-oriented open innovation and ignore another important dimension—outward-oriented open innovation. Dual innovation should be encapsulated in the concept of openness, which is two-way (inbound and outbound) and interactive. A NIS evaluation framework that considers both absorptive capability and radiative capability needs to be developed. In addition, as a country's long-term capability to produce and commercialize new-to-the-world technologies [32], the multi-stage process of national innovation capability also deserves more attention. Although several past studies have conducted theoretical analysis on the characteristics of NISs, perhaps for methodological reasons, there is insufficient process-oriented empirical research on the innovation process [33]. The overall capability in the innovation process is obtained from the innovation capability of all sub-processes, and thus, it is necessary to set up the stage capability index based on the innovation process [34,35].

We address the gaps mentioned above by providing a framework of dual innovation capability (DIC) from a systemic perspective to represent the IDC and the external exploitative capability, including the aspects of both absorptive capability and radiative capability. This framework can be used to assess the DIC of a NIS and encourage better data collection to strengthen future iterations of the index. We try to introduce a measurement tool based on the innovation process (scientific research, SR; and technology transfer, TT), which enables the DIC framework to analyze innovation performance from different innovation stages and different sources of innovation elements. Using this framework, we develop and assess the DICs based on data from 65 countries as shown in Appendix A for which reliable information is available. By comprehensively evaluating the DIC of NISs and focusing on the spatial heterogeneity of innovation capability around the world, we yield an overall perspective of the internal and external innovation capability of NISs [36].

The present study makes the following contributions. On the theoretical level, first, we apply duality theory to the level of the NIS and enrich its connotations. This study proposes a replicable, process-oriented, and open conceptual framework of NISs, which embeds the concept of open innovation in the evaluation of NISs and pays more attention to the external radiation capability. Second, by stimulating the potential role of openness in dual innovation and establishing a new paradigm for national innovation systems, the inward-to-outward process of integrating externalized resources of NIS radiating capabilities completes a two-way (inward and outward) path for NIS knowledge and technology transfer. It expands the research scope of dual innovation collaborative development theory, enriching the relevant literature research. Third, we attempt to open the "black box" of DIC in NISs by dividing it into upstream and downstream stages through a process-based framework to refine the development stage of DIC. Metrics of staged capabilities for the innovation process are needed since there is no doubt that the low score of DIC in the whole innovation process results from the integrated score embedded in all the sub-processes within it.

At a practical level, we provide a measurement of the DIC of NISs based on the process-oriented concept by using a multi-indicator approach, which provides a more comprehensive picture of a sectoral national innovation system compared to currently used metrics. It is this process-oriented conceptual framework of DIC that provides a basis for assessment and policy recommendations. Six evaluable sub-dimensions are determined to evaluate the national DIC at different scales, which provides different types and strategies for promoting the innovation capability of NISs throughout the innovation process and assure the decision quality of innovations.

2. What Is Process-Oriented Dual Innovation?

2.1. What Is Dual Innovation?

Duality theory was proposed by ML Tushman and CA O'Reilly III [22] and applied to the research of enterprise innovation capability. They considered that exploitation and exploration are equally important in the enterprise innovation process. Subsequently, their theory was widely adopted in the field of innovation and was interpreted as an interactive development of internal and external knowledge and technology of the innovation system, including the elements of absorption, transformation, and dissemination of innovation. At the same time, dual innovation theory emphasizes two aspects—the mobility of knowledge and technology, and the openness of the innovation system—which greatly affect the innovation capability of the innovator and constitute an important basis for the sustainable development of the innovation system.

Dual innovation of enterprises includes both exploitative innovation and exploration innovation and emphasizes their balanced development [37]. Exploitative innovation uses knowledge and information from customers, competitors, and the market for development based on existing products. By comparison, exploration innovation is carried out by investing more development time and capital and by taking more risks. The complementarity of exploitative innovation and exploration innovation improves the effectiveness of innovation activities and could promote the development capabilities of enterprises through obtaining sustainable competitive advantages.

More and more attention has been paid to the exploitative innovation and exploration innovation of enterprises, and the concept of ambidexterity innovation has gradually entered the field of vision of researchers. Ambidextrous organizations are supposed to gain a sustainable competitive advantage by reaching an efficient equilibrium between exploration and exploitation [38] and by efficiently transferring to exploitation the disruptive innovations generated by exploration [39,40]. In an open innovation system, ambidexterity takes place at a regional level through inter-organizational coordination, which gives some new thinking to the dual innovation in our research [41]. The dual innovation should be encapsulated in the concept of openness, which is two-way and interactive.

The dual innovation of enterprises pays attention to the capability of enterprises in acquiring knowledge from the outside [23], which partially overlaps with the definition of DIC in this study. However, dual innovation mainly focuses on inward-oriented open innovation and ignores another important dimension—outward-oriented open innovation [42]. The absorption and radiation of knowledge and technology in an innovation system enhances the EEC of the organization in the open innovation network and can effectively increase the knowledge reserve of the innovation system [43]. Through external exploitation, a NIS absorbs new ideas and new technologies, radiates its innovation influence, and improves a country's global competitiveness.

A key feature of the DIC framework constructed in this study is that it incorporates both inward-oriented and outward-oriented aspects of the open innovation process. Inward-oriented open innovation focuses on absorbing and localizing external valuable knowledge in the process of internal knowledge construction and commercialization. Outward-oriented open innovation emphasizes the radiation of valuable knowledge, products, and resources to external systems to interact with each other and create value [44]. The outward-to-inward process of resource absorption and internalization (inward-oriented) and the inward-to-outward process of integrating externalized resources (outward-oriented) are integrated into the open system [45]. In this way, the dimension of "external system exchange" includes not only the absorption and localization of external knowledge, but also the external radiation and diffusion of knowledge and technology.

The external exploitation of a NIS needs effective internal management for guidance; therefore, its own IDC plays an important role in the efficiency of its external exploitation capability. The internal driving force of a NIS supports the growth of its external exploitation capabilities because innovation efforts and investment tend to improve a country's imitation ability and expand the pool of resources that can be used for technological activities in the future, thereby broadening the country's external influence and competitiveness in the global innovation network. The improvement of the absorptive capability of a NIS, in turn, can maintain innovation momentum by improving the production efficiency of the R&D department [30]. It is necessary to evaluate a NIS from a systemic perspective to comprehensively examine the IDC and the EEC of the NIS and to measure its effectiveness using various internal and external innovation elements.

2.2. Process-Oriented Dual Innovation

By J Schumpeter and U Backhaus [46]'s definition of innovation, an innovation process includes two stages: knowledge recognition and development, and knowledge production and commercialization. There is a growing awareness of the significance of considering innovative development paths within a system framework [32,33,47]. Although the two stages of the innovation process are not a dichotomy between "basic" and "applied", Pasteur's Quadrant model presents a useful point of departure [48]. Stokes applied his model to help explain that scientific research is a complex process within a larger, complex ecosystem of innovation-related activities. For reference, we decompose the dual innovation of NIS into two parts of "quest for fundamental understanding" and "consideration of use", which correspond to the two stages of the innovation process in this article: the upstream sub-process of the input of scientific knowledge and technological resources to the output of technological achievements, and then to the downstream sub-process of the transformation of economic benefits.

