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Research Article

Knowledge Innovation Mechanism Based on Linkages between Core Knowledge and Periphery Knowledge: The Case of R&D Cooperation between Latecomers and Forerunners

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With rapid changes in technology, knowledge innovation has become more and more complex. Complex partners facilitate knowledge creation and innovation in complex problem-solving. Relying on R&D cooperation with forerunners, latecomers can acquire new knowledge factors and new ideas and use them to create new knowledge. This study demonstrated the knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge with knowledge map theory and set methodology. A case of R&D cooperation between latecomers and forerunners was introduced to verify this mechanism. The results show that latecomers could share forerunners' periphery knowledge in R&D cooperation through formal and informal interaction and acquire the core knowledge factors in periphery knowledge based on the linkages between them. With these core knowledge factors, latecomers integrate them into their internal knowledge system and create new knowledge. By analyzing the linkages between periphery and core knowledge factors, this study creatively demonstrates the knowledge innovation mechanism in knowledge linkage perspective. It deepens the understanding of R&D cooperation between latecomers and forerunners and expands the focus of knowledge innovation theory. This study provides a new insight into latecomers effectively activating internal and external knowledge resources through R&D cooperation.

1. Introduction

With the rise of the global knowledge economy, innovation has become an essential element for companies to gain competitive advantage and demonstrate excellent performance. Knowledge innovation is the process of exploring and combining knowledge factors, and creating new knowledge or new knowledge combinations based on existing knowledge [1]. With the rapid changes in technology, knowledge innovation has become more and more complex. Creativity, the source of new ideas and creative processes, "is a complex and diffuse construct" [2]. Complexity can be used as a sense-making framework to gain insight into innovation [3]. R&D input substantially promotes innovation performance [4], and R&D cooperation with diverse partners facilitates reciprocal learning and co-evolution. Various inputs can facilitate knowledge creation and innovation in complex problem-solving [5]. By establishing collaborative R&D relationships with external organizations, latecomers can acquire new knowledge factors and new ideas outside the organizational boundaries [6] and use them to create new combinations of knowledge paradigm and new knowledge. However, the internal knowledge base accumulated by latecomers will affect the effectiveness of the external R&D cooperation [7]. Integrating the acquisition of new knowledge factors and the existing knowledge of latecomers, and analyzing the knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge has theoretical and practical significance on understanding innovation and improving the efficiency of innovation for latecomers.

Existing research on R&D cooperation focuses on the impact of specific partners, such as competitors [8], universities, and research institutions [9], and the intensity and diversity of latecomers' innovation. For latecomers, R&D partner selection is influenced by technological relevance and firm development experience [10], technological strength, and openness and status [11]. Through knowledge creation and technology transfer, R&D cooperation can help latecomers maximize the value of resources and promote the establishment of connections between latecomers and external resources with lower market transaction costs.

The intention of R&D cooperation is related to latecomers' R&D capability [12], the human capital of founders [13], existing technology level [14], and trust among partners [15]. Industry environmental uncertainty, industry proximity to partners [16], and financial support from the government at the macro level are also the main driving forces for R&D cooperation. The R&D cooperation within and between industries usually involves competition and cooperation. Due to the high possibility of overlapping technology fields, the value distribution of R&D cooperation among peers is more cautious. The linkage between internal knowledge and external knowledge on innovation is ignored. Therefore, latecomers' knowledge innovation through R&D cooperation has not been fully revealed.

Changes in industrial leadership from an incumbent to a latecomer are often observed in several industries [17]. Latecomers create opportunities for R&D cooperation with forerunners to improve the efficiency of technology catch-up [18]. In the catch-up cycle, core knowledge is critical for breakthrough core technology because it is the core competitiveness of enterprises directly related to the strategic resources that can bring radical innovation [19]. However, forerunners are only willing to share their periphery knowledge in the process of R&D cooperation in which the core knowledge is closely protected to maintain their competitive advantage [20]. Therefore, latecomers need to construct the core knowledge with the linkages between the core knowledge and periphery knowledge through sharing the periphery knowledge with the forerunners. New linkages reconstruct and change knowledge structure, resulting in new core knowledge. Reconstruction and changes of core knowledge are usually radical innovations, along with the development of technological capabilities and significant technological breakthroughs [21].

By linking the internal and external knowledge, this study intends to find the knowledge innovation mechanism from a microcosmic perspective of knowledge factors. The mechanism is deduced in the knowledge map with set methodology, and a case of R&D cooperation between latecomers and forerunners is introduced to verify this knowledge innovation mechanism. This study would develop knowledge innovation and R&D cooperation literature and deepen the understanding of knowledge linkage theory with set methodology. Practically, it would provide insights into the latecomers who try to update their core knowledge through R&D cooperation and realize technology breakthroughs.

1.1. Literature and Research Framework

1.1.1. Knowledge Map and Knowledge Linkages. Knowledge Map (KM) is a structured organization of knowledge factors in which knowledge factors exist in the relationship between the cause and the result and constitutes a complete knowledge structure that comprehensive utilization of knowledge can logically solve a specific problem [22]. A knowledge map is a tool for building linkages between knowledge factors and presenting knowledge structure visually. It is a directed graph containing nodes and linkages, where nodes are knowledge factors and linkages are connections between them. Knowledge map provides the path among knowledge factors and structure based on their linkages. According to the Resource Description Framework (RDF) [23], a knowledge map can be described as a set of triples shown in the following formula:

$$\mathrm{KM} = \{\mathrm{KF}_1(A_1), R, \mathrm{KF}_2(A_2)\}. \tag{1}$$

Here, KM means the knowledge map, KF means the knowledge factors, A represents the attribute of knowledge factors, and R means the relationships of knowledge factors.

The knowledge map comprises the resource layer, knowledge element layer, and theme layer, which embodies the structure of knowledge assets. The different linkages of knowledge factors in three layers constitute various knowledge structures intertwined to form knowledge maps. Figure 1 shows the knowledge map and linkages between knowledge factors.

In the resource layer, O_i $(i = 1, 2, \ldots, n)$ represents the various resources owned by the enterprises, such as information, data, skill, experience, etc. The resource can be divided into two categories: tangible and intangible. Substantial resources consist of the material of enterprise, equipment, personnel, etc. These resources are the material basis for knowledge construction. Intangible resources include the know-how, production and management processes, corporate culture, and information systems, vital components for knowledge construction. These resources form knowledge elements through various linkages.

