Context sensitivity of regional complex knowledge: From an analytical framework to empirical studies

Doctoral dissertation

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Submitted by

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DECLARATION

I declare that under the guidance of my supervisor, Prof. Robert Hassink, I worked on my PhD thesis from September 2019 to May 2023.

The submission contains five chapters. In Chapter 2, section 2.1 is primarily based on the manuscript currently submitted and under review in European Planning Studies, as Xue, S. Advancing the understanding of knowledge complexity in economic geography: Towards an analytical framework, and the manuscript currently published in Journal of Geographical Science, as Xue S. & Liu, C. Combinatorial knowledge dynamics, innovative performance, and transition studies. Moreover, section 2.2.1 and section 4.1 are mainly based on the manuscript currently published in Cogent Social Science, as Xue, S. & Hassink, R. Combinatorial knowledge dynamics and proximity analysis in the Shanghai high-end medical device industry.

The thesis has been prepared subject to the Rules of Good Scientific Practice of the German Research Foundation.

My academic degree has never been withdrawn.

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Place: Kiel Date: 31.05.2023

Catalogues

Catalogue for figures and tables

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On September 8th, 2019, at 6:30 pm, a plane from Shanghai arrived at Hamburg airport via Helsinki. I quickly disembarked to retrieve my luggage. I vividly recall receiving a WeChat message from a friend who had kindly offered to pick me up, which read, "I will be waiting for you at the airport exit." Upon arrival, my friend took me on a two-hour bus ride from Hamburg Airport to Kiel train station. He generously shared various details about life in Germany and gave me valuable information regarding my PhD work. Once we arrived at the Kiel train station, we boarded the 34 bus and proceeded to my pre-booked hotel. After dropping me off at the hotel, my friend bid me farewell and left. It was nearly 10 pm. I am truly grateful to Dr. Xu, the first friend I made in Germany.

Upon arriving in Kiel, I immediately fell in love with the city. The tranquil afternoons, the picturesque bay, the sparkling turquoise lake, the playful squirrels on the lawns, and the vibrant and colourful houses all combined to create a dramatic scene that reminded me of the cartoons from my childhood.

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Robert was delighted and shared the good news with other scholars who also attended the same online conference with him on that day.

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Extended Abstract

Regional complex knowledge evolution has become a popular topic in the economic geography literature. Scholars measure regional complex knowledge to explain regional economic complexity or the agglomeration of innovative activities. According to the literature, such knowledge is tacit in nature, and it is mainly static and ingrained in the workers, companies, and institutions of specific locations. While studies have provided valuable insights into the agglomerative spatial patterns of complex knowledge production, making significant advancements in how it is measured and evaluated, they have not addressed the sensitivity of the context of complex regional knowledge in economic geography. To address such a gap, this dissertation aims to advance the understanding of complex knowledge by examining knowledge base combinations. I do so by exploring and comparing knowledge evolutionary processes in two industries in Shanghai: high-end medical devices and electric vehicles.

High-end medical devices and electric vehicles are multidisciplinary, knowledge-intensive, and capital-intensive industries where cross-sector research and development (R&D) prevail. I selected these industries because they can be expected to include the combination of several knowledge bases and knowledge interaction. Moreover, these two industries are highly dependent on national institutions and regional policy support in China. As such, the effects of governance complexity on regional industrial innovation are visible.

This dissertation draws four conclusions. First, compared to Shanghai's high-end medical device industry, there are relatively strong upstream–downstream interactions in the Shanghai electric vehicle industry. Original equipment manufacturers (OEMs) specializing in high-end medical devices need to mobilize innovative sources at different spatial scales by multi-dimensional proximities. OEMs specializing in electric vehicles promote and are promoted by related sectoral development in the upstream position of the electric vehicle industry chain in terms of multi-scalar institutional changes. Second, multiple actors, such as institutes, entrepreneurs, and governments, contribute to the evolution of complex knowledge in the innovation system reconfiguration (ISR) process in these two cases. Among these, institutional evolution is relatively weak in the Shanghai high-end medical device industry because of the very limited application of optical knowledge, which is highly dependent on university affiliations. Moreover, in these two cases, the dynamic capabilities of entrepreneurs are similar. There are strong alignments in the dynamic capabilities of OEMs and part manufacturers (PMs) are visible. While Shanghai companies face more challenges than international giants in terms of accumulating technology, Shanghai entrepreneurs strive to enhance their product offerings and innovation capabilities. And then, a broadening and deepening of innovation policy in the Shanghai electric vehicle industry are visible, whereas policies, rules, and regulations for the final medical device products lead to governance complexity, whereas the policies, rules, and regulations for the medical device industry suffer from governance complexity. Third, the similarities of the policy upgrading process in the two industries include the industry chains' national–regional institutional changes and upstream–downstream policies. They differ insofar as policies for the Shanghai electric vehicle industry are stricter than in the Shanghai high-end medical device industry. Also, policy upgrading emphasizes firms in the upstream position of the electric vehicle chain to a greater extent than in the high-end medical device industry. Fourth, by advancing the understanding of complex knowledge from a combinatorial knowledge base (CKB) perspective and linking CKB to ISR in these two cases, I show that, in turn, advancing an understanding of complex knowledge and complex knowledge evolutionary theory is feasible, reliable, and effective.

This dissertation makes four main contributions. First, it advances the understanding of complex knowledge from a CKB perspective, providing a complementary approach to measuring complex knowledge in economic geography. Second, it introduces a context-sensitive theory of complex knowledge evolution by combining the concepts of CKBs and ISR. Third, it draws on a recent empirical study of the Shanghai medical device and automobile industries to illustrate the theory and shed light on complex knowledge trajectories and the relations among multiple sectors at the regional level. Fourth, it examines upstream–downstream interactions in the Shanghai medical device and electric vehicle industrial chains, refining complex knowledge research at different spatial scales and transitional contexts.

Erweiterte Zusammenfassung

Die Entwicklung von regionalem komplexem Wissen ist zu einem beliebten Thema in der wirtschaftsgeografischen Literatur geworden. Die Wissenschaftler messen regionales komplexes Wissen, um die regionale wirtschaftliche Komplexität oder die Agglomeration innovativer Aktivitäten zu erklären. In der Literatur wird davon ausgegangen, dass dieses Wissen stillschweigend vorhanden ist und hauptsächlich statisch und in den Arbeitnehmern, Unternehmen und Institutionen bestimmter Standorte verankert ist. Studien haben zwar wertvolle Einblicke in die agglomerativen räumlichen Muster der Produktion von komplexem Wissen geliefert und bedeutende Fortschritte bei der Messung und Bewertung dieses Wissens gemacht, aber sie haben sich nicht mit der Sensibilität des Kontextes von komplexem regionalen Wissen in der Wirtschaftsgeographie befasst. Um diese Lücke zu schließen, zielt diese Dissertation darauf ab, das Verständnis von komplexem Wissen durch die Untersuchung von Wissensbasiskombinationen zu verbessern. Ich tue dies, indem ich Wissensentwicklungsprozesse in zwei Branchen in Shanghai untersuche und vergleiche: hochwertige medizinische Geräte und Elektrofahrzeuge.

Hochwertige medizinische Geräte und Elektrofahrzeuge sind multidisziplinäre, wissens- und kapitalintensive Branchen, in denen sektorübergreifende Forschung und Entwicklung (FuE) vorherrschen. Ich habe diese Industrien ausgewählt, weil man davon ausgehen kann, dass sie die Kombination verschiedener Wissensgrundlagen und Wissensinteraktionen beinhalten. Außerdem sind diese beiden Branchen in hohem Maße von nationalen Institutionen und regionaler politischer Unterstützung in China abhängig. Daher sind die Auswirkungen der Komplexität der Governance auf die regionale industrielle Innovation sichtbar.