Specifically, the front-end of the innovation process represents the generation of ideas and concepts for innovation, which is called the upstream sub-process of innovation [49]. It ranges from the generation of ideas to the development process, that is, the implementation decision of the development process and the input of innovation resources [50,51]. After the launch of a market, the innovation process enters the downstream sub-process, which introduces market innovation. This process is affected by the non-innovation commercialization input, from incremental technical knowledge to profit creation [33]. It is noteworthy that the two sub-processes are not independent of each other but connected by technological innovation products.

We aim to establish a two-step analytical method to measure the phased development trend of the NIS and to reveal its determinants. This study develops a process-oriented conceptual framework of NIS to comprehensively describe the innovation process from a systematic perspective and further divides it into SR and TT capabilities, as shown in Figure 1.

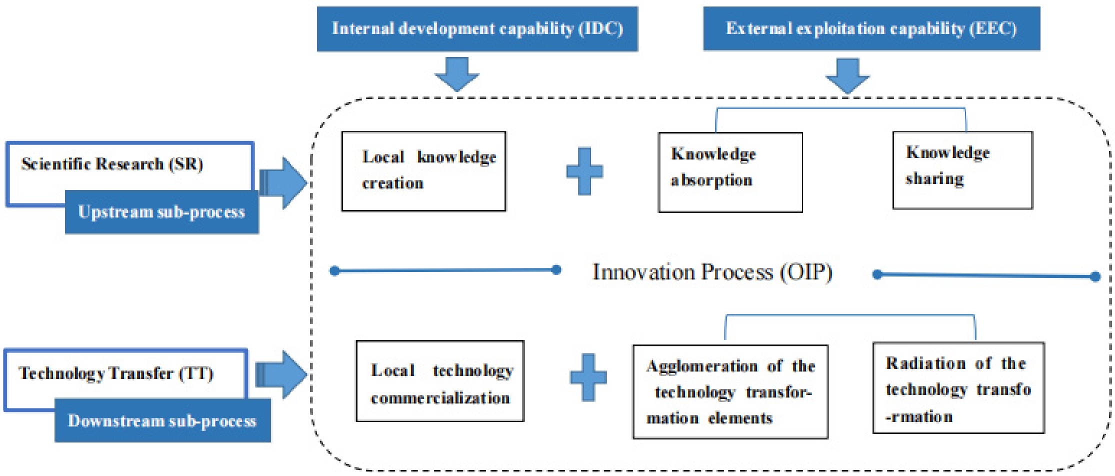

Figure 1. Dual innovation capability function model.

3. Research Framework, Methods, and Data

3.1. The Scientific Research/Technology Transfer Function Model

One of the objectives of this study is to evaluate the DIC of NISs by decomposing the innovation process into upstream and downstream stages. We emphasize two continuous sub-processes in a NIS, that is, (1) the upstream knowledge and technology acquisition process for generating new technological knowledge (SR); and (2) the downstream knowledge and technology commercialization process for generating the profit of the technology market (TT). The DIC framework enables decision makers to benefit from a quantifiable framework that uses SR and TT as the core of the analysis.

The SR and TT processes of innovation development, including internal and external interaction processes, do not exist in isolation. The IDC and the EEC are nested in the analysis framework of the two stages of innovation processes. The IDC emphasizes the capability and potential of innovation development within a NIS, which constitute the internal evaluation of the NIS; the EEC places the NIS in the global innovation network, focuses on the connection between the internal system and the outside, and highlights the role of openness in the efficiency of the NIS. This connection is bidirectional, including both the absorptive capability of the system and its radiation capability.

Specifically, this study further deconstructs the EEC functions mentioned above into absorption (agglomeration) and sharing (radiation) capabilities. The former is an inbound process, emphasizing the absorption of new knowledge and technology in the internal system and their integration into the commercialization process. The latter focuses on sharing innovative knowledge and resources with external systems for business activities, which is an outbound process. In summary, we describe the DIC of a NIS through six functions, namely, local knowledge creation, knowledge absorption, knowledge sharing, local technology commercialization, agglomeration of the technology transformation element, and radiation of the technology transformation.

3.2. Index and Data

This study established a DIC index system with 30 indicators and selected 65 countries as research samples to analyze their DIC indexes from 2010 to 2018. According to the development stage of the innovation process, our indicators were divided into two parts: SR and TT. Furthermore, the internal and external interactions of NISs were embedded through actual indicators. The data and relevant sources are shown in Table 1. Most of the indexes were adopted and modified from those used by the Global Competitiveness Report [52], Global Innovation Index [53], European innovation [54] and other previous studies [30,55] to measure a country's degree of dual innovation capability. Source of indicators are shown in Appendix B.

3.2.1. Scientific Research (SR)

The innovation process begins with the discovery and creation of new knowledge and technology from innovative investment to incremental scientific and technological knowledge, that is, the upstream process of innovation [33]. In this study, starting from the internal and external aspects of the DIC, we comprehensively consider the process of knowledge creation and flow and decompose this process into three aspects: local knowledge creation, knowledge absorption, and knowledge sharing.

Table 1. Indicators, sources, and weight.

Process	Function	Indicators and Sources	Type of Weights		
			AHP	Entropy Methods	Weight
Scientific research (SR)	**Local knowledge creation (0.2)**	F_1: GERD as a percentage of GDP [A]	0.3482	0.1405	0.1796
		F2: Researchers (FTE) [A]	0.2434	0.1605	0.2225
		F_3: Scientific and technical journal articles (per million population) [B]	0.1289	0.1734	0.1156
		F_4: Total patent applications (per million population) [C]	0.1398	0.4118	0.3341
		F_5: Trademark applications, direct resident (per million population) [C]	0.1398	0.1139	0.1481
	Knowledge absorption (0.15)	F_6: Fixed-broadband Internet subscriptions (per 100 population) [D]	0.1578	0.3619	0.2288
		F_7: Internet users (% of adult population) [D]	0.1578	0.1617	0.1358
		F_8: Education: outbound mobility ratio [A]	0.0885	0.0280	0.1946
		F_9: Intellectual property protection [D]	0.2979	0.2132	0.2076
		F_{10}: Country's capability to attract talent [D]	0.2979	0.2352	0.2332
	Knowledge sharing (0.15)	F_{11}: % Docs cited [E]	0.2033	0.0020	0.0557
		F_{12}: Category normalized citation impact [E]	0.3930	0.0260	0.1412
		F_{13}: Times cited [E]	0.1632	0.3032	0.2616
		F_{14}: ARWU world top 500 candidates [F]	0.1541	0.2631	0.3121
		F_{15}: Foreign-oriented patent family by origin and destination office [C]	0.0864	0.4057	0.2293
Technology transfer (TT)	Local technology commercialization (0.2)	F_{16}: R&D ranking of the world's top 1000 companies [H]	0.1245	0.5534	0.3758
		F_{17}: Extent of staff training [D]	0.2928	0.0278	0.0947
		F_{18}: University-industry collaboration in R&D [D]	0.3176	0.0443	0.1052
		F_{19}: Charges for the use of intellectual property, payments (BoP, current US$) [B]	0.1781	0.3535	0.3700
		F_{20}: Industry, value added (% of GDP) [B]	0.0870	0.0210	0.0543
	Agglomeration of the technology transformation elements (0.15)	F_{21}: Royalties and license fees (Import) [G]	0.1603	0.1994	0.3149
		F_{22}: ICT goods imports (% total goods imports) [B]	0.1603	0.4988	0.2457
		F_{23}: Prevalence of non-tariff barriers [D]	0.3027	0.0628	0.1107
		F_{24}: Foreign direct investment, net inflows (BoP, current US$) [B]	0.0975	0.2071	0.2427
		F_{25}: Time to start a business (lower is better) [D]	0.2791	0.0319	0.0860
	Radiation of the technology transformation (0.15)	F_{26}: High-technology exports (current USD) [B]	0.1488	0.3416	0.3300
		F_{27}: High-technology exports (% of manufactured exports) [B]	0.1488	0.0606	0.1200
		F_{28}: Merchandise exports (% of GDP) [B]	0.1614	0.0619	0.0971
		F_{29}: Exports of goods and services (% of GDP) [B]	0.1614	0.0597	0.1074
		F_{30}: Royalties and license fee (export) [G]	0.3796	0.4762	0.3454