In the knowledge element layer, K_{ei} $(i = 1, 2, \ldots, n)$ represents the knowledge elements composed by all kinds of resources according to specific linkages. The knowledge element is the smallest independent unit of knowledge structure and cannot be divided anymore [24]. The knowledge element has the characteristics of independence, topology, and linkability [25]. Independence means the position of one knowledge element in a knowledge structure is unique and stable. It is impossible to change or transform this position because the attributes of the knowledge element determine it. The topology refers to the semantic association between knowledge elements. These semantic associations combine different knowledge elements to a semantic network. The linkability represents the various associations between knowledge elements, including semantic associations, making other knowledge elements establish a knowledge network [26]. Knowledge elements flow in the network and play different roles.

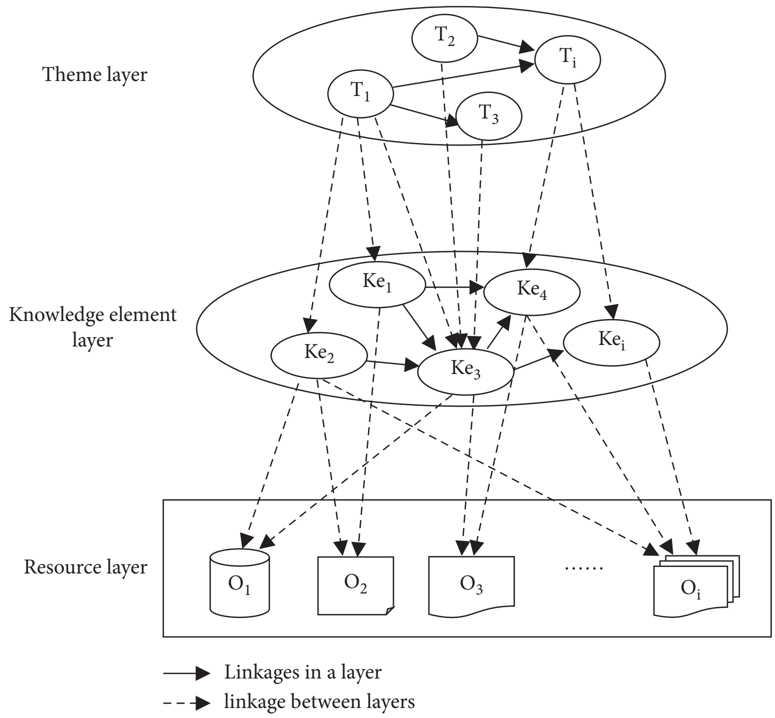

Figure 1: Knowledge map and linkages between knowledge factors.

In the theme layer, T_i ($i = 1, 2, \ldots, n$) represents the themes, a collection of various knowledge elements interlinked by a particular association. A theme can be people, things, time, relationships, etc. All the objects can be a theme, and each theme can usually be given a name [27]. A theme may contain one or more knowledge elements associated with the topic. Furthermore, different knowledge elements, or the same knowledge element with other relationships, can also constitute different themes.

The three layers are not isolated but mutually interrelated and supported. Knowledge linkages associate them. The linkages among resources form the knowledge element, the linkages among knowledge elements form the theme, and the linkages among the themes include the whole knowledge structure. These linkages among the three lays are not unique. Different resources can compose other knowledge elements, and the same group of resources can also form different knowledge elements according to various linkages. One knowledge element can belong to one theme, determined by their linkages. In a knowledge map, knowledge linkages provide the navigation path between knowledge factors, and the knowledge factors construct different knowledge structures by various knowledge linkages.

1.1.2. Core Knowledge and Periphery Knowledge in the Knowledge Map. Knowledge in a firm can be divided into two types: core knowledge and periphery knowledge. Core knowledge is the firm strategic resource regarding core competitiveness and usually leads to radical innovation [28], while periphery knowledge is a supplementary resource [29]. As the necessary components of knowledge structure, core knowledge and periphery knowledge play essential roles in constructing new knowledge.

Although there is difference in structure and importance, core knowledge and periphery knowledge are very close. First, they share the same resource as a firm. As knowledge belongs to the same firm, core knowledge and periphery knowledge are constructed by the same resources. That is, they are homologous. The homology provides a necessary condition to find the linkages between core knowledge and periphery knowledge. Second, they construct a complete knowledge system together. A comprehensive knowledge system contains core knowledge and periphery knowledge inevitably. They are complementary and support each other when creating a knowledge system. Based on these relationships, one may infer some core knowledge factors even if they only were told the periphery knowledge.

In a knowledge map, the theme layer decides the attribute of knowledge structure. A core knowledge structure does not mean that all the knowledge factors must be core knowledge as long as the theme is core knowledge. This knowledge structure, formed from core knowledge elements and resource or periphery knowledge elements and resources, is identified as core knowledge. If the theme is periphery knowledge, this structure is identified as periphery knowledge, no matter how many core knowledge factors.

1.1.3. Linkages between Core Knowledge and Periphery Knowledge. Complete knowledge structure contains both periphery knowledge and core knowledge connected with various linkages. These linkages can be demonstrated in a knowledge map, a chart that describes all the actions taken [30].

Both periphery knowledge and core knowledge are intellectual results of internal staff in forerunners, and they are constructed following the same or similar rules of organization and expression. The similarity constitutes the identity relationship of periphery knowledge and core knowledge. Although periphery knowledge and core knowledge belong to different categories at the knowledge level, they may appear in the same category under other criteria. For example, heat treatment technology and testing technology belong to the core technology and periphery technology at the technical level. Still, both belong to the core knowledge in the product development process. As the two types of knowledge in the same enterprise, periphery and core knowledge play their respective roles in the development process. They are also complementary to each other.

Latecomers can find the linkage between periphery knowledge and core knowledge in forerunners. The latecomers can identify the core knowledge factors in periphery knowledge with knowledge processing and extraction technology. They can dig deeper into the relationships between core knowledge and periphery knowledge factors with knowledge linkage technology, build more abundant core knowledge, and increase the core knowledge obtained from the forerunners.

Knowledge linkages can be divided into three types: identity, membership, and relativity [31]. Identity refers to the similar characteristics between knowledge factors. Membership means every knowledge factor can belong to a specific category. Relativity is associated with the consistency between knowledge factors, such as the opposite, causality, citation, and influence. Core knowledge and periphery knowledge may link in the three types of linkages. First of all, both core knowledge and periphery knowledge are the intellectual achievements of staff so that they may be constructed and expressed following the same or similar rules. This ensures their linkage of identity. Second, although core knowledge and periphery knowledge belong to different categories at the technical level, they may appear in the same category under other criteria. The testing technology (core technology) and heat treatment technology (periphery technology) belong to higher and lower technical levels separately, but both are constituent parts of the product development process. This ensures their linkage of membership. Third, as knowledge in the same enterprise, core and periphery knowledge are complementary and supportive, especially when playing roles in the new technology development process.