In dieser Dissertation werden vier Schlussfolgerungen gezogen. Erstens gibt es in der Shanghaier Elektrofahrzeugindustrie im Vergleich zur High-End-Medizinprodukteindustrie relativ starke Upstream-Downstream-Interaktionen. Erstausrüster (OEMs), die auf hochwertige medizinische Geräte spezialisiert sind, müssen innovative Quellen auf verschiedenen räumlichen Ebenen durch mehrdimensionale Nähe mobilisieren. OEMs, die sich auf Elektrofahrzeuge spezialisiert haben, fördern und werden durch die damit verbundene sektorale Entwicklung in der vorgelagerten Position der Elektrofahrzeug-Industriekette im Hinblick auf multiskalare institutionelle Veränderungen gefördert. Zweitens tragen in diesen beiden Fällen mehrere Akteure, wie Institute, Unternehmer und Regierungen, zur Entwicklung von komplexem Wissen im Prozess der Rekonfiguration des Innovationssystems (ISR) bei. Dabei ist die institutionelle Entwicklung in der Shanghaier High-End-Medizinprodukteindustrie relativ schwach, da die Anwendung von optischem Wissen sehr begrenzt ist und in hohem Maße von Universitätszugehörigkeiten abhängt. Außerdem sind die dynamischen Fähigkeiten der Unternehmer in diesen beiden Fällen ähnlich. Bei den dynamischen Fähigkeiten von OEMs und Teileherstellern (PMs) sind starke Angleichungen zu erkennen. Während Shanghaier Unternehmen bei der Anhäufung von Technologien vor größeren Herausforderungen stehen als internationale Giganten, bemühen sich Shanghaier Unternehmer, ihr Produktangebot und ihre Innovationsfähigkeit zu verbessern. Außerdem ist eine Ausweitung und Vertiefung der Innovationspolitik in der Shanghaier Elektrofahrzeugindustrie zu beobachten, während die Politik, die Regeln und die Vorschriften für die Endprodukte der Medizintechnik zu einer komplexen Steuerung führen, während die Politik, die Regeln und die Vorschriften für die Medizintechnikindustrie unter der Komplexität der Steuerung leiden. Drittens sind die Ähnlichkeiten des politischen Modernisierungsprozesses in den beiden Industrien die nationalen und regionalen institutionellen Veränderungen der Industrieketten und die vor- und nachgelagerten Politiken. Sie unterscheiden sich insofern, als die Politik für die Shanghaier Elektrofahrzeugindustrie strenger ist als für die Shanghaier High-End-Medizinprodukteindustrie. Außerdem werden Unternehmen in der vorgelagerten Position der Elektroautoindustrie stärker gefördert als in der High-End-Medizinprodukteindustrie. Viertens zeige ich durch die Weiterentwicklung des Verständnisses von komplexem Wissen aus der Perspektive der kombinatorischen Wissensbasis (CKB) und die Verknüpfung von CKB und ISR in diesen beiden Fällen, dass die Weiterentwicklung des Verständnisses von komplexem Wissen und der Evolutionstheorie für komplexes Wissen machbar, zuverlässig und effektiv ist.

Diese Dissertation leistet vier wesentliche Beiträge. Erstens wird das Verständnis von komplexem Wissen aus einer CKB-Perspektive weiterentwickelt und ein ergänzender Ansatz zur Messung von komplexem Wissen in der Wirtschaftsgeographie bereitgestellt. Zweitens wird eine kontextsensitive Theorie der Entwicklung von komplexem Wissen eingeführt, indem die Konzepte von CKB und ISR kombiniert werden. Drittens wird eine aktuelle empirische Studie über die Shanghaier Medizinprodukte- und Automobilindustrie herangezogen, um die Theorie zu veranschaulichen und die komplexen Wissensverläufe und die Beziehungen zwischen verschiedenen Sektoren auf regionaler Ebene zu beleuchten. Viertens werden die vor- und nachgelagerten Interaktionen in den Industrieketten der Shanghaier Medizinprodukte- und Elektrofahrzeugindustrie untersucht, um die Forschung zu komplexem Wissen auf verschiedenen räumlichen Ebenen und in Übergangskontexten zu verfeinern.

1. Introduction

Regional complex knowledge production has recently become a popular topic in the economic geography literature, in which scholars usually measure regional complex knowledge to explain regional economic complexity or the agglomeration of innovative activities (Balland & Rigby, 2017; Balland et al., 2020; Broekel, 2019; Mewes & Broekel, 2022; Hidalgo, 2021). This literature has shown that "…complex knowledge is relatively immobile, in large part remaining embedded in the workers, firms, and institutions of particular places …" partly because of the tacit character of parts of knowledge (Balland and Rigby, 2017, p16; Hidalgo, 2021).

Although these studies are insightful concerning agglomerative spatial patterns of complex knowledge production and made large advancements in measuring and metrics (Hidalgo, 2021), they lack enough power to explain and tackle some fundamental questions in economic geography, such as why do some regions, despite having similar industrial structures, have a stronger concentration of knowledge complexity than others? Or why do regions differ in their complex knowledge evolution over time? These are questions related to processes and mechanisms of complex knowledge evolution, which have been insufficiently dealt with in current complex knowledge theorizing in economic geography.

Moreover, and in a similar vein, I concur with a recent critical statement made by Martin and Sunley (2022, p73) on the complexity literature in economic geography: "… economic complexity is in effect regarded as both cause and effect: complexity shapes economic development which then shapes changes in economic complexity, and so on. The danger with this conflation is that spatial economic evolution becomes synonymous with changes in the 'complexity networks' of regional economies … Yet whether and in what ways changes in complexity … over time act[s] as historical causal processes are by no means self-evident. Nevertheless, the use of such morphological measures is rarely critically examined. Indeed, their exponents have been moved to make bold, all-inclusive claims for economic complexity. I am concern with such claims is that what are morphological measures of the economic structure are being elevated into universal, all-encompassing causal processes of economic evolution, and risk pushing agents and their contexts completely out of the picture."

Since, on the one hand, knowledge complexity is a crucial issue for the above-mentioned core questions in economic geography; on the other hand, theorizing on complex knowledge evolution is weak. Particularly, the existing measurements of knowledge complexity are primarily based on quantitative analyses, which result in a limited understating of complex knowledge evolutionary processes (Gap 1). Hence, I see the need for advancing the understanding of complex knowledge and for a nuanced, context-sensitive theory, which I coin a theory of complex knowledge evolution.

Most contemporary technologies have value chains that straddle multiple industries, making cross-sector knowledge spillovers necessary (Stephan et al., 2019; Malhotra et al., 2019). As a result, the value chains of these technologies frequently connect many industries that offer the various knowledge bases and industrial capabilities needed for different knowledge bases and production competencies (Jacobsson & Bergek, 2011; Stephan et al., 2017). According to Andersen et al. (2020, p349-p350), "The nature and interaction of these heterogeneous sectors involved in the value chain are central for understanding the industrial dynamics of how technology emerges, transforms or declines as part of transitions … How actors in upstream sectors respond to those change signals can impact both the direction and pace of the transition. An inter-sectoral linkage perspective provides a nuanced view of the sectors and firms engaged in a particular technology. It can connect those changes in upstream sectors to transition processes in a focal sector….”

Since complex knowledge often involves more than one sector, cross-sector and cross-spatial knowledge combinations and characteristics of upstream-downstream interactions have not been sufficiently explored in empirical studies in economic geography (Gap 2). Therefore, I also see the need to analyze complex interactions between actors in different sectors in the regional complex knowledge evolutionary process.

This dissertation aims to explore the context sensitivity of regional complex knowledge evolution. Three questions are answered: (1) What are the characteristics of upstream-downstream interactions in the complex knowledge evolutionary process? (2) Which do actors enter more complex activities, and how do they accomplish them? And (3) how can policy support upgrading towards higher levels of complexity?