Local Knowledge Creation (LKC)

The process of local knowledge creation is realized through the investment of innovative resources, and the results are reflected through the generation of new knowledge. The measure of this function is represented from the perspective of the input-output of knowledge and technology. Innovative input represents the total efforts and investments carried out by each country for R&D and innovative activities. Scientific output denotes the result of research and innovation activities carried out by the public S&T system (e.g., scientific and technical publications) [30]. The investment part focuses on the R&D funds and personnel investment of a NIS, expressed in gross domestic expenditure on R&D (GERD) as a percentage of GDP (F_1) and researchers (F_2). The output of knowledge and technology is represented by non-commercial innovation indicators, such as scientific journals (F_3), patents (F_4), and trademarks (F_5). Although publication in scientific journals and applying for patents are the product of inventive effort, they are more the result of the process of SR than the process of commercializing innovation [32].

Knowledge Absorption (KA)

Knowledge absorption refers to the ability to connect and link to international networks of knowledge and innovation, that is, the capability of a NIS to absorb external knowledge. It is common knowledge that there are obvious differences in the capability of different NISs to absorb knowledge and skills [55]. This capability depends on two aspects: the attractiveness to the NIS of acquiring external knowledge and the convenience to the NIS of obtaining external knowledge. A greater level and quality of infrastructures, such as networks, increase the country's capability to absorb foreign advanced technologies [56]. Absorptive capacity can refer to both techno-economic characteristics (e.g., resource availabilities), as well as socio-institutional conditions (e.g., the effectiveness of intellectual property protection) [57]. At the same time, international tertiary student mobility is also crucial in countries' access to international knowledge spillovers [58]. To capture these differences, we use the indexes F_6, F_7, and F_8 to show the convenience of acquiring knowledge and F_9 and F_{10} to measure the attractiveness of a NIS with respect to external knowledge.

Knowledge Sharing (KS)

The knowledge sharing capability refers to the capability of a NIS to share knowledge with external countries and to deliver innovation impact [59]. Knowledge here includes not only knowledge produced by the NIS itself but also internalized knowledge after absorbing external knowledge. This study mainly measures the quantity and quality of knowledge dissemination of a NIS from two aspects: the important carrier of explicit knowledge points, that is, papers and patents; and the important place of tacit knowledge spreading, that is, higher education institutions. It is quite obvious that the education system has an important role in enhancing the knowledge sharing of a country through its particularity as an important channel of international talent flow [58]. For these measurements, the three indicators of F_{11}, F_{12}, and F_{13} are used to express the degree of dissemination of knowledge through papers based on the number, frequency, and influence of citations, respectively. The external communication of patents is indicated by index F_{15}. First-class universities (F_{14}) are more attractive to international students, as they have stronger knowledge dissemination and influence.

3.2.2. Technology Transfer

According to R. Dvir and E. Pasher [60], innovation is the process of transforming knowledge into innovation value. In this subsection, we focus on the downstream stage of the innovation process, namely, TT, and define this function as the capability of a NIS to commercialize, agglomerate, and radiate new knowledge in the value creation stage of innovation. Considering the internal and external factors of NIS innovation value transformation, the process is divided into three parts: local technology commercialization, agglomeration of the technology transformation element, and radiation of the technology transformation.

Local Technology Commercialization (LTC)

Local technology commercialization is an essential function of a NIS; otherwise, economic development could neither benefit from new knowledge and technology nor avoid the risk of brain drain and flight of enterprises and investors [55]. The process of technology commercialization depends on effective interaction between universities, research institutes, and R&D enterprises. This framework offers an intuitionistic approach considering both process and result factors of value creation. The study's focus was, therefore, not on innovation output but on its economic consequences [61]. The capability of enterprise innovation value transformation is expressed by R&D investment and staff training degree. The cooperation degree of universities, research institutes, and R&D enterprises is reflected by index F_{18}, and the effect of value transformation is directly characterized by indexes F_{19} and F_{20}.

Agglomeration of the Technology Transformation Element (ATTE)

The agglomeration of the technology transformation element measures the external attraction of a NIS as a place for the transformation of innovation value. It is part of the EEC in the downstream stage of innovation, which manifests as the capability of the system to gather innovation resources in the process of knowledge transformation into innovation value. This function can be regarded as a process in which a NIS acquires innovation resources from the outside and realizes internalization. A superior business environment is an important consideration when enterprises decide to invest or produce abroad. A business environment that helps new entrants easily start a business, resolve insolvency, and pay taxes reduces uncertainty about doing business and encourages competitiveness necessary for innovation [62]. The level of market conditions is another factor that influences national innovation capability, which reflects the availability of credit and investment funds and the intensity of competition in local markets that is essential for businesses to innovate [63]. The framework for the agglomeration of the technology transformation element reflects the market and environmental attractiveness of a NIS to external innovation resources, including the import of capital (F_{24}) and commodities (F_{21} and F_{22}) and the business environment (F_{23} and F_{25}).

Radiation of the Technology Transformation (RTT)

Radiation of the technology transformation is the external radiation and influence of technology in the downstream process of a NIS. It is another part of the EEC in the downstream stage of innovation, which is an inward-to-outward process of integrating and externalizing innovation resources [45]. We are concerned about the economic consequences of the outward flow of NIS innovation resources, which can be directly represented by international trade [64]. In this study, we mainly use the export of products (F_{26}, F_{27}, and F_{28}) and services (F_{29}) to characterize the radiation capability of the NIS. Royalties and license fees (exports) (F_{30}) are used to visually represent the value conversion brought by commercial radiation. To reveal the radiation capability of a country's innovation value transformation in the global innovation network, the indicators are mostly expressed in the form of proportions.