Latecomers can find the linkages between core knowledge and periphery knowledge of forerunners based on the analysis of knowledge. Alternatively, the latecomers may identify the core knowledge factors in periphery knowledge with knowledge processing and extraction technology. However, it should be noticed that acquiring all the linkages between core knowledge and periphery knowledge in forerunners needs deep interaction. As a result, R&D cooperation is always chosen by latecomers to interact with forerunners.

1.2. Research Framework. Based on the analysis of linkages, the framework of the knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge (shown in Figure 2) is conducted. In R&D cooperation between latecomers and forerunners, the forerunners share their periphery knowledge. The latecomers might acquire some core knowledge factors through the linkages between forerunners' periphery knowledge and core knowledge. The latecomers create new core knowledge by integrating those core knowledge factors with the internal core knowledge.

We use the set theory to explain the linkages between knowledge factors in the knowledge map to demonstrate the knowledge innovation mechanism. According to the set theory, the knowledge map (KM) can be expressed as

$$\mathrm{KM} = \left\{k \mid k \in \mathrm{KM}_f, \cap k \in \mathrm{KM}_r\right\}, \quad (2)$$

$$\mathrm{KM}_f = \{(T_i, Ke_i, O_i)\}\ (i = 1, 2, \ldots\ldots n), \quad (3)$$

$$\mathrm{KM}_r = \left\{A_{Tij}, A_{Keij}, R_{TiKei}, r_{KeiTi}\right\} \cdot (i = 1, 2, \ldots\ldots n;\ j = 1, 2, \ldots\ldots n). \quad (4)$$

Here, KM_f represents the set of knowledge factors in the knowledge map, including the theme T_i, the knowledge element K_{ei}, and the resource O_i; KM_r represents the linkages of factors in knowledge map, including the linkages between themes (A_{Tij}), the linkages between knowledge elements (A_{Keij}), the linkages between the theme and the knowledge element (R_{TiKei}), and the linkages between the knowledge element and the knowledge resource (K_{eiji}).

In R&D cooperation between latecomers and forerunners, forerunners will only share their periphery knowledge to keep their competitive advantage [32]. However, knowledge is always a complex system. There will be core knowledge factors in the periphery knowledge system. The latecomers can gain these core knowledge factors through sharing forerunners' periphery knowledge and construct new core knowledge through integrating these core knowledge factors with their knowledge factors.

We assume that forerunners share their periphery themes T_2 and T_3. T_2 contains one periphery knowledge element (K_{e1}) and two core knowledge elements ($K_{e3,}$ and K_{e6}), two periphery resources (O_2 and O_{n-1}), and two core resources (O_3 and O_4); T_3 contains one periphery knowledge element (K_{e4}), one core knowledge element (K_{e2}), one periphery resource (O_{n-1}), and two core resources (O_4 and O_n) (shown in Figure 3).

Those themes, knowledge elements, and sources could construct many periphery knowledge structures. We choose four of them who contain core knowledge factors: $\mathrm{KS}_{ps1}(T_2\text{-}\ K_{e6}\text{-}\ O_3)$, $\mathrm{KS}_{ps2}(T_2\text{-}\ K_{e3}\text{-}\ O_4)$, $\mathrm{KS}_{ps3}(T_3\text{-}\ K_{e2}\text{-}\ O_4)$, and $\mathrm{KS}_{ps4}(T_3\text{-}\ K_{e4}\text{-}\ O_8)$. In the theme layer, periphery themes T_2 and T_3 are linked with core themes T_1 and T_4, so that the latecomers may be aware of some core knowledge factors in themes T_1 and T_4. The latecomers will link the periphery knowledge factors to the core knowledge factors to construct new advanced knowledge. This process is shown below.

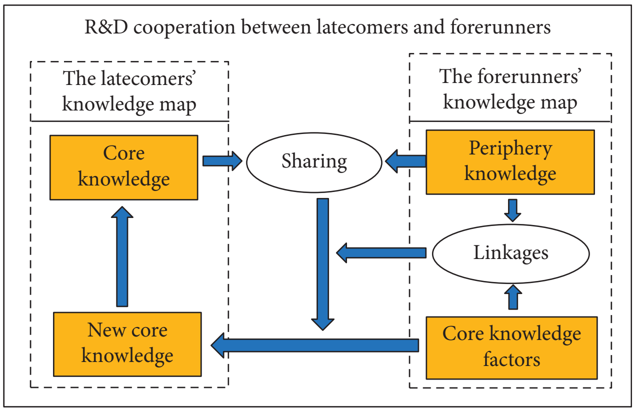

Figure 2: Framework of knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge.

First, the four periphery knowledge structures are expressed as

$$\begin{aligned}\mathrm{KS}_{ps1} &= \left\{k_{ps1} \mid k_{ps1} \in \mathrm{KS}_{psf1}, \cap k_{ps1} \in \mathrm{KM}_{psr1}\right\},\\ \text{with } \mathrm{KS}_{psf1} &= \{T_2, Ke_6, O_3\},\\ \mathrm{KS}_{psr1} &= \{R_{26}, r_{63}\},\\ \mathrm{KS}_{ps2} &= \left\{k_{ps2} \mid k_{ps2} \in \mathrm{KS}_{psf2}, \cap k_{ps2} \in \mathrm{KM}_{psr2}\right\},\\ \text{with } \mathrm{KS}_{psf2} &= \{T_2, Ke_3, O_4\},\\ \mathrm{KS}_{psr2} &= \{R_{23}, r_{34}\},\\ \mathrm{KS}_{ps3} &= \left\{k_{ps3} \mid k_{ps3} \in \mathrm{KS}_{psf3}, \cap k_{ps3} \in \mathrm{KM}_{psr3}\right\},\\ \text{with } \mathrm{KS}_{psf3} &= \{T_3, Ke_2, O_4\},\\ \mathrm{KS}_{psr3} &= \{R_{32}, r_{24}\},\\ \mathrm{KS}_{ps4} &= \left\{k_{ps4} \mid k_{ps4} \in \mathrm{KS}_{psf4}, \cap k_{ps1} \in \mathrm{KM}_{psr4}\right\},\\ \text{with } \mathrm{KS}_{psf4} &= \{T_3, Ke_4, O_8\},\\ \mathrm{KS}_{psr4} &= \{R_{34}, r_{48}\}.\end{aligned} \tag{5}$$