The concept of knowledge bases was first put forward by Asheim and his colleagues (2005; 2007; 2011) and emphasizes three kinds of knowledge creation: analytical, synthetic, and symbolic knowledge bases that contribute to a new knowledge distinction. Compared to older distinctions, such as tacit versus codified knowledge (Gertler, 2003), which have only weak connections to knowledge dynamics, knowledge bases are particularly relevant to these three types of innovation processes. This provides a better understanding of the nature of knowledge sharing and innovative activities (Boschma, 2018). Among these, analytical knowledge bases, characterized by formal models, usually take place in science-based innovative projects (Asheim et al., 2011; Davids & Frenken, 2018), such as biomedicine. In contrast, synthetic knowledge creation is mainly based on experiential learning, such as trial and error. This kind of knowledge is easier to observe in construction and traditional automobile industries (Asheim et al., 2011; Davids & Frenken, 2018). The generation of symbolic knowledge is strongly associated with cultural codes or aesthetic elements within cultural industries (Asheim, 2007; Klement & Strambach, 2019).

Advancing the understanding of knowledge complexity from a knowledge base combination perspective is feasible. Asheim (2022, p52) stressed that "As the knowledge base approach does not discriminate against any knowledge and argues that all knowledge types can be the basis for industries pursuing an innovation-based competition, it has become instrumental in designing and implementing a broad-based innovation policy…the knowledge base approach is closer to an institutional than to an evolutionary way of reasoning. The policy dimension with a focus on intentional actors and agencies requires a social ontology as a foundation to understand and explain how emerging industries and new path developments, which often result from public policy interventions and innovative entrepreneurs, take place …"

I build a CKB-complex knowledge analytical framework. I regard the transition from individual knowledge bases, either analytical, synthetic, or symbolic knowledge bases, to a combination of knowledge bases as a complex knowledge evolution trajectory. The CKB concept helps us to identify key technology nodes and related strategies from actors in different sectors. Moreover, in complex knowledge evolution processes, the cross-domain knowledge (base) combination is highly dependent on multi-dimensional proximities, multi-scalar institutional changes, and innovation system reconfigurations in multiple sectors (Baumgartinger-Seiringer et al., 2022; Miörner & Trippl, 2017; 2019; Miörner, 2022). Distinguishing the detailed attributes of actors/organizations and their power in context sensitivity offers a nuanced insight into the complex knowledge evolutionary process, i.e., how it happens and why it succeeds or fails.

Proximity, institutions, and innovation system reconfiguration are introduced as the primary lens with which to unravel the process and its mechanisms: (1) In terms of proximity, I analyze the question of how five dimensions (viz., institutional, cognitive, organizational, social, and geographical proximities) influence the combination of knowledge bases at regional, national, and international levels, providing insight into the complex knowledge evolution across space and sectors. (2) From an institutional perspective, I explore how interactions between upstream-downstream sectors take place and how they influence knowledge base combinations in green and green digital transitions. (3) In terms of innovation systems, I examine how different actors adjust their strategies to facilitate the regional industrial evolutionary process in the innovation system reconfiguration. Specifically, I examine the evolution of institutions, the dynamic capabilities of entrepreneurs, and governance complexity.

The dissertation focuses on complex knowledge evolutionary processes in two industries in Shanghai: medical devices and electric vehicles. Shanghai is in fifth place in the world according to GaWC 2020, where complex knowledge is highly agglomerated. Many disruptive breakthroughs and crucial technological innovations in China originate in Shanghai because of its rich sources of innovation, advanced knowledge infrastructure, and many research institutes. In Shanghai, crucial manufacturing industries include the electronics and information sectors, automobile industry, petrochemicals, fine chemical manufacturing, refined steel, biopharmaceuticals (including medical devices), and industrial machinery.

Medical devices and electric vehicles are multidisciplinary, knowledge-intensive, and capital-intensive high-tech industries (Davey et al., 2011; Zhao et al., 2018) where joint R&D prevails (Bergsland et al., 2014). These two industries were selected because in them we can expect to see a combination of several knowledge bases and complex knowledge interactions. Furthermore, medical devices and electric vehicle industries are characterized by high risk and uncertainty, and they consequently tend to have government support, particularly in the early developmental stage (Antonson & Carlson, 2018; Skjølsvold & Ryghaug, 2020). Therefore, these two industries are likely to have complex interactions among multiple actors. The dissertation draws four key conclusions. Firstly, Shanghai's electric vehicle industry exhibits stronger upstream–downstream interactions than Shanghai's high-end medical device industry. To remain innovative, high-end medical device manufacturers must seek resources at different spatial scales. Electric vehicle manufacturers benefit from and contribute to regional related sectoral development and multi-scalar institutional changes. Secondly, multiple actors—namely, institutes, entrepreneurs, and government departments—play a significant role in producing complex knowledge in the innovation system reconfiguration (ISR) process in both industries. However, institutional evolution is comparatively weak in the high-end medical device industry, due to the limited application of optical knowledge, which heavily relies on university affiliations. Additionally, the dynamic capabilities of entrepreneurs in these two industries are similar. Strong alignments in the dynamic capabilities between original equipment manufacturers (OEMs) and part manufacturers (PMs) are visible. In particular, internet entrepreneurs exhibit a positive attitude towards digital technologies in both industries, particularly those who have transitioned to OEMs. Thirdly, a broadening and deepening of innovation policy has been visible in the Shanghai electric vehicle industry, whereas the policies, rules, and regulations for medical devices contribute to governance complexity. Similarities in the two cases during policy upgrading refer to national–regional institutional changes and upstream–downstream policies within the industry chains. However, the power of policies for the Shanghai electric vehicle industry is higher than in the high-end medical device industry, with greater emphasis on firms upstream of the electric vehicle chain. Finally, by applying the analytical framework of CKB and complex knowledge along with the theory of CKB and ISR in these two cases, I show that an advanced understanding of complex knowledge and its evolution is feasible and effective.

The dissertation makes four main contributions. First, it offers an understanding of the concept of complex knowledge from a CKB perspective and contributes to efforts to measure complex knowledge. Secondly, a nuanced and context-sensitive theory of complex knowledge evolution is proposed by combining CKBs and ISR concepts. Thirdly, it examines upstream-downstream interactions in Shanghai's medical device and electric vehicle industrial chains, refining complex knowledge research at different spatial scales and in different transition contexts. Fourthly, drawing on a recent empirical study of the Shanghai medical device and automobile industries, it illustrates the theory and provides insights into complex knowledge trajectories and the related linkages and coordination among multiple sectors through actors at the regional level.

This dissertation consists of five chapters and is structured as follows:

Chapter 1 begins with a discussion of the progress in complex knowledge research and identifies existing gaps. The research aims, contributions, and main conclusions of the dissertation are introduced.

Chapter 2 elaborates on the theoretical framework of the dissertation. On one hand, it advances the understanding of complex knowledge through the CKB concept. On the other hand, it constructs a comprehensive analytical framework for examining the role of context sensitivity in the complex knowledge evolutionary process.

Chapter 3 addresses the methodology used in the dissertation. This chapter specifies how the research was conducted under scientific guidance. This is done by introducing the macro-level ideological guidance, including the ontology and epistemology of critical realism, the research strategy and methodology, case selection, and research processes.

Chapter 4 focuses on empirical studies. It analyses how multi-dimensional proximities affect knowledge combinations in the Shanghai medical device industry. It then examines how institutional changes influence upstream-down interactions in the Shanghai electric vehicle industry chain during the twin transition. Finally, by drawing on recent empirical studies of the Shanghai medical device and automobile industries, the chapter illustrates the theory and provides insights into complex knowledge trajectories, related linkages, and coordination among multiple sectors through regional-level actors.

Chapter 5 presents conclusions and outlines a research agenda. It emphasizes the spatial characteristics of knowledge combinations, patterns of upstream-down interactions, and strategies of critical actors across sectors in complex knowledge evolution. Additionally, it offers several policy proposals for complex knowledge generation based on the research findings and outlines a research agenda for advancing economic geography and complexity studies.