3.3. Methods

Generally, the subjective weighting method pays attention to the economic and technical significance of indicators. By contrast, the objective weighting method is used to determine the weight value of the index according to the correlation or variability between the index values, and its absolute objective attribute, to some degree, violates the economic or technical significance of the index. Therefore, it is necessary to combine the subjective and objective weights to reflect the real situation of the study area. In this study, a comprehensive weighting method is adopted which considers both subjective and objective views, as well as value and information. To ensure the rationality of the index weight, we combine an analytic hierarchy process (AHP, subjective analysis) and the entropy weight method (objective evaluation). On this basis, an optimization model is established to determine the comprehensive weight of indexes by using the least square method.

The weighting vector determined by AHP is expressed as

$$v = (v_1, v_2, \ldots, v_m)^T \tag{1}$$

The weight vector determined by the entropy weight method is expressed as

$$u = (u_1, u_2, \ldots, u_m)^T \tag{2}$$

The integrated weighting vector is

$$w = (w_1, w_2, \ldots, w_m)^T \tag{3}$$

To make the error of comprehensive weight evaluation as small as possible, we use the least-square minimization problem of the integral weight wj, which is given by

$$\min H(w) = \sum_{i=1}^{n} \left\{ \left[(u_i - w_i) z_{ij} \right]^2 + \left[(v_i - w_i) z_{ij} \right]^2 \right\} \tag{4}$$

$$\text{s. t. } \sum_{j-1}^{m} w_j = 1,\ w_j \geq 0 (j = 1,\ 2, \cdots, m).$$

Referring to previous studies, we construct a Lagrange function to solve the optimization model [65,66].

The above model is used to calculate the measurement of six sub-dimension indicators, and each sub-dimension is weighted according to the goal-setting. See Table 1 for details.

4. Empirical Results

We analyzed country-level data by means of (process-based) dual innovation capability function modelling to deconstruct the DIC of NISs into six sub-dimensions (LKC, KA, KS, LTC, ATTE and RTT) to analyze the development status of DIC across countries and over time. We used annual time-series data from 2010 to 2018 at the national level and calculated the DIC index scores. The DIC score consists of individual scores for the 6 sub-dimensions and represents the results for the 65 countries in the sample through 2 stages of overall innovation capability. This study analyzed the change trend of the overall and sub-dimension DIC, as well as the spatial heterogeneity of countries. This provides simple evidence for measuring DIC at the national level, considering the role of internal and external innovation elements, as modeled in the DIC.

4.1. The General Trend of National Dual Innovation Capability

Overall, the means of the DICs in the countries we studied showed a gradually rising trend (Figure 2), and the acceleration of national DIC slowed from 2015. The means of the DICs in most countries were less than 0.5, representing a fairly low score across the 9 years. The mean DICs at the country level varied from a low of 0.065 in Madagascar to a high of 0.620 in the US. A notable result is the considerably higher variation created by differing DIC levels among countries in different years. The DIC of China rose dramatically during the study period, from 0.282 to 0.350, which was the largest increase in the selected countries. The DIC index of some countries declined instead of rising; among these countries, Japan's DIC showed the worst drop, from 0.420 to 0.409.

From the detailed analysis of each dimension of the DIC (Figure 2), we observed that the sub-dimensions of national DIC showed different trends. The capability of knowledge absorption and agglomeration of technology transformation element scored higher, indicating that most countries attach great importance to absorbing external knowledge and technology. Among them, the knowledge absorption index and the DIC index showed the same change trend. The knowledge absorption index is also the fastest-growing of all indexes, from 0.363 in 2010 to 0.444 in 2018. This shows that the growth of the DIC value mainly depends on the absorptive capability of knowledge, and acquiring knowledge from outside is an important driving force to improve the DIC of the NIS [11,67].

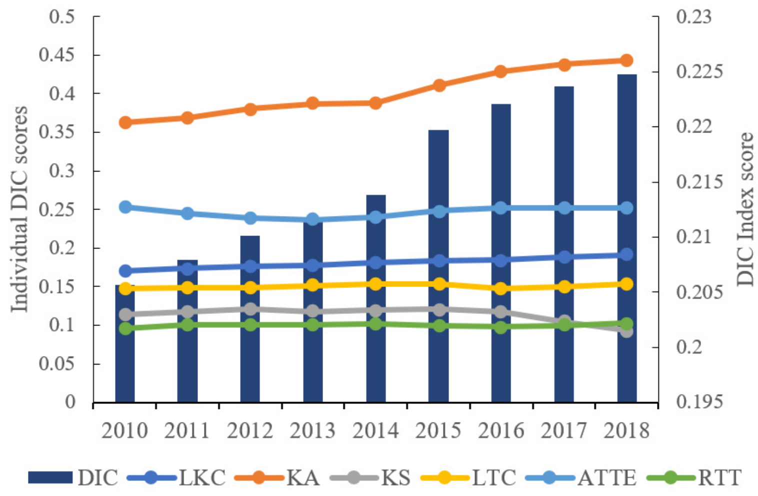

Figure 2. Change in the means of the dual innovation capability index and individual dual innovation scores.

The three indexes of local knowledge creation, local technology commercialization, and radiation of technology transformation show a slight growth trend. However, the knowledge sharing index of the study shows a certain degree of decline, from 0.114 to 0.093. Although the development of communication equipment and technology makes the exchange of knowledge between countries increasingly convenient [68,69], the effect of external knowledge dissemination of the NISs has not intensified because the states' protection of proprietary technology at the national level becomes increasingly stronger to ensure their technological uniqueness and decisive advantage in a certain field.

According to the score of the national DIC index, the 65 countries in the study can be divided into 5 levels (Figure 3). We selected the years 2010, 2014, and 2018 as temporal nodes to visualize the global DIC spatial pattern. The DIC of the US has always been in an absolute leading position, while China has the strongest growth. Of all countries in the sample, 32% had an annual average DIC score less than 0.150, whereas only 2% had a score greater than 0.400. Among them, the US continuously maintained the top score of close to or more than 0.600. Three European countries (the UK, Spain, and Germany) ranked second, third, and fourth, respectively, at least until China's ranking rose to third place in 2018. Similar to the conclusion of S Lee, H Lee and C Lee [11], we found that China is a primary attraction for external innovation resources and has strong radiation capability, especially in the downstream stage of the innovation process. China is an important emerging economy in the global innovation network, and its rapid economic growth, huge market, and series of preferential policies have greatly improved its attractiveness for external innovation resources; this has become an important basis for the continuous improvement of China's external influence on innovation [70,71].

Over the past years, the landscape of global DIC has undergone dramatic shifts. Traditionally centered in the US, Western Europe, and Japan, the spatial pattern now gradually presents the spatial characteristics of multi-polarization. This result is similar to existing studies, as mentioned in the Science and Engineering Indicators [72]. Generally, the growth of science and technology in developing countries has been faster than that in developed countries, and the relative share of global scientific and technological activities of historically dominant developed nations has shrunk, even as their absolute capability levels have continued to rise [73,74]. Simultaneously, China's rapid, unprecedented, and sustained growth has attracted the attention of researchers globally [75]. Furthermore, India, South Korea, and other Asian economies have demonstrated their relative strengths in global innovation capabilities [76]. This highlights the importance of introducing the conceptual framework of DIC in this study, because these developments have taken place in the context of an increasingly interconnected world rather than within the national system [77,78]. Therefore, a comprehensive evaluation framework integrating the internal and external innovation elements of the NIS is particularly important.