To transform these four periphery knowledge structures into core knowledge structures, the core themes T_1 and T_4 need to be introduced. Four core knowledge structures can be obtained according to the relation between core theme T_1 and T_4 and periphery theme T_2 and $T_{3.}$

According to formula (2), A_{Tij} represents the linkages between themes. The links between the core theme T_1 and the periphery theme T_2 can be described as A_{T12}, and the links between the core theme T_4 and the periphery theme T_3 can be described as A_{T43}. Then, A_{T12} and A_{T43} are added to the periphery knowledge structures KS_{ps1}, KS_{ps2}, KS_{ps3}, and KS_{ps4}, to obtain four core knowledge structures KS_{cs1}, KS_{cs2}, KS_{cs3}, and KS_{cs4}.

$$\begin{aligned}\mathrm{KS}_{cs1} &= \left\{k_{cs1} \mid k_{cs1} \in \mathrm{KS}_{csf1}, \cap k_{cs1} \in \mathrm{KM}_{csr1}\right\},\\ \text{with } \mathrm{KS}_{csf1} &= \{T_1, T_2, Ke_6, O_3\},\\ \mathrm{KS}_{csr1} &= \{A_{12}, R_{26}, r_{63}\},\\ \mathrm{KS}_{cs2} &= \left\{k_{cs2} \mid k_{cs2} \in \mathrm{KS}_{csf2}, \cap k_{cs2} \in \mathrm{KM}_{csr2}\right\},\\ \text{with } \mathrm{KS}_{csf2} &= \{T_1, T_2, Ke_3, O_4\},\\ \mathrm{KS}_{csr2} &= \{A_{12}, R_{23}, r_{34}\},\\ \mathrm{KS}_{cs3} &= \left\{k_{cs3} \mid k_{ps3} \in \mathrm{KS}_{csf3}, \cap k_{cs3} \in \mathrm{KM}_{csr3}\right\},\\ \text{with } \mathrm{KS}_{csf3} &= \{T_4, T_3, Ke_2, O_4\},\\ \mathrm{KS}_{csr3} &= \{A_{43}, R_{32}, r_{24}\},\\ \mathrm{KS}_{cs4} &= \left\{k_{cs4} \mid k_{cs4} \in \mathrm{KS}_{csf4}, \cap k_{cs1} \in \mathrm{KM}_{csr4}\right\},\\ \text{with } \mathrm{KS}_{csf4} &= \{T_4, T_3, Ke_4, O_8\},\\ \mathrm{KS}_{csr4} &= \{A_{43}, R_{34}, r_{48}\}.\end{aligned} \tag{6}$$

The four core knowledge structures form a new core knowledge map: $\mathrm{KM}_{cs} = f(\mathrm{KS}_{cs1}, \mathrm{KS}_{cs2}, \mathrm{KS}_{cs3}, \mathrm{KS}_{cs4})$ (Figure 4). The description of the knowledge innovation mechanism reveals that, in R&D cooperation between latecomers and forerunners, the latecomers share and extract core knowledge factors that existed in the forerunners' periphery knowledge and construct new core knowledge by linkages between periphery knowledge and core knowledge.

Although the latecomers cannot share the core knowledge of forerunners, some core knowledge factors can also help the latecomers construct core knowledge. The recombination of knowledge factors can create new knowledge and identify the linkages among those knowledge factors [33]. According to constructivist learning theories, constructing knowledge depends on what is already known. What is already known depends on the kinds of experiences we have had and how we organize these into existing knowledge structures. According to different linkages in knowledge factors, knowledge structures are organized differently, creating different knowledge. Park described the relationships among science units, i.e., science knowledge elements [34]. Therefore, far more combinations of science units and far more potential relationships exist. However, meaningful relationships might be escaping our notice. Until those units, like fragments of a puzzle, are brought together, the relationships among them may remain undiscovered [35]. Knowledge linkages can link many knowledge factors to build an integrated knowledge structure, through which organizations acquire the target knowledge they want.

2. Method

2.1. Case Selection. To more intuitively demonstrate the knowledge innovation mechanism in R&D cooperation, a case of R&D cooperation between latecomers and forerunners was selected. We select the cases followed by these criteria: the partners of R&D cooperation must be latecomers and forerunners, the partners share their periphery knowledge in R&D cooperation, and the latecomers create new core knowledge and make critical technical breakthroughs after the R&D cooperation.

Based on the above criteria, R&D cooperation between Company D and Company G was selected. Firstly, the

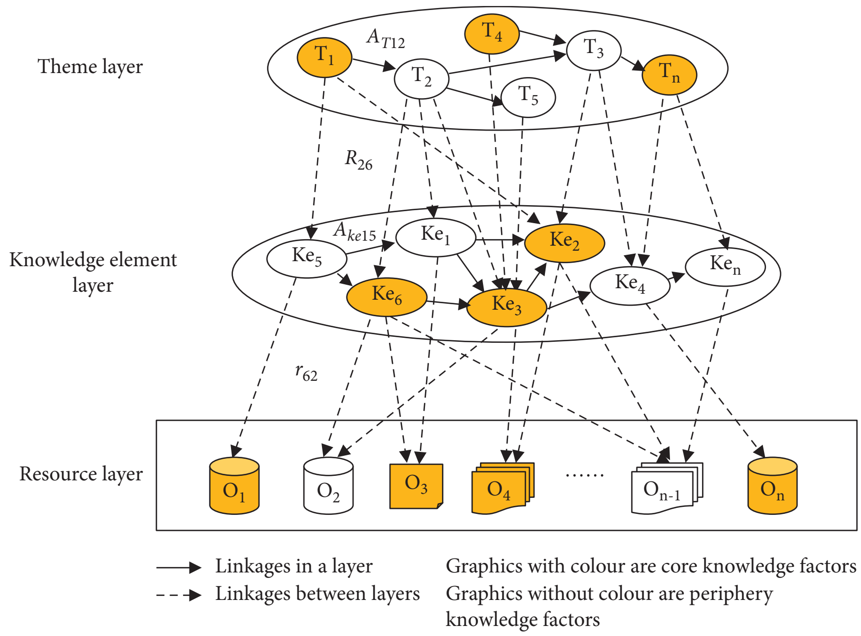

Figure 3: Knowledge map of forerunners shared in R&D cooperation.