2. Theoretical framework

This chapter is a comprehensive theoretical framework for complex knowledge evolution and is divided into four sections (see Figure 2.1). The first section (Chapter 2.1) advances the understanding of complex knowledge from a CKB perspective. In economic geography, scholars have used the theoretical lens of complexity thinking to analyze regional economic phenomena (Chapter 2.1.1), such as complex knowledge production, in which diversified subsets and relationships between subsets are emphasized (Chapter 2.1.2). As two mainstream measurements of knowledge complexity in economic geography zoom in on the spatial clustering characteristics of complex knowledge and do not provide an in-depth explanation of context sensitivity, I apply the CKB concept in complexity thinking (Chapter 2.1.3) to analyze the contextualization of complex knowledge (Chapter 2.1.4). Then, by comparing the existing approaches with the approach I developed from ontology, research objects, research methods, strengths, and weaknesses perspectives (Chapter 2.1.5), I suggest this new approach can be seen as a complementary analysis to the existing measurements associated with complex knowledge.

The second section (Chapter 2.2) analyses the processes and driving mechanisms of complex knowledge evolution from a CKB perspective. Three theoretical lenses are presented separately, namely proximity, institutions, and innovation system reconfiguration. This section confirms that analyzing complex knowledge from a CKB perspective is feasible and reliable. The third section (Chapter 2.3) builds on the first and the second sections by linking all the concepts in Chapter 2, identifying the characteristics of concepts, and exploring potential relationships between them. The fourth section (Chapter 2.4) provides a summary of

Chapter 2. It offers a detailed overview of the core content of the chapter and its theoretical contributions.

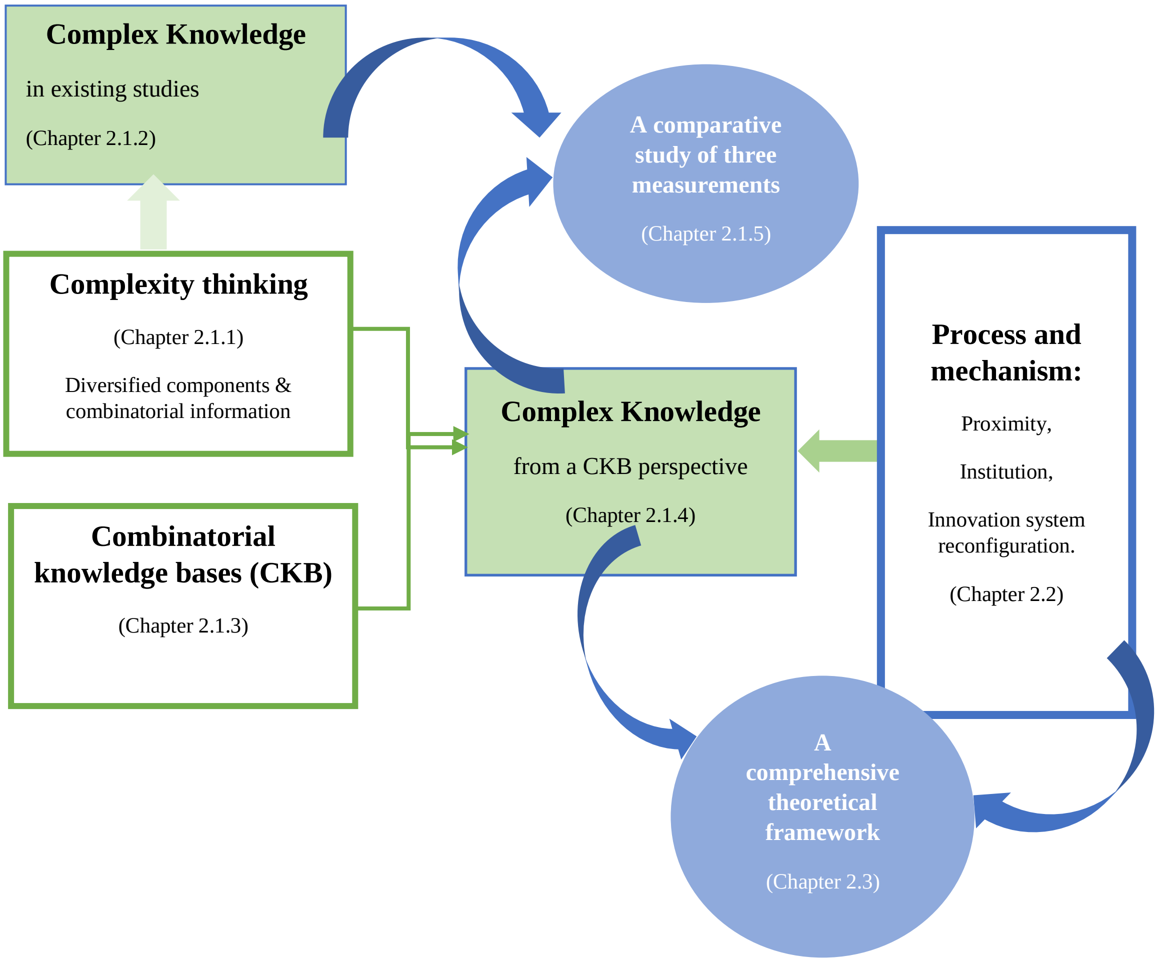

Figure 2.1. Mind mapping of the theoretical analysis

2.1 Advancing the understanding of knowledge complexity: towards an analytical framework

2.1.1 Complex science and regional economic evolution

2.1.1.1 Complex science and human geography

Complex systems science began in the 1980s. With more than 40 years of development, it has been widely applied in multiple research domains to explore the world (Schwanen, 2018; Spies & Alff, 2020). A complex system is the primary focus of this scientific field. In Herbert Simon's work (1962), a complex system consists of many components that interact in non-linear ways, either highly or lowly. He stated, 'In such systems, the whole is more than the sum of the parts, not in an ultimate metaphysical sense, but in the important pragmatic sense that, given the properties of the parts and the laws governing their interactions, it is not a trivial matter to infer the properties of the whole. Faced with complexity, an in-principle reductionist may also be a pragmatic holist' (ibid, p. 267).

Scholars have identified three key characteristics of complex systems science: (1) It spans a range of disciplines, facilitating interactions across domains. (2) It emphasizes the world's nonlinearity. (3) It is framed by basic concepts and essential traits (see Table 2.1) (Ladyman et al., 2013; Martin & Sunley, 2007; Wang, 2014; Manson, 2001).

Table 2.1. Several essential traits of complex systems

Property	Attributes
Distributed nature and representation	The functions and relationships are distributed across system components at a whole variety of scales, giving the system a high degree of distributed connectivity.
Openness	The boundary between a complex system and its environment is neither flexible nor easy to identify, making operational closure dependent on context (and observer). Such non-isolated systems tend to be dissipative—subject to constant interaction and exchange with their environments.
Non-linear dynamics	Complex systems display non-linear dynamics because of various complex feedbacks and mutually self-reinforcing interactions amongst components. Complex systems are thus often characterized by path dependence.
Limited functional decomposability	Because of its high degree of connectivity, and the open, dynamic nature of its structure, there is limited scope for decomposing a complex system into stable components.
Emergence and self-organization	There is a tendency for macro-scale structures (including spatial structures) and dynamics to emerge spontaneously out of the micro-scale behaviours and interactions of system components.
Adaptive behavior and adaptation	The same processes of self-organization imbue complex systems with the potential to adapt their structures and dynamics, whether in response to changes in the external environment, or from within through co-evolutionary mechanisms or in response to 'self-organized criticality'.

Non-determinism and non-tractability	Complex systems are fundamentally non-deterministic. It is not possible to anticipate precisely their behavior even if we completely know the function of their components. This does not imply, however, that the behaviour of such systems, is random in the sense of being haphazard.

Sources: The author copied from Martin and Sunley (2007, p578)

Steven Manson (2001) identified three types of complexity: algorithmic complexity, deterministic complexity, and aggregate complexity. Algorithmic complexity invloves examining the computational difficulty (Chaitin, 1992). Deterministic complexity deals with changing behaviors of relatively simple deterministic systems. The variability is easily observed when original conditions vary (Manson, 2001). Aggregate complexity analyses phenomena involving interactions among numerous components (Manson, 2001; O'Sullivan, 2004). This complexity theory is remark influential powerful, having a long-lasting effect on how scientists conduct their work. It places a strong emphasis on relations between entities while examining the behavior of collections of entities. According to Cilliers, a complex system cannot be fully comprehended by merely analyzing its constituent parts because of the interactions among the system's constituents and that between the system and its environment (Cilliers, 1998; O'Sullivan, 2004) (see Table 2.2).