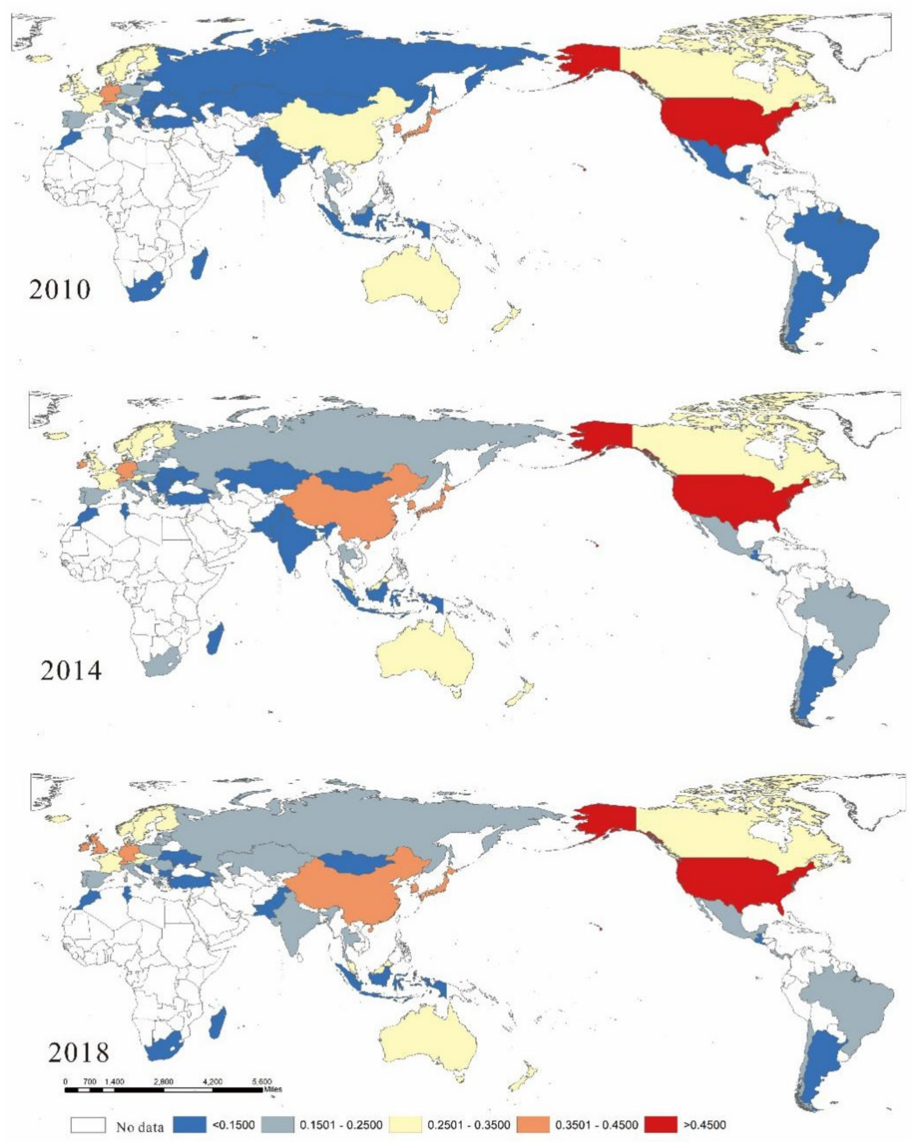

Figure 3. Spatial pattern of dual innovation capability index scores in 2000, 2014, and 2018 for 65 countries.

4.2. Empirical Results and Analysis

4.2.1. Internal Comparison of the Dual Innovation Capability Framework

Different stages of the innovation process show different degrees of growth trend, among which the index score of upstream sub-process (SR) is higher, changing from 0.212 in 2010 to 0.237 in 2018. From a process-oriented perspective, we consider the different stages of DIC of NIS development in isolation, which helps policymakers pinpoint weaknesses at different stages. Combined with the results of this study, we found that the growth rate of SR was faster others and became the main contribution of the change in DIC [79]. Meanwhile, the TT score was low, with a growth rate of only 0.47% over 9 years. The capability improvement of the downstream innovation stage needs to be further strengthened.

The IDC and EEC of the DIC framework showed a growth trend, and the change trend of DIC of the NIS is highly consistent with that of EEC. In the process of improving national DIC, the communication of a NIS with other countries and the diffusion of knowledge and technology became increasingly important. The EEC of the NIS is crucial for successful co-creation [80,81] and increased contribution of DIC.

By deconstructing DIC, it can be divided into six sub-dimensions covering different stages and aspects inside and outside the system so as to better discover the trends and laws of various parts inside the system and better guide policymaking. Based on this framework, we found that the two dimensions in the DIC framework, SR/TT and IDC/EEC, had certain regularity (Figure 4). The change of the upstream innovation stage (SR) is highly consistent with the change of EEC of the NIS. The higher the capability of knowledge and technology creation of the NIS, the stronger the attraction and internalization of external knowledge [82,83] and the greater the influence of innovation on external radiation. Simultaneously, the supplement of external knowledge can stimulate and supplement a lack of knowledge and technology in the process of internal innovation [84]. Their effective interaction fully proves the importance and urgency of improving the capability of DIC for a NIS. Meanwhile, the change trend of the downstream innovation stage (TT) is highly consistent with the change of IDC of the innovation system, which means that the commercialization and value realization of the NIS still rely on the contribution of internal knowledge. Most countries adopt a blockade policy for core knowledge and technology, which can lead to high-value output, so as to ensure its own advantages in cutting-edge technologies [85,86].

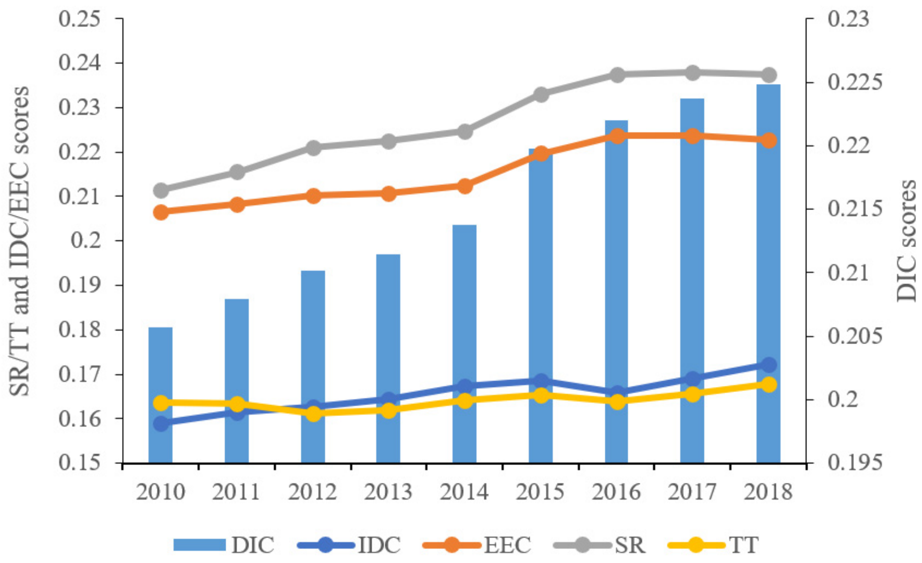

Figure 4. Change in the means of individual scientific research/technology transfer and internal development capability/external exploitation capability scores.