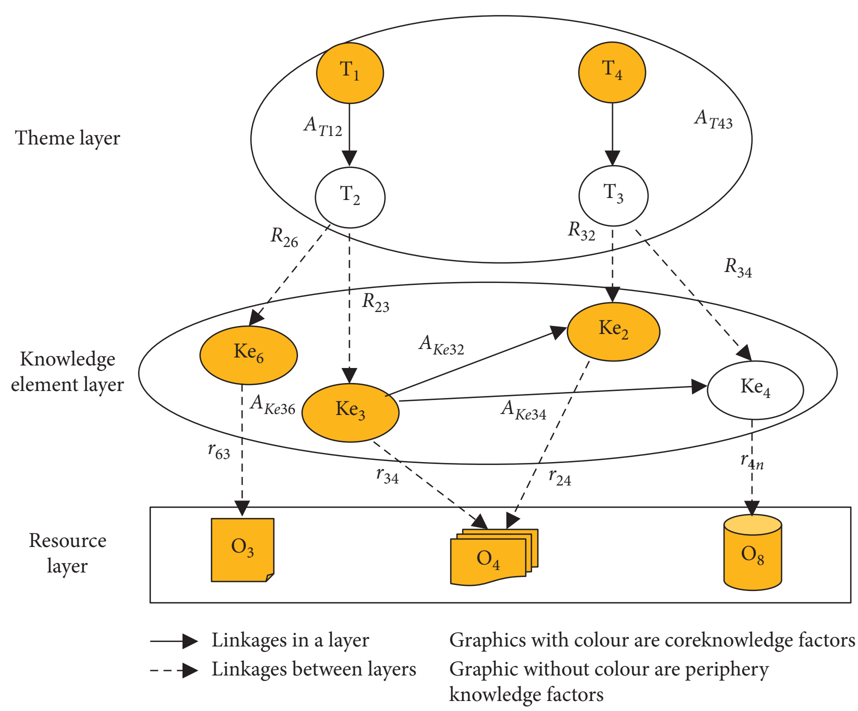

Figure 4: Reconstruct knowledge map of latecomers.

partners of R&D cooperation, Company D and Company G, were latecomers and forerunners. Company D is an equipment manufacturing corporation affiliated with the Aviation Industry Corporation of China. It has the most advanced helicopter engine in China. Its main products were $4G_1$ and $4G_9$ series gasoline engines with the displacement from 1.3 L to 2.0 L and automatic transmission (4AT, 5AT). It is the first enterprise in China to own the manufacturing technology for automotive engines, automatic transmission, and manual transmission. Although the outstanding achievements were made in manufacturing technology, Company D was still a latecomer for Company G. Company G is an American manufacturing company that owns the leading technology in automatic engine R&D and manufacture. Secondly, Company D and G shared their periphery knowledge in R&D cooperation. In 2003, company D and G signed an agreement to jointly develop the turbo 5E (Model WJ5E). The agreement stipulates that company D is responsible for the design work of the WJ5E, and company G is responsible for the manufacturing work of the WJ5E and instructs and helps company D's design work. In this collaboration, Company D and Company G only shared their periphery knowledge to protect their core knowledge and competitive advantage. Thirdly, Company D created new core knowledge and made critical technical breakthroughs after the R&D cooperation. Through the R&D cooperation, Company D developed the advanced turbo WJ5E, which was in the leading position in China. Compared with the original model WJ5A-1, WJ5E is desired because of lower fuel consumption and higher performance. The improvement targets of WJ5E are shown in Table 1. Besides advanced products, Company D established a complete aero engine and helicopter transmission system test system, and built the first-class manufacturing system in the later development process.

2.2. Data Collection. The research data were "triangulated" through a variety of data sources. The primary data sources are as follows (Table 2): (a) On-site interviews. We conducted eight in-depth interviews, efficiently collecting rich case data [36]. Each interview ranged from 30 to 70 min and was conducted by research team members. The numbers of managers and technical experts and interview time in the case are shown in Table 2.

The interviewees' selection was made with the following considerations: involved in the R&D cooperation; be responsible for a specific R&D work; positions included middle and senior managers and technical experts; sectors included several management and technology sectors in R&D partners to enhance the unit triangulation of data [37]. The interview was semistructured and focused on the actions, interactions, and perceptions of interviewees in R&D cooperation (the semistructured interview list is shown in Appendix). (b) Public information: we also collected secondary data on documented procedures, reports, bulletins, and publications, which enabled us to obtain more background information about the overall context, thus allowing for empirical triangulation of the firms' R&D cooperation. Table 3 shows evidence sources and coding.

2.3. Validity and Reliability. Several measures were taken to address the validity and reliability of the study. Firstly, the semistructured interview list (Appendix) was designed based on relevant literature and our research objective, ensuring the internal validity of case information; secondly, the case information obtained through various sources was recorded, transcribed, and coded carefully. All the case data were contrasted and compared with multiple sources of evidence to triangulate data and thereby improve the reliability deliberately.

2.4. Findings

2.4.1. The Dilemma of Company D in Design Work. Design is the critical step of engine R&D. The main work of Company D in this step is turbine's aerodynamic design, mechanical design, life analysis, and reliability analysis. The aerodynamic design is complex for Company D to breakthrough. The aerodynamic design of the turbine requires very high design technology, especially for the turbine flow channel, the third level working blades, and the guide blades. The main problems why Company D is difficult to solve in aerodynamic design are:

(i) The irrational design of flow channel leads to leakage of turbine rotor
(ii) A too big gap between the third level working blades
(iii) The roots of the working blades and the guide blades cannot be sealed
(iv) The first level working blades cannot be cold
(v) Turbine casing leaks air

Table 1: The improvement targets of WJ5E.

Themes	Improvement targets
Fuel consumption rate per unit	Reduced by 9.4%
Service life	No less than 3000 hours
Temperature	No higher than WJ5A-1
Starting performance	No lower than WJ5A-1
Surge margin	No lower than WJ5A-1

Table 2: The numbers of managers and technical experts and interview time.

Index	Company D	Company G
Number of managers	3	1
Number of technical experts	2	2
Total numbers	5	3
Total interview time	270 minutes	150 minutes

2.4.2. The Core Knowledge Factors of Company G in Manufacturing Work. Although the manufacturing work is mainly related to company G's periphery knowledge, there will always be some core knowledge factors, such as new materials, structures, and crafts used in the process. Some new materials, structures, and new crafts that Company G used in manufacturing are shown in Table 4. The new materials include the axial sealing teeth and the anticorrosive blade coating; the new structures have the W-ring structure, the elastic ring structure, the honeycomb outer ring structure, and the fan-shaped turbine outer ring structure. The new crafts include the Vacuum Brazing craft of the third-level working blade and the Processing Technology of the working blade's cooling groove.