Table 2.2. Essential characteristics of aggregate complexity

Dimension	Explanation
Relationships	The relationships between components are central to aggregate complexity. Consumers, companies, and the government are the main components of an economy. The relationship among these components mostly defines a complex system to a large extent rather than its parts per se.
Internal structure	A system's internal structure is defined by varying power relationships between components.
Environment	The general term for what is outside the system is the environment. The source exchange between a system and the environment is continuous.
Learning and memory	A system has its memory regarding its internal structure.
Emergence	In a complex system, self-organization always occurs in a situation where no guidance from a higher level is observed, leading to emergence. Self-organization ranges from ordered and highly structured to disordered or random.
Change and evolution	Three types: (1) its ability to modify its internal structure to exchange sources with its surroundings better is a result of self-organization; (2) when external or internal disturbances push a system to a highly disorganized state before abruptly transitioning into a more organized one, the system is said to be dissipative; (3) self-organized criticality is a concept used to describe a complex system's capacity to strike a randomness-stasis balance. A system may hit a breaking point where its internal structure is on the verge of collapse without actually doing so rather than occasionally weathering a crisis.

Sources: Manson (2001, p409, p410).

The last type, aggregate complexity, has inspired many scholars specializing in social science, particularly in human geography. For example, Spies and Alff (2020, p2) discussed "four guidelines" (namely, socio-nature, emergence/historicity, rationality, and self-organization) in the interaction between assemblage thinking and complex adaptive systems, identifying substantial overlaps as well as differences that might be used to cross-pollinate the two viewpoints. They proposed that assemblage thinking may learn from complex adaptive systems to expand its understanding of how elements interact and work together, whereas complex adaptive systems would gain from a more thorough engagement with the society-nature theories rooted in the assemblage literature. Moreover, the ordered street structure and the calculable network efficiency can be found in terms of hidden clues, which are deeply embedded in the urban socioeconomic system (Portugal, 2000; Salingaros, 2003). As Hillier et al. (1993, p32) stated, non-residential economic and service activities in urban neighborhoods are "determined by the structure of the urban grid rather than by the presence of specific attractors or magnets.” That is to say, the configuration of a city’s street network can shape or reshape its socioeconomic dynamics and structure (Wang et al., 2014). Finally, idealized equilibria can be linked to path-locking in economic geography. Path dependence can be understood as a function of the system’s past state and current trajectory characteristics, which is in extreme contrast to the concept of stable equilibrium in mathematical economics. This argument is debated by Liebowitz and Margolis (1995). In their view, although the concept of lock-in is still debatable in economics, it is not new in human or economic geography, where regional differences and economic advantages are susceptible to the effect. The idea of path dependence indicates that history and geography are significant because a path is a series of locations across time. However, it is not stressed in most complex scientific explanations (O’Sullivan, 2004).

2.1.1.2 Complex Science and Economics

Complex science also plays a decisive role in complexity economics (Arthur, 2013; Holt et al., 2011; Foster, 1997). Several classical comments regarding internal structures and evolution attributes are as follows.

Potts (2000, p91) held that the complex system theory is the best foundation for constructing evolutionary economics: “The hypothesis of evolution towards complexity is a conjecture to the effect that a balance between order and chaos, between stasis and change, is the ultimate principle underlying all evolutionary processes. Where equilibrium is the expression of ‘balance’ in an inert, mechanical world of point-like existence, complexity is the expression, the structural signature, of balance in a world of interacting dynamic systems. The hypothesis of evolution towards complexity is the logical principle that interlinks the geometry of all economic systems.”

Beinhocker (2006) emphasized that an adaptive, iterative, evolutionary algorithm is a fundamental complexity framework encompassing natural and social systems. He added that there is “too much loose analogizing about how the economy might be like an evolutionary system” (p12).

The strength of interactions between components in agglomeration complexity may be influenced by the distance (physical distance) between the two, which is also well represented in complex economic systems. One typical example is the spillover effect of knowledge. If intra-regional components (i.e., urban) are highly interactive, knowledge flows are easier to observe, and hence a self-organization complex system is formed (Biggiero & Angelini, 2015; Foster, 1997; He et al., 2011).

The interaction between agents and the social-economic--institutional context is central to applying complex thinking in economics (Foster, 2005). Arthur (2021, p142) emphasized that complexity economics “relaxes the assumptions of neoclassical economics, the assumptions of representative, hyper-rational agents, each of which faces a well-defined problem and arrives at optimal behavior given this problem… — and, thus, gives a different style to economics. It is an economics in which the agents in the economy are realistically human and realistically diverse, in which path-dependence and history matter, in which events trigger events and in which the networks channel these events matter. ”

Recently, complexity economics has shown its advantages in crisis studies (Harré et al., 2021; Foxon et al., 2013). For example, focusing on a range of seminars on complexity economics, Foxon et al. (2013) used the heterodox economic analysis to resolve the environmental issue. They built a practical policy agenda in terms of economic actors and systems, technological and market niches, research tools, driving forces of consumption, as well as updated metrics for economic activities' social-ecological worth.

2.1.1.3 Complexity thinking and evolutionary economic geography

Knowledge is recombinant, and technological changes are the precondition for applying complex thinking in regional economies (Martin & Sunley, 2007). As such, structure and agency in economic geography also revolve around knowledge evolution processes.

According to Martin and Sunley (2007, p592), "The micro level of analysis refers to individuals' carrying of rules and actualization of these rules, while the macro level is the population or deep structure of meso-rules that defines how rules coordinate with each other and fit together (Dopfer et al., 2004). At the meso level, generic rules undergo phases of origination, diffusion and adaptation, and retention and replication."

They also pointed out that "The emergence of a new rule disrupts the coordinated structure and produces a period of de-co-ordination in actualizations. As the new rule moves through diffusion and retention phases, re-co-ordination occurs as a new division of labor, possibly involving regional and industrial organization, stabilizes… rules and their actualizations form ‘meso units’, which are the dynamical building blocks of an economic system. Work on industrial districts, regional knowledge clusters, learning regions, inter-firm organization, national innovation systems, networks with weak or strong ties, or technical support communities all falls under the heading of meso economics from the evolutionary perspective …” (ibid, p592).

On the one hand, the excellent debate contributes to economic geography by linking the concepts in economic geography to complexity science. Typical cases are the understanding of knowledge, industrial structures, institutional environments, and network topologies at different scales in economic geography. Based on such an analysis, evolutionary economic geography has entered a boom period (Balland et al., 2019; Vallance, 2016; De Noni et al., 2021; Boschma & Martin, 2010).

On the other hand, it provides a vast space for further restructuring theories in economic geography (Gong & Hassink, 2020). While scholars have made significant efforts to explain key points in the interaction between complex thinking and evolution, it remains somewhat abstract. Due to the limitations imposed by the state of the discipline at that time, there are still areas where further elaboration is needed.Therefore, it is necessary to integrate the recent studies in economic geography to further identify how complex thinking promotes regional economic evolution, such as knowledge combination and recombinant innovation activities.

2.1.2 Knowledge complexity

2.1.2.1 Measurement, advantages, and disadvantages

Knowledge creation and knowledge diffusion across space offer insights into the geographical disparities regarding regional economic growth and technological innovativeness (Balland & Rigby, 2017). However, not all knowledge is equal. As Tolstoy stated (1997, p331), “It is important to know what knowledge is significant, what is less so, and what is trivial.”

To better understand valuable, competitive, and not easily replicated knowledge, the concept of knowledge complexity has been proposed. One attribute of complex thinking is visible in the understanding of complex knowledge, namely the diversified components. By now, in economic geography, two measurements have been used in the real world to measure knowledge complexity.