4.2.2. Detailed International Comparative Study on Dual Innovation Capability

For most countries, the capabilities of different dimensions of innovation systems (IDC/EEC) are not synchronous, and more specific innovation policies should be formulated according to the different characteristics of the innovation process in the NISs. Referring to previous studies [87], mean value and standard deviation are used to classify data to avoid selecting an arbitrary threshold to distinguish IDC and EEC. Therefore, based on the IDC/EEC classification of NISs, this study integrated node DIC index and SR/TT type information and finally obtained country differences based on different dimensions within the DIC framework. Figure 5 visually presents the categories of the 65 countries' DIC.

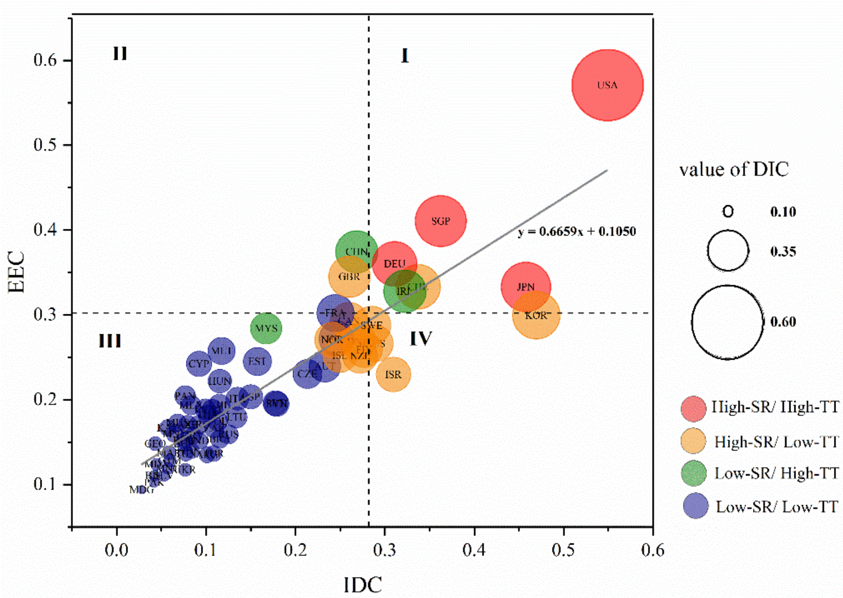

Figure 5. International comparison of internal development capability/external exploitation capability.

Figure 5 shows a positive correlation between the IDC and EEC values: a positive change of one unit in the degree of IDC causes an increase of 0.666 in EEC. The IDC of the NIS and its absorption and radiation capabilities of external knowledge and technology complement and promote each other. As F Castellacci and JM Natera [30] show in an empirical study of 87 countries from 1980 to 2007, the power of the national system is driven by two main aspects, innovation ability and absorptive ability, while the co-evolution of innovation ability and absorptive ability is the common mode of the entire national group. Different from previous studies, we not only considered the capability of NISs to attract external innovation resources but also integrated other aspects of EEC: the external radiation ability of knowledge and technology and the improvement of the national system's global competitiveness. Our results demonstrated that the synchronization of internal and external (IDC and EEC) innovation capability has changed.

Specifically, the 65 countries were divided into 4 categories according to their score in 2 dimensions (IDC and EEC). From the perspective of country classification, the DIC value of most countries was low. There were 52 countries of the "low IDC and low EEC" type (III) and 6 countries of the "high IDC and high EEC" type (I). According to the different characteristics of the countries distributed in the four quadrants, we proposed the corresponding optimization direction.

Type I countries have a high internal development capability and high external exploitation capability. The countries of this type are DIC leaders, whether they be strong in internal knowledge and technology creation or external knowledge attraction and radiation capability. This type provides a benchmark for other countries to improve their DIC. In addition, we observed how their NISs perform in the two stages of innovation. As we expected, the major countries of this type performed well in different stages of the innovation process.

Type II countries have a high external exploitation capability and low internal development capability. This type of country has outstanding performance in the absorption of external knowledge and technology, as well as in external radiating capability and influence around the world. Such countries should combine their own advantages in different stages of innovation and development, pay more attention to the improvement of their independent R&D capabilities, maintain their attractiveness to external innovation resources, and improve their localization efficiency of external knowledge and technology, so as to stimulate and drive knowledge creation vitality within the system.

Type III countries have a low external exploitation capability and low internal development capability. Most of the selected countries (52) belong to this type. Their performance in the internal and external interaction of their NISs is insufficient. From the stage of innovation development, most of the countries in type III still need improvement in both stages, while some countries have certain advantages in a certain stage. Countries in this quadrant often have low SR and TT scores at the same time and should take action to simultaneously improve the two sub-processes of dual innovation. These countries should create their own advantages in a DIC dimension and improve their competitiveness.

Type IV countries have a high internal development capability and low external exploitation capability. This type of country is a leader in knowledge creation, but its capability to communicate with other innovation systems needs to be improved. Further policies that these countries can implement include acquiring knowledge from the outside, integrating it with local knowledge, and then strengthening the transformation of knowledge, improving the value creation of innovation resources, and finally, improving their influence and competitiveness in the global innovation network.

For type II, III, and IV countries, three possible paths can be chosen to improve DIC and achieve high IDC and EEC. Path 1 is a one-sided optimization path (II→I; IV→I). Type II and IV NISs can improve their DIC by reducing the gap with type I countries in their internal and external weak dimensions, respectively. Path 2 is a gradual improvement path (III→II→I; III→IV→I), in which type III NISs concentrate superior resources, adopt specific policies and flexible measures, and develop into type III or IV NISs first, and then into type I NISs. Path 3 is a positive optimization path (III→I), which requires the NIS to solve the weaknesses of internal development and external exploitation at each stage of the innovation process.

5. Discussion

In response to the increasing interest of researchers and professionals in open innovation and dual innovation, a process-oriented conceptual framework of DIC is constructed. Our methods allow us to build upon the prior literature, showing mixed results regarding the performance of NISs [11]. We attempt to explore the adoption of DIC by NISs from the perspective of “process”, that is, the influence of internal and external resource elements of a NIS on its innovation development capacity. This study highlights the role of open innovation and process-oriented in the process of justifying the DIC of NISs.