2.5. The Improvement of Design in Company D. The design and manufacturing are two essential activities of the R&D process of WJ5E, which are complementary and promote each other. On the one hand, design is the foundation of manufacturing. The production of the desired turbine depends on a rational design; on the other hand, manufacturing can provide insights to design for its improvement. The problems in the manufacturing process can reflect the flaws in the design work, guiding design

Table 3: Evidence sources and coding.

Source code	Type	Source	Content
E_1	Interviews	Managers and technical experts of Company D and Company G	Interview records and documents provided by the interviewees
E_2	Documented procedures	Managers of company D and G; official websites of company D and Company G	Rules and regulations, technical manuals, operating instructions
E_3	Reports and bulletin	Managers of Company D and Company G; official websites of Aviation Industry Corporation of China	Annual reports and interim reports, statistics bulletin about Chinese helicopter engine technology
E_4	Publications	China national knowledge infrastructure; national press and publication administration	Papers, dissertations, and monographs about aviation industry, helicopter engine technology, and R&D cooperation

Table 4: New materials, structures, and crafts in company G's manufacturing process.

Process	Aspect	Index
Product manufacturing	New materials	Axial sealing teeth Anticorrosive blade coating (aluminized silicon)
	New structures	W-ring structure Elastic ring structure Honeycomb outer ring structure Fan-shaped turbine outer ring structure
	New crafts	Vacuum brazing craft of the third level working blade Processing technology of the working blade's cooling groove

advancement. The design work and manufacturing are different acts to the same object: design chooses materials, manufacturing uses materials, design decides aerodynamic structure, and manufacturing products and assembles aerodynamic parts.

Due to the close relationship between design and manufacturing, the core knowledge in the design process must be linked to the core knowledge factors in manufacturing. Company D's designers communicated deeply with company G's manufacturing staff and gradually understood these core knowledge factors. Company D's designers linked these core knowledge factors with their knowledge and created new core knowledge. This new core knowledge solved design problems and improved company D's technology of WJ5E.

2.6. Technology Breakthrough of Company D in WJ5E. By sharing the periphery knowledge of Company G, Company D acquired the core knowledge factors in manufacturing and linked them with the core knowledge factors in the design to construct new core knowledge. This new core knowledge solved the problems in the design and improved design technology of Company D. With this new core knowledge, the engine fuel consumption was reduced, the life and stability of the engine were improved, and Company D's goal of R&D cooperation was also successfully achieved. In September 1990, the WJ5E engine passed the tests of bench performance, axial force, and machine vibration. The results show that all the performance reached the design requirements, the unit fuel consumption rate decreased by 9.4%, and the life of the improved structure of turbine engine is longer than other structures in domestic market. At the same time, the performance, structure, and airworthiness of WJ5E were also better than the original one. By cooperating with Company G, Company D improved its technology and innovation ability. In the following two decades, from repairs, imitations, modifications to independent R&D, Company D continues to learn, accumulate, innovate, and improve. It has established a complete aero engine and helicopter transmission test system, mastered the aero engine and aero transmission system test technology, and formed the technical capabilities of helicopter transmission system component test under 15 tons, the whole machine test, and the aircraft and engine accessory transmission.

Company D built the first-class manufacturing system in the later development process, possessing high, precise, and cutting-edge equipment and technology in magnesium-aluminum casting, gear processing, heat meter treatment, physical and chemical measurement, etc., and cultivated a first-class talent team. It has independent solid research and development capabilities and unique technical advantages. To accelerate internationalization, Company D has extensively cooperated with internationally renowned companies such as Pratt and Whitney in Canada, Euro copter, Turbomeca in France, Honeywell in the United States. At present, Company D has accumulated repairs, development, and production of dozens of aircraft types with more than 15,000 sets of aero engines and 9,000 sets of helicopter transmission systems. It has become a professional R&D and production company in aero engines and helicopter transmission systems in China.

3. Discussion

3.1. Knowledge Innovation Mechanism in R&D Cooperation. Based on the case of R&D cooperation, this study analyses the linkages between periphery knowledge and core knowledge in forerunners, the link process of periphery knowledge and core knowledge between latecomers and forerunners, and the creation of new core knowledge in latecomers. This study analyses the actual process to identify the critical factors that determine the knowledge innovation mechanism in R&D cooperation and sets up a framework to explain how the essential factors act in R&D cooperation (Figure 5).

R&D cooperation with various partners increases the complexity and facilitates reciprocal learning and knowledge innovation. In the R&D cooperation between Company D and Company G, with deep interaction and learning between technicians of partners, Company D's technicians shared Company G's periphery knowledge in manufacturing, and some core knowledge factors (such as new materials, new structure, and new craft) exist in this periphery knowledge relying on knowledge linkages. Furthermore, Company D's technicians linked these core knowledge factors with its core knowledge in design, solved design problems, and created new core knowledge in design.

The W-ring structure and Elastic ring structure provided ideas for company D to improve the flow channel. Company D redesigned the trail of the diversion disc and reduced the clearance of the lower edge of the working blade, thereby reducing the turbine rotor leakage; The use of Vacuum brazing craft of third level working blade reduced the gaps between the tips of third level working blades and stopped the leakage; The use of Axial sealing teeth and Honeycomb outer ring structure improved the seal design of company D so that the roots of the working blades and guide blades were sealed very well; the use of anticorrosive blade coating (aluminized silicon) and processing technology of the working blade's cooling groove made it possible that the engine can stop the cooling of first-level work blade; fan-shaped turbine outer ring structure improved the structure of the turbine engine and reduced its air leakage and the volume of cold air.

To deepen the understanding of the knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge, we divide the knowledge innovation process into the following three phases: Phase I: Knowledge share in R&D cooperation; Phase II: Identification of linkages between periphery knowledge and core knowledge; Phase III: Knowledge integration and creation.

3.1.1. Phase I: Knowledge Share in R&D Cooperation. The most significant advantage of R&D cooperation over independent R&D is that it can share partners' knowledge resources and expand the resource base for knowledge innovation [38, 39]. In R&D cooperation between latecomers and forerunners, knowledge flows from forerunners to latecomers because of the potential knowledge gap. Forerunners only share their periphery knowledge to protect their competitive advantage [40]. However, as periphery knowledge and core knowledge jointly constitute the knowledge system of a company, there must be an indissoluble connection between them. This connection gives a chance to latecomers to share the core knowledge factors of forerunners. The R&D process contains a series of activities. We identify the R&D process as a series of activities including idea generation, conception, design, development, test, and manufacturing [41]. These activities are shown in the knowledge map of WJ5E's R&D (Figure 6).