The first measurement of knowledge complexity emphasizes the sticky characteristics of knowledge. It considers the number of subsets and the interdependence between knowledge subsets, which make knowledge replication difficult. This measurement was initially developed by Simon, Fleming, Sorenson, Hidalgo, Hausmann, Balland, and Rigby. Simon (1962) first proposed that various components of knowledge lead to complexity and introduced a complex model to measure the diversity of these components. However, Simon’s complex science model is primarily used in simulation-based studies.

Building on Simon (1962)’s fundamental ideas, Fleming and Sorenson (2001) developed a search-oriented model to measure technological patents from the recombinant invention perspective. This opens up avenues for further exploration of technological changes and industrial revolutions. Hidalgo and Hausmann (2009) introduced a network model to analyze the location complexity of products in terms of diversity. They argued that the relative scarcity of products is as important as their overall quantity. However, Hidalgo and Hausmann (2009)'s approach has not been widely applied at the technological level.

Balland and Rigby introduced the economic complexity indicator, initially analyzing the national export complexity to patents and constructing indicators of knowledge complexity. Additionally, , Balland and Rigby (2017) expanded on this approach by using US patent information to determine the technical profile of US cities between 1975 and 2010. Their research demonstrated that knowledge complexity is not evenly distributed at the city level and that higher rates of patenting do not necessarily result from more sophisticated technological architecture. Building on the same model, Balland et al. (2019) showed that EU regions tend to experience more rapid technological development when they focused on complex technologies associated with local technologies already in use.

Recently, this measurement has been widespread application in various topics within economic geography, including firm production, smart specialization, and global value chain. For example, Antonelli et al. (2022) conducted an analysis of patent data spanning 1997 to 2009 from 189 European regions. They demonstrated that knowledge complexity expands the potential for recombination, allowing companies to generate more knowledge within their budgetary constraints. Meanwhile, they also found that the complexity of knowledge bases has debatable impacts on productivity: the indirect impacts are favorable since more knowledge is generated upstream, but direct consequences may pose challenges in utilizing a highly diverse knowledge stock.

Surana et al. (2020) investigated the relationship between technological complexity and global suppliers in the wind energy industry from 1990 to 2006. They observed that new suppliers tend to specialize in technologies located in the midstream or downstream segments of the global value chain. High-complexity technologies are rarely accessible to supplier firms, especially subsidiaries of international giants.

Li and Rigby (2023) provided insights into the indicator of smart specialization and its two sub-indices, relatedness and complexity, by studying patent data from Chinese cities between 1991 and 2015. They found a statistically significant positive correlation between smart specialization and its two sub-indices, relatedness and complexity, and the rate of GDP development over time. In other words, adopting “smarter” innovation patterns can facilitate urban economic growth: Economic growth is not solely determined by the amount of money regions invest in innovation; investing in fields related to a region’s existing knowledge capacity is equally crucial.

The first measurement has been debated by Broekel (2019, p2). In his view, “The index of Balland and Rigby rests on the assumptions that complex knowledge is relatively scarce geographically and that it tends to co-concentrate with other complex knowledge in space …However, the spatial distribution of knowledge may have multiple explanations, including complexity. For instance, the diffusion of knowledge in space and, hence, its geographic distribution, depending on its degree of maturity, popularity, natural conditions, geographic distance, place of origin, and (again), crucially, economic potential… From an empirical perspective, constructing a complexity index based on the spatial distribution of knowledge raises two additional issues: It represents a potentially endogenous variable in many spatial research settings, and its values are conditional on the delineation of the employed spatial units."

The second measurement of knowledge complexity, proposed by Broekel (2019), focuses on the structural diversity of knowledge. In management and engineering, technologies are seen as systems composed of interconnected components (Hargadon, 2003; Arthur, 2009; Mcnerney et al., 2011). Similar descriptions are found in innovation studies, particularly those using a network perspective to calculate complexity.

Broekel (2019, p3, p4) held that "What differentiates simple networks from more complex ones is the existence of certain kinds of organizational principles underlying their structures. These principles allow for condensing the information required to describe a network. Usually, these structuring principles are the result of specific network formation mechanisms, such as preferential attachment or transitivity. The existence of organizational principles tends to translate into specific (sub) network structures (e.g., stars, lattices, cliques, hierarchies) that appear in a network. These are called network topologies in the remainder of the paper, and they are the basis for the proposed approach for measuring technological complexity. In line with an information theoretical view on network complexity, I argue that the more information required to describe the topology of a technology's combinatorial network, the more complex it is. Moreover, multiple topologies will usually be needed to describe a combinatorial network's structure, as these networks may consist of subnetworks, each with different topologies. In other words, it is unlikely that a technology's components will connect in just one way (e.g., in a star-like manner). Alternatively, topologies may also be mingled. For instance, a small-world network combines tree-like and clique-like topologies. "

Building such a convincing framework, Broekel (2019) introduced the Network Diversity Score (NDS) as a new measure of knowledge complexity based on the concept of component combinations and the characteristics of complex network topologies. He analyzed European patent data between 1980 and 2015, finding that younger technologies require more collaborations in R&D activities than older technologies because the former is more complex. He and his colleagues have recently applied this model to regional economic growth and linked it to smart specialization. For example, they evaluated technological complexity in Europe from 2000 to 2014 and observed that the complexity of technologies plays a significant role in predicting regional economic growth (Mewes & Broekel, 2022).

These two measurements have similar points:

1. They both consider one property of complexity: the diversity of subsets.
2. They use patent data to measure knowledge complexity via the quantitative methodology.
3. They primarily focus on knowledge in polytechnical fields.
4. They both aim to address similar same problems, such as, comparing knowledge complexity and analyzing the spatial clustering of knowledge complexity.

The differences between these two approaches include two aspects. The first difference pertains to ontology. For Balland and Rigby (2017), knowledge complexity results from the implicit character of complex knowledge and the non-universality of space. In contrast, according to Broekel (2019), knowledge complexity is developed based on the topological nature of knowledge structure. The second difference lies in the metrics used in the network analysis process. The first approach employs the City–Tech Knowledge Network, while the second approach introduces the Network Diversity Score (NDS) of knowledge.

Although these two research strands provide insights into the measurement of complex knowledge, contributing to the unevenness of knowledge in economic geography, three deficiencies are visible.

First of all, the discussion of knowledge complexity mainly focuses on the analytical knowledge in science-based sectors but neglects other types of knowledge bases. For example, knowledge in art, design, and culture has a high degree of spatial agglomeration. Aesthetic design and high-precision engineering technology in some manufacturing fields has become essential to the market competition. Therefore, exploring complex knowledge with inter-knowledge bases is necessary.

Secondly, the existing studies only respond to the geographical characteristics of complex knowledge and provide a shallow and simple explanation of why complex knowledge is highly agglomerated in metropolitan areas. However, in different metropolitans and different sectors, interactions between firm-level and system-level agents may differ. As Gong and Hassink (2020) stated, context sensitivity could help us better understand what we observe and reconstruct theories by considering more nuanced elements in relation to history, institutions, intermediaries, or firm attributes.

Thirdly, the calculating process is overly complex. Simon (1991, p475) pointed out, “How complex or simple a structure depends critically upon how I describe it. Most complex structures in the world are enormously redundant, and I can use this redundancy to simplify their description. However, to use it, to achieve the simplification, I must find the right representation.” Manson (2001) reviewed all kinds of complexity calculation in existing studies and called for a trend toward simplifying complexity.

2.1.2.2 Knowledge Complexity and related studies

Knowledge complexity evolves with regional economic complexity. Economic geographers hold that knowledge complexity is central to economic complexity. Similar to knowledge complexity analysis, the economic complexity concept is also based on complex scientific thought (Hidalgo, 2021). The existing literature proved that economic complexity leads to the structural transformation of social-economic systems. Several indicators, such as labor, publications, industries, occupations, and technologies, are widely applied in the evaluation of structural transformation. For example, Balland et al. (2020) calculated the complexity of these four elements (i.e., publications, industries, occupations, and technologies) based on US urban data from 1985 to 2015, finding the increasing concentration of occupations and innovative activities may be a result of the growing economic complexity. Hidalgo (2021) reviewed the studies on relatedness and metrics of economic complexity, measuring the degree of economic complexity in terms of specialization patterns and reduction techniques (income, economic growth, emissions, and income inequality) all over the world. Mewes and Broekel (2022) found that a 10% increase of technological complexity is strongly related to a 0.45% increase in GDP per capita growth.