5.1. Open Innovation in the NIS

The openness perspective has revealed a fresh insight into innovation. Sustainable innovation today is considered more the product of a network than NIS alone. The inbound and outbound flow of knowledge and technology in an open environment lays the foundation for the sustainability of innovation and directly or indirectly affects dual innovation. Inbound OI primarily serves to improve the system’s “exploration” capabilities, whereas outbound OI is very much related to leveraging the “exploitation” of the system’s basis of knowledge and technologies. The OI pathway typically begins with the inbound mode of transaction-based absorption and later progresses to more complex, ambidextrous modes [88].

By introducing the concept of OI, this study examines the innovation capability of NIS more comprehensively and deeply, placing the system in a global innovation network and emphasizing the connection and interaction between the system and internal and external innovation resources. The DIC of the NIS has been deconstructed into two stages, SR and TT, and by including the internal and external aspects of IDC and EEC, we could analyze the relevance of the internal information of the DIC framework in a more detailed way than previously. It is proved that the IDC of the NIS and its absorption and radiation capability of EEC complement and promote each other. This result confirms the need to introduce the concept of open innovation in NIS research. In addition, we found that the commercialization and value realization of NISs still mainly rely on the contribution of internal knowledge creation, and the external exchange of knowledge mainly plays a role in the SR stage. Most countries still adopt a blockade policy for core technologies, especially innovative resources that can bring high-value output.

Different from the evaluation of national-scale innovation capability in previous studies, we focus on the comparison of national innovation capability under open innovation. The spatial distribution of DICs is similar to previous studies; that is, the United States is in an absolute dominant position in the global innovation capability ranking, and China has a strong growth momentum [75]. In contrast, previous studies paid more attention to the evaluation of the innovation capability attributes of the system itself, such as human resources and finance and support, while the proportion of indicators designed for external connection was relatively small. This study aims to evaluate the innovation capability of NISs at different stages under the combined effect of internal and external linkages. Therefore, more attention is paid to the adoption of systematic absorptive and radiative capacity indicators in the selection of indicators in an attempt to evaluate the innovation capability and spatial differences at the national level from an open perspective.

5.2. Dual Innovation in the NIS

Dual theory, in essence, stresses the importance of pursuing divergent but complementary goals in order to achieve sustained organizational performance. This paper introduces the concept of dual innovation, which integrates the attribute concept of the system itself and the interaction effect produced by the system and the outside network. For NIS, the question of whether external resources are substitutes or supplements for internal R&D is still controversial and needs to be explained scientifically. DI focuses on combining explorative elements and exploitative elements to maintain continuous innovation competitiveness.

With dual innovation capability as our focal construct, NISs were placed in an open global innovation network rather than a closed consideration of its own attributes. As previous studies have pointed out, an ambidextrous system that is capable of simultaneously conducting exploration and exploitation is more likely to achieve superior performance than emphasizing one at the expense of the other [41]. As our research results show, there is a positive correlation between the IDC and EEC values; the two complement each other. If NISs focus one-sidedly on exploration without taking efficiency in exploitation into consideration, they begin to take excessive risks and fail to extract profits. In turn, a lack of focus on exploration has resulted in gradually losing the core competitive capabilities of a NIS—eventually endangering their long-term sustainable development. NISs need dual innovation to maintain long-term sustainable competitiveness in the global innovation network.

According to the DIC score of each country, the 65 countries in the study can be divided into 5 categories. Through the projection of classification results in space, we found that the landscape of global DIC has undergone dramatic shifts. Traditionally centered in the US, Western Europe, and Japan, the spatial pattern now gradually presents the spatial characteristics of multi-polarization. Developing countries in Asia, especially China, have attracted worldwide attention for their rapid improvement of DIC. Compared with countries with higher innovation capacity in the traditional sense, they tend to be developed countries, and the growth rate of science and technology in developing countries is faster. Therefore, its relative share in global science and technology activities has increased significantly, which has increasingly become the focus of innovation research.

Most countries with different capabilities in both dimensions of the DIC framework need more innovation policies for specific stages, which can be combined with the advantages of IDC and EEC of the system. Considering the development conditions of different countries, the strategy of a country with a high degree of DIC can be imitated and applied by other countries. Countries should be placed in the global innovation network and consider the optimization path from an overall viewpoint, rather than just improving a single factor. Governments need to pay attention to any capability gap in one of the six functions of the system and should consider effective interventions to make up for this disadvantage in the particular capability.

5.3. The Process-Oriented of DIC in the NIS

Innovation is a systematic and complex linkage process. The innovation capabilities of NISs are complex and multi-faceted; a "recipe" for implementation does not exist. It is the process-oriented conceptual framework of DIC that provides a basis for assessment and policy recommendations. A clear conceptual framework can help a NIS to manage ideas and innovations throughout the innovation process and assure the decision quality of innovations. Different indicators are assigned to a phase of the innovation process, which is important to reflect the entire innovation process and to control for the ex-ante applicability of each indicator.

In contrast to studies that did not consider the stage of innovation development, our main focus is to understand how two-way flows of open innovation elements combine with the properties of the system itself to produce dual innovation effects at different stages of innovation. We attempt to open the black box of DIC in NISs and divide it into upstream and downstream stages through a process-based framework to refine the development stage of DIC. On this basis, we draw lessons from dual innovation, comprehensively consider the exploration and exploitation capabilities of the system, and integrate the concept of ambidextrous open innovation, which makes up for the neglect of output innovation in previous studies. Through systematic sorting and the subdivision of different stages of the innovation process, different ways of obtaining system innovation results and different flow directions of innovation elements, the key points for improving the innovation ability of different types of NISs can be that targeted policy guidance and further development paths can be provided.

Our results also suggest that a more granular, process-focused set of measures for innovation capability is practiced within NIS yields further important findings. We found that the overall DIC of a NIS largely depends on the value of the upstream sub-process (SR). This reminds us that most countries should not only increase investment in efficiency during the SR phase but also pay attention to the TT process and give full play to the external interaction effect of knowledge and technology. Meanwhile, the change trend of the downstream innovation stage (TT) is highly consistent with the change of IDC of the innovation system, which means that the commercialization and value realization of the NIS still rely on the contribution of internal knowledge. Most countries adopt a blockade policy for core knowledge and technology, which can lead to high-value output, so as to ensure their own advantages in cutting-edge technologies [85,86].

6. Conclusions

This study focused on the analytical understanding of how the DIC of NISs evolves over time and provides a case study of empirical measurement. This was accomplished by shifting the focus to the innovation process (SR/TT) and proposing that the DIC of the NIS be driven by the synergy of two main aspects: IDC and EEC. The main purpose of this study was to propose a complete process-oriented analysis framework to simulate the interaction between the IDC and the absorption/radiation-based EEC. The process-oriented framework and resulting DIC measurement tool provide a new way to evaluate national innovation capability in terms of SR and TT. Countries should be analyzed based on their placement within the global innovation network instead of their innovation efficiency in isolation.