Partners need to share relative knowledge to complete the R&D process. In the R&D cooperation of WJ5E, Company D shared its knowledge in design, and Company G shared its knowledge in manufacturing. According to the knowledge map of WJ5E's R&D, we can find that design and manufacturing share two core elements (structure and crafts) and two core resources (welding technique and ring structure). These core knowledge elements and resources play an essential role in latecomers' knowledge innovation.

3.1.2. Phase II: Identification of the Linkages between Periphery Knowledge and Core Knowledge. In R&D cooperation, the forerunners share periphery knowledge with the latecomers [42], but some core knowledge embedded in periphery knowledge could also be shared. The periphery knowledge and core knowledge of forerunners have been embedded in personnel, products, technologies, tools, processes, and routines. As an organized, purposeful, and structured system, R&D activities are interrelated and interdependent [43]; the periphery and core knowledge embedded in these R&D activities will be linked with each other too. Identifying these linkages is the key to latecomers' knowledge innovation [44].

The latecomers may identify these linkages between shared periphery knowledge and core knowledge factors through formal and informal interactions. Formal interactions refer to meetings, seminars, brainstorming sessions, teaching and learning, etc., which R&D partners organize. In contrast, informal interactions refer to chatting, visiting, on-site guiding, discussion off duty, etc., which are personal behaviours between members of R&D partners [45]. Both formal and informal interactions promote mutual learning and strengthen the ties between partners [46], facilitating latecomers to identify the linkages between shared periphery knowledge and core knowledge factors. In-depth interactions may weaken and break organizational boundaries, forming cross-organizational teams [47]; when the relationship between organizations reaches a certain strength, the knowledge flow between organizations becomes fast [48]. Core knowledge factors embedded in the cross-organizational teams will inevitably flow to the latecomers through the linkages with periphery knowledge. However, due to the stickiness of knowledge, the flow of embedded knowledge is prolonged and awkward. So, informal interactions become an essential lubricant for the flow [49]. Chatting in a dinner or tea party may establish more complex and intimate relationships between members of R&D partners.

As two essential activities of WJ5E's R&D, design and manufacturing are closely related. When designing WJ5E, technicians and managers of Company D need to communicate with Company G. The design must be feasible for manufacturing. Company G will report to Company D as

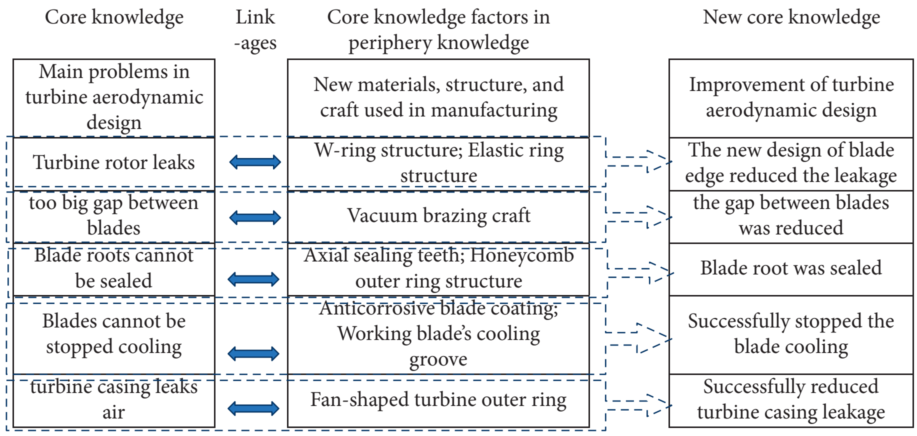

Figure 5: Knowledge innovation mechanism in R&D cooperation.

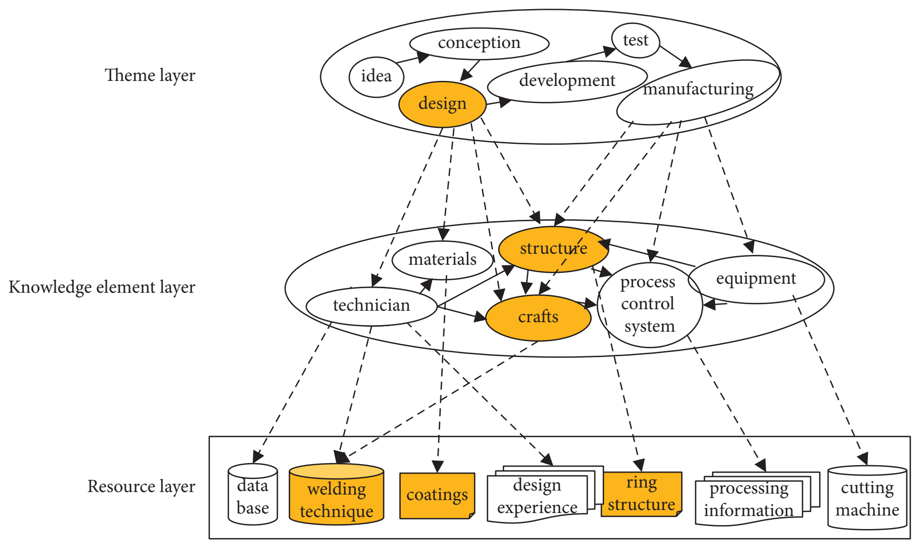

Figure 6: The knowledge map of WJ5E's R&D.

soon as they find the manufacturing design problems. They often discuss these problems in offices or workshops. Sometimes, technicians of Company G show how the equipment is used in manufacturing, which gives the technicians of Company D a chance to know some new and advanced materials, structures, and crafts in Company G's manufacturing process. Staff of Company D and Company G always have staff dinner or tea parties. Some technicians like to tell their stories, and others share their experiences in work and life. With these formal and informal interactions, technicians and managers of Company D find the linkages between axial sealing teeth and leaf roots, ring structure and turbine rotor, vacuum brazing craft and third-level working blade, etc. These linkages facilitate the integration of Company G's core knowledge factors and Company D's internal knowledge.

3.1.3. Phase III: Knowledge Integration and Creation. Based on the linkages between periphery knowledge and core knowledge factors, the latecomers will integrate them into their internal knowledge system and create new knowledge. The essence of knowledge integration is knowledge connection [50], and the reason why different knowledge factors can be integrated to form new knowledge is the connection between knowledge factors.

There are two types of knowledge integration: one is based on existing knowledge factors and believes that knowledge integration is a rearrangement and combination of existing knowledge factors; the other one is based on new knowledge factors and believes that knowledge integration is the transformation of new knowledge factors to original knowledge structure [51]. The knowledge integration in this study is of the second type. The latecomers analyze and categorize the acquired core knowledge factors, determine their value and position in the knowledge system, and then create new knowledge by integrating internal and external knowledge.