In economics, management, and organization fields, scholars are concerned with the relationship between knowledge complexity and innovation. For example, Mat and Razak (2011) analyzed the role of knowledge complexity in the relationship between organizational learning and technological innovation, offering insights into how knowledge complexity affects innovation. Moreover, Pérez-Luño et al. (2011) acknowledged that the effect of knowledge complexity on radical innovation can only be visible when complex knowledge and social capital are combined. Although these studies are valuable, they are confined to the relationship between knowledge complexity and social or organizational systems. However, the direct relationship between knowledge complexity and innovation (modes), and its increasingly complex economic geography, are under-researched. Recently, Maleki and Rosiello (2019) introduced a new term, namely knowledge base complexity, contributing to complexity studies by examining how this complexity influences the spatial characteristics of innovation in the upstream petroleum industry. More recently, these two scholars investigated the complexity and variety of knowledge bases in three industries, identifying increased complexity as the main reason for the difficulty of catching up with advanced technologies for latecomer countries (Rosiello & Maleki, 2021). Although these studies offer insights into complexity and knowledge bases, the relationship between knowledge complexity and knowledge bases remains underexplored in economic geography.

2.1.3 Combinatorial knowledge bases

2.1.3.1 What are differentiated knowledge bases?

According to Boschma (2018, p24), the differentiated knowledge bases (DKBs) literature elaborated "…the nature of knowledge sharing and its geographical extent which were claimed to vary between analytical, synthetic and symbolic knowledge bases…", and is hence an excellent example of context-sensitive theorizing in economic geography (Gong & Hassink, 2020). In comparison to other distinctions and approaches, such as high- vs. low-tech and codified vs. tacit knowledge, the DKB approach is strongly connected to knowledge creation and innovation processes within industries (Asheim & Gertler, 2005) (see Table 2.3). These studies contribute to a more nuanced, fine-grained understanding of the increasingly complex economic geography.

Table 2.3. The typology of Differentiated knowledge bases (DKBs)

Characteristics	Analytical knowledge base	Synthetic knowledge base	Symbolic knowledge base
Main relational	Science-based (know why)	Engineering-based (know how)	Artistic or culture-based (know who)
Knowledge creation	Reductive process, formal models	Inductive process, applied, problem-related	Interactive, informal, creative, problem-oriented
Innovation pattern and process	Radical innovation by the creation of new knowledge	Incremental innovation by application/ combination of existing knowledge	Innovation by creative recombination of existing knowledge
Knowledge exchange partners	Research cooperation between firms and research organizations	Interactive learning with customers and suppliers	Interaction in professional communities, learning from youth/ street or “fine” culture
Knowledge attribute	Strong codified knowledge	Strong tacit knowledge	Cultural knowledge, strong tacit attributes
Geographical Proximity	High sensitivity for spatial proximity	High importance of spatial proximity	High sensitivity for spatial proximity

Sources: Asheim and Gertler (2005), Moodysson et al. (2008), Asheim et al. (2011, p898) and the author.

The original theoretical literature states that analytical knowledge plays a vital role in science-based industries, such as the pharmaceutical and biotechnology industries (Asheim & Gertler, 2005). The analytical knowledge base is often based on cognitive processes or scientific models, mainly from research institutes and universities (Asheim & Coenen, 2005; Benneworth et al., 2019). Due to the codified characteristic of analytical knowledge, innovation networks are often observed at the national or international level in this knowledge base (Davids & Frenken, 2018).

Synthetic knowledge mainly refers to artifact engineering for electronics and construction industries (Asheim & Gertler, 2005). Technological transfer offices and vocational training schools (Asheim et al., 2011; Van Tuijl and Walma van der Molen, 2016) influence the generation of synthetic knowledge. The interaction between actors generating synthetic knowledge, which is often tacit and requires face-to-face communication, is often characterized by co-location and in-house collaborations (Moodysson et al., 2008; Davids & Frenken, 2018).

Symbolic knowledge is strongly related to cultural codes within the cultural and creative industries (Manniche & Larsen, 2013). The symbolic knowledge base is primarily associated with cultural and artistic codes and often occurs in project teams or interactive learning in professional communities (Asheim, 2007; Van Tuijl and Walma van der Molen, 2016). Interactive learning for symbolic knowledge, often tacit in character, tends to occur in local and regional networks (Gertler, 1995; Davids & Frenken, 2018).

In the early stage, the DKB studies primarily agglomerated in the Department of Social and Economic Geography and Centre for Innovation, Lund University, Sweden. Bjørn T.Asheim, Lars Coenen, Jerker Moodysson and Roman Martin at Lund University are main researchers.

According to Asheim and Coenen (2005)'s hypothesis, an industry's underlying unique knowledge base shapes the innovation process within that industry. In the "territorially embedded regional innovation system", the innovation mode might be stronger linked to synthetic knowledge, which is highly dependent on face-to-face communication. In contrast, a "regionalized national innovation system" with relatively few interactions between local firms and scientific organizations might primarily rely on the innovation mode associated with analytical knowledge. It differs from a "regionally networked innovation system" in which the mix of innovation modes stems from the combination of various knowledge bases (2005, p1179, p1180). After that, Eder (2019, p47) pointed out that “Knowledge bases have been frequently combined with other approaches to arrive at a more nuanced understanding of innovation practices of different industries and regions… relates them to … proximity dimensions, while … build a connection to regional innovation systems (RISs) …”

Inspired by the studies mentioned above, scholars primarily from European countries have done various studies specializing in DKBs, clusters, locational preferences, and occupations. For example, Martin, Moodysson, and Zukauskaite (2011) investigated the implications of regional innovation policy (Martin & Trippl, 2014), examining how regional policies supported initiatives aimed at three industries in Sweden’s Scania region. Structured interviews with firm-level actors and in-depth conversations with system-level actors served as the basis for data collection. They found that regional networking policies strongly associated with academics and industry would be more suitable for analytical sectors but make little sense for synthetic and symbolic sectors. They concluded that policy initiatives should be tailored to the demands of businesses due to their participation in various knowledge bases.

Asheim and Hansen (2009) stated that the DKB approach can be applied to locational selection and residential preferences. They investigated several regions in Sweden and elaborated that “... in regions where synthetic knowledge bases dominate, business climate scores tend to be higher than people climate scores, and that a people climate tends to be of greater importance than a business climate in regions that are dominated by the analytical and, especially, the symbolic knowledge bases” (p439).

Martin (2012) examined whether there are differences between Swedish regions' levels of knowledge base specialization using occupation data and knowledge base links. According to the study, there are differences among regions in terms of the three knowledge bases' expertise. Compared with analytical and symbolic knowledge, synthetic knowledge was specialized in many regions, and only a small number of regions have more than one kind of knowledge base.

Gress (2015) proved that Photovoltaik (PV) solar firms participated in diversified "regionally networked RIS" in Korea, which indicates "Korea's historically dirigiste system toward an approach which is more balanced among regions" (p1432).

The DKB concept is also applied in a new regional typology. Eder (2019, p47) held that "The periphery discourse has also been related to key variables of the knowledge economy, such as knowledge-intensive business services (KIBS)… However, the relationship between peripheralization, on the one hand, and knowledge bases, on the other hand, has not yet been conceptualized. Unpacking this relationship is promising for two reasons. First, the prevalence of knowledge-intensive branches is seen as an important dimension of the peripheralization discourse. As such, the knowledge base approach cannot only hint at the existence or absence of these businesses but also provide further insights into their characteristics and nature. Second, the existence of knowledge bases is usually seen as a main driver for economic prosperity, but their regional occurrence and their relations to geographic, demographic, and economic dimensions (going beyond mere innovation indicators) remain largely unclear."

Recently, the advantage of the DKB approach has been debated. On the one hand, Manniche, Moodysson, and Testa (2017) criticized the DKB approach for not fully transcending the traditional dichotomy between codified and tacit knowledge because, in empirical studies, scholars are likely to "reify the traditional dichotomy rather than superseding it" (p11).

They also pointed out that the categories of DKBs are very similar to traditional categories, i.e., codified and tacit knowledge or high and low technologies. On the other hand, scholars have not zoomed in on the relationships between DKBs and complex knowledge. In the literature on DKBs, researchers have long been interested in the geography of knowledge and the driving mechanisms behind different types of knowledge bases in regional industries, which are, knowledge bases per se, rather than deconstructing complexity in terms of the DKB concept.

2.1.3.2 From DKB to CKB

Although one type of knowledge base can represent the primary knowledge creation in particular businesses, previous research suggests that it is impractical to strictly separate knowledge bases in a single industry from one another (Asheim et al., 2017; Manniche et al., 2017). For instance, analytical, synthetic, and symbolic knowledge bases are present in the eco-building industry (Strambach, 2017). Key knowledge creation in the industries may also alter over time as a result of industrial transformation or upgrading. In light of this, the combinatorial knowledge base (CKB) concept has been proposed and is seen as a more sophisticated substitute.

The combinatorial knowledge base (CKB) is the combination of intra-knowledge base or inter-knowledge base leading to complex innovation (Asheim et al., 2017; Manniche, 2012), which offers a more nuanced insight into knowledge flows and innovation characteristics of regional industries. They can help to understand under which conditions combinations between the intra-knowledge base or inter-knowledge base matter most for innovation in regional firms and industries (Bennat & Sternberg, 2020; Marques, 2019).

In comparison to the DKB, four characteristics of the CKB can be identified.

First, it concerns the actors who carry knowledge. The generation of DKBs only refers to one kind of actor specializing in scientific analyses or engineering or art and culture, whereas CKB may be highly dependent on more agents with different domains (Xue & Liu, 2023).

Secondly, the CKB refers to a dynamic process, whereas the DKB is more static in character. In other words, the evolution of DKBs leads to CKBs (Boschma, 2018).

Thirdly, it refers to geographic embeddedness. Geographical proximity has a more significant impact on synthetic and symbolic knowledge bases than analytical knowledge bases (Boschma, 2018), whereas the space of CKBs varies. Various types of CKBs result in vague geographical embeddedness. For example, the combination of intra-analytical knowledge bases is easier to transfer and diffuse across space, while the combination of intra-synthetic knowledge bases usually takes place locally.

Fourthly, it contains codified vs. tacit features. Similar to geographical embeddedness, the codified or tacit characteristics of knowledge bases are clear. The synthetic and symbolic knowledge bases are dominated by tacit knowledge, whereas the analytical knowledge base is dominated by codified attributes (Asheim et al., 2011). However, CKBs with tacit and codified features bring about some uncertainties (Xue & Hassink, 2023).

2.1.3.3 CKB: research progress

Existing studies

Recently, scholars have zoomed in on the innovative performance of firms from a CKB perspective and the role of local and nonlocal sources in CKBs. For example, Tödtling and Grillitsch (2015) addressed the ICT sector in three regions of Austria, pointing out that combinations of three types of knowledge bases or diverse sources are conducive to innovative activities and avoid “lock-in”. Grillitsch and his colleagues (2017) analyzed the Sweden community innovation surveys, indicating that analytical knowledge outweighs the importance of synthetic and symbolic knowledge and that firms benefit most from being located in a region with a balanced mixture of all three knowledge bases. Zukauskaite and Moodysson (2016) investigated the food sector in Sweden, identifying three types of CKBs influenced by rules, norms, and procedures. The combination of analytical and synthetic knowledge bases is mainly affected by changes in the European Food Safety Authority (EFSA) regulations, which emphasize the intersection of food and health would enhance the value of foods and market competitiveness. The combination of intra-synthetic knowledge bases, focusing on minor improvements in taste, composition, and packaging, is prevalent in Sweden due to the necessity for traditional food manufacturers to develop substitute products within the context of environmental sustainability. The combination of intra-synthetic knowledge bases from several fields (i.e., food engineering and process technologies) is not often observed, which usually results from changing norms in the social families’ structure. Strambach (2017) linked the combination of three types of knowledge bases to transnational sustainability innovation and examined how micro-knowledge dynamics in the German-Chinese eco-building sector influenced and are influenced by national institutions. In

Germany, national formal and informal institutions play a significant role in creating CKBs regarding transnational sustainability innovation in the building industry. However, the application of these CKBs in China is not successful because of cognitive, cultural and user behaviors' differences between Germany and China. Klement and Strambach (2019) examined the creation of new music genres is mainly based on various symbolic knowledge bases, such as following musical heritage or absorbing the latest trends and fashions, which are strongly relevant to diversifying and artistic-based innovation processes (artistic-based DUI modes). Through calculating the related and unrelated variety of these symbolic knowledge bases, they found that related variety matters only when it comes to the knowledge base combination, whereas an overspecialization hinders innovation in music genres. Marques (2019) zoomed in on the knowledge base combination in the wine industry in three less-developed areas in Portuguese via intra-firm vertical integration or inter-firm knowledge diffusion. Both the combination of synthetic and analytical knowledge bases, as well as the combination of synthetic and symbolic knowledge bases, contribute to technological advancement and more added value for firms. Tschumi and Mayer (2022) examined the combination of knowledge bases in the healthcare sector in a Swiss marginal area, finding that the synthetic knowledge base is the most commonly employed kind via social innovation and is frequently paired with analytical or symbolic knowledge bases. Local and locally embedded actors are the main contributors.

Inflows of external sources and policy support triggering regional knowledge base combinations have also been discussed in Isaksen and Trippl's (2017) research. They showed how external sources for analytical and synthetic knowledge (relevant to STI and engineering-based DUI modes), as well as policies, played a crucial role in the Mühlviertel ICT development in Upper Austria and Arendal–Grimstad in southeastern Norway. In

Mühlviertel, complex knowledge creation in the ICT industry highly relies on the settlement of three institutes early, namely RISC (Research Institute for Symbolic Computing), FAW (Institute for Applied Knowledge Processing), and FLL (Fuzzy Logic Laboratorium, Department of Knowledge-Based Mathematical Systems). These three organizations moved from Johannes Kepler University Linz, Upper Austria’s capital city, offering analytical knowledge, which led to the development of ICT. Policies, particularly regional strategies, play a significant role in facilitating and subsidizing the establishment of the institutes. In Arendal–Grimstad, pioneer firms within the region, as well as the arrival of engineers from other regions in Norway specializing in synthetic knowledge and engineering-based DUI modes, brought about the emergence of the ICT industry. By comparing the two cases, regional policy power is not very strong in the ICT industrial development in Arendal-Grimstad compared to Mühlviertel. Bennat and Sternberg (2020) have stated that regional innovation policies play a significant role in facilitating knowledge and innovation, although local factors hampered combinatorial knowledge dynamics for a long time. Plechero and Grillitsch (2022) addressed the local productive system of Vicenza mechatronics in Veneto, Italy, identifying that firms with excellent innovation performance generally have access to local, national, and international sources. Additionally, firms with complementary knowledge bases can easily get advanced knowledge outside the local productive system.

Overall, both Industry 4.0 and creative culture encourage manufacturing organizations not simply to innovate but to innovate in more radical and diverse ways, frequently embracing new sorts of information. Recent research in Innovation and Economic Geography highlights the importance of enterprises combining information in creative ways to enhance such sorts of innovation. As Asheim (2022, p50) stated, drawing on “combinatorial knowledge bases promises novel insights into how combinations of different knowledge bases relate to the innovativeness of firms, industries, and regions. Furthermore, this focus brings a new understanding of how various forms of new regional path development (path upgrading, path importation, path diversification [related (path branching) and unrelated], and path creation) can take