6.1. Theoretical Contributions

This study makes important contributions to the extant literature. First, it embeds the concept of open innovation to complement the evaluation of DIC. Although the extant literature has highlighted the importance of openness to both exploitation and exploration innovation of dual innovation [24], methods of how to evaluate the practical significance of two dimensions of OI (inward-oriented and outward-oriented) in DIC have not been systematically explained. The knowledge and technology flow of inward-oriented (absorptive) capability and outward-oriented (radiative) capability constitute the complete process of open innovation. To date, most research on dual innovation has relied on the importance of absorbing and utilizing external knowledge and technology for innovation performance to describe the effect of openness on DI [89]. Our study contributes new insights into a more comprehensive consideration of the two aspects of OI and their interactions in dual innovation research. We extend this research by highlighting the role of the radiation capabilities of NISs in open innovation processes. Enhanced radiation capabilities will further expand the international influence of a NIS, which in turn increases the absorptive capabilities of the system itself and further enhances its dual innovation competitiveness.

Second, although the extant literature has highlighted the importance of dual innovation and open innovation in sustainable innovation, the empirical testing from different research scales is obviously insufficient. Most DI and OI studies have focused on the firm- or sector-level studies, while only a few articles have addressed the issues at other levels [26]. In particular, quantitative research at the national scale needs to be carried out. Open innovation strategies at the national level are worth addressing under the paradigm of globalization [12]. By exploring the application of dual innovation at the national level, the present study contributes to a better understanding of the linkages and interactions of NISs with the inside and outside of the system, which is scarcely researched, though acknowledged to be important, in the extant OI research [11].

Third, although a large amount of past research has theorized about the character of national innovation systems, there has been limited process-oriented empirical investigations of this matter [33], and the DIC assessment of NISs based on an open perspective is even less studied. This study's contribution presents a framework based on the idea that the integration of internal and external sources of knowledge and technology creates combinations of activities that build up a NIS's innovation capabilities, utilizing the process-oriented conceptual perspective. Our research attempts to open the "black box" of dual innovation at the national level. We draw lessons from dual innovation, comprehensively consider the exploration and exploitation capabilities of the system, and integrate the concept of ambidextrous open innovation, which makes up for the neglect of output innovation in previous studies. Through systematic sorting and subdivision of different stages of the innovation process, different ways of obtaining system innovation results and different flow directions of innovation elements, the key points for improving the innovation ability of different types of NISs can be implemented into targeted policy guidance, and further development paths can be provided.

6.2. Practical Implications

This study benefits national innovation capacities and policymakers in several ways. First, as one of the earliest attempts to develop a dual innovation strategy at the national level, our framework can help decision makers, planners, and government agencies develop DI strategies of NIS. Our findings may also assist decision makers in recognizing how innovation elements inside and outside the system affect the improvement of the dual innovation capacity of the NIS from the six sub-dimensions of the DIC framework.

Second, the implication for public policymakers that emerges from the results of this study is that if governments need to engage in open innovation networks to enhance innovation capabilities, it is important to not only increase investment in efficiency during the SR phase, but also pay attention to the TT process and give full play to the external interaction effect of knowledge and technology, which in the case of this study was found to be the DIC that a NIS largely depends on. In this way, and specifically in the case of countries with low TT, as shown in Figure 5, countries that complement the shortcomings of innovation and development gain important direction for their future innovation policy formulation.

6.3. Limitations and Future Research Opportunities

Although we tried to collect various databases in this study, data from some countries were not available. Existing studies usually shorten the research period to obtain more national unit data (usually a period of 1 year), but this study considered the trend of long time series to also be of great significance in NIS research. Therefore, although there were not enough countries to verify the DIC framework, this study selected representative countries from different regions, and in so doing, reflected the global change trend since 2010 and provided a new conceptual framework to enrich research on national innovation systems. Besides, we have carried out research on the national dual innovation capability from a systematic perspective, but due to practical considerations, there is a linear simplification in the modeling. As a tentative study, there are still many aspects to be improved in the method. In our next study, the model construction and method selection will be optimized.

The empirical characteristics of this study can open up new research opportunities in NIS studies. We incorporate the concept of external exploitation capability, focusing not only on the absorption of knowledge but also on the radiation of the NIS. However, the study focuses on the construction of the DIC framework and the application of the framework in evaluating the innovation ability of a NIS. However, it is obviously insufficient to research the relationship between the various sub-parts within the framework. A more detailed study of the relationship between explorative elements and exploitative elements, and how the coupled open innovation acts on the national-scale innovation development process, is an important direction for future research.

With the gradual deepening of open innovation research, researchers have gradually realized that the adoption of open innovation is not only a source of opportunities for companies but can also present risks [90]. These heterogenous views inevitably spur on a growing theme of the 'paradox of openness' in the open innovation literature [91–93]. The DIC measure developed in this paper is dedicated to bringing NIS to the global innovation network. Whether dual innovation at the national level using inbound and outbound flow of knowledge and technology in an open environment also has the risks of open innovation, and how to characterize this heterogeneity at the national level, is worth considering.

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Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: The study did not involve humans.

Data Availability Statement: Data is contained within the article, please see Appendix B for details.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. List of Countries

Below is a list of the 65 countries that have been selected to validate the DIC.

Argentina (ARG)	Georgia (GEO)	Mongolia (MNG)
Australia (AUS)	Greece (GRC)	Mauritius (MUS)
Austria (AUT)	Guatemala (GTM)	Malaysia (MYS)
Azerbaijan (AZE)	Croatia (HRV)	Norway (NOR)
Belgium (BEL)	Hungary (HUN)	New Zealand (NZL)
Bulgaria (BGR)	Indonesia (IDN)	Pakistan (PAK)
Bosnia and Herzegovina (BIH)	India (IND)	Panama (PAN)
Brazil (BRA)	Ireland (IRL)	Poland (POL)
Canada (CAN)	Iceland (ISL)	Portugal (PRT)
Switzerland (CHE)	Israel (ISR)	Romania (ROU)

Chile (CHL)	Italy (ITA)	Russian Federation (RUS)
China (CHN)	Japan (JPN)	Singapore (SGP)
Costa Rica (CRI)	Kazakhstan (KAZ)	El Salvador (SLV)
Cyprus (CYP)	Korea, Rep. (KOR)	Slovenia (SVN)
Czech Republic (CZE)	Lithuania (LTU)	Sweden (SWE)
Germany (DEU)	Latvia (LVA)	Thailand (THA)
Denmark (DNK)	Morocco (MAR)	Tunisia (TUN)
Spain (ESP)	Moldova (MDA)	Turkey (TUR)
Estonia (EST)	Madagascar (MDG)	Ukraine (UKR)
Finland (FIN)	Mexico (MEX)	United States (USA)
France (FRA)	Malta (MLT)	South Africa (ZAF)
United Kingdom (GBR)	Montenegro (MNE)	

Appendix B. Source of Indicators

Reference Mark	Source of Indicators
A	UNESCO
B	World Bank
C	WIPO IP Statistics Data Center
D	World Economic Forum, Executive Opinion Survey
E	Web of Science
F	Shanghai Ranking's Academic Ranking of World Universities
G	UN Comtrade Database
H	EU Industrial R&D Investment Scoreboard

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