By learning the new materials and advanced crafts of Company G, technicians of Company D found that these new materials and advanced crafts could improve their design. These new materials and advanced crafts provide

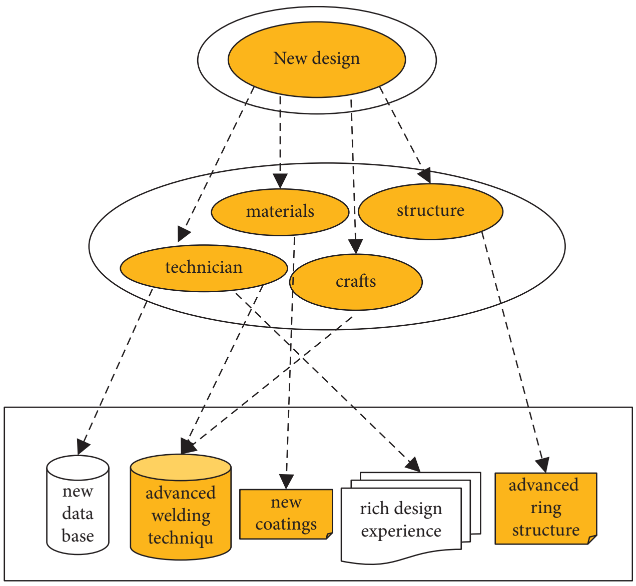

Figure 7: The knowledge map of new design.

new ideas to the technicians. These new ideas improved the original design of materials, crafts, structure, and technicians. The new design was put forward, and it solved all the problems in the turbine design. The knowledge map of the new design is shown in Figure 7.

All the resources were updated or advanced in this knowledge map, so all four elements became core knowledge elements, and the new design became core knowledge. The latecomers further apply the new core knowledge to their Company, constructing more knowledge through improvement and adjustment. A new advanced knowledge system will be constructed, and the innovation capability of the latecomers will be raised to a considerable extent.

4. Conclusion

How can latecomers create new knowledge in R&D cooperation with forerunners? This study answered this question from the perspective of knowledge linkage. The linkages between periphery knowledge factors and core knowledge factors were noticed and used creatively to demonstrate the knowledge innovation mechanism in this study. Knowledge map theory and set methodology were used to reveal the knowledge construction process. A case of R&D cooperation between Company D and Company G was introduced to verify this knowledge innovation mechanism. The results show that: (1) the latecomers create knowledge based on linkages between periphery knowledge and core knowledge in R&D cooperation with forerunners; (2) through formal and informal interaction, latecomers could share forerunners' periphery knowledge and have a chance to acquire the core knowledge factors in periphery knowledge based on the linkages between them; (3) there are three phases in the process of knowledge innovation in R&D cooperation: latecomers share periphery knowledge of forerunners and identify the linkages between this periphery knowledge and core knowledge factors; relying on these linkages, the latecomers could get access to these core knowledge factors, and integrate these core knowledge factors into their internal knowledge system and create new core knowledge.

This study makes three main contributions to the literature. Firstly, by taking a microcosmic perspective, this study contributes to the literature on knowledge innovation theory by revealing the knowledge innovation mechanism based on linkages between periphery knowledge and core knowledge factors. This study stands in contrast to prior literature that focused on the function of shared knowledge on knowledge innovation. Instead, this study focuses on the function of shared knowledge factors, especially the core knowledge factors, on creating new knowledge. Secondly, this study deepens the understanding of knowledge linkage theory with set methodology. The set methodology is introduced to the analysis of the knowledge construction process. Knowledge is considered as a set of various knowledge factors. The linkages among these knowledge factors and the transformation from the periphery to core knowledge were deduced clearly by set methodology. Thirdly, this study discloses the latecomers' knowledge innovation process in R&D cooperation with forerunners, deepening the understanding of R&D cooperation between latecomers and forerunners. Prior literature only declares R&D cooperation's function on improving latecomers' knowledge innovation. This study demonstrated this function by explaining the complexity of R&D cooperation and the linkage process of periphery knowledge and core knowledge factors. R&D cooperation with various partners increases the complexity of knowledge factors; some core factors in periphery knowledge might be spilt to latecomers with formal and informal interaction among R&D partners. Latecomers could recombine these core and periphery knowledge factors by identifying or creating new linkages and constructing advanced core knowledge.

The practical implications are equally important. This study provides a new insight into latecomers effectively activating internal and external knowledge resources through R&D cooperation. In collaboration with forerunners, the latecomers should focus on analyzing the knowledge structure of forerunners and exploring the linkages between periphery knowledge and core knowledge factors. They could use the shared periphery knowledge, especially the periphery tacit knowledge, such as organizational practice, corporate culture, and design concepts to infer forerunners' knowledge organization rules and knowledge linkages, giving signs to latecomers of the construction of advanced core knowledge. In addition, the latecomers should consciously improve their involvement in the R&D cooperation and interact with forerunners deeply to facilitate the sharing of periphery knowledge and the affluence of core knowledge factors. If the interaction is not deep enough, it cannot be sustained to obtain forerunners' periphery knowledge and core knowledge factors to form an advanced core knowledge structure.

There are some limitations to this study. The potential knowledge gap between R&D cooperation partners must not be too big or too small to share partners' knowledge and integrate it into internal knowledge. How to choose R&D partners to ensure appropriate knowledge potential gap? This question needs to be discussed in future research.

Appendix

The outline of the interview

1. Brief introduction

Self-introduction, academic purpose, corporate, and interviewee privacy protection.

2. Basic situation of the interviewee and department

2.1 please briefly introduce your department

2.2 please briefly introduce the R&D cooperation and the main work you are responsible for in it

3. The knowledge innovation process

(i) Knowledge sharing

3.1 Please introduce how did you communicate with your R&D partners to share technologies and experiences.

3.2 please introduce the technologies and experiences shared by your R&D partners.

(i) Finding the core knowledge factors in shared knowledge

3.3 Did you find some new or valuable technologies and experiences from your R&D partners, which are very helpful to your work.

(i) Linking core knowledge factors with internal knowledge

3.4 How did you deal with those new or valuable technologies and experiences? Did you link them with technologies and experiences in your work? And how?

(i) Constructing new core knowledge

3.5 Please introduce the challenging problems in your work before cooperating with your R&D partners.

3.6 Please introduce how did you solve those problems; did you rely on those new or valuable technologies and experiences shared from your R&D partners?

3.7 Did you improve your technologies or experiences? Did you invent new products or some components?

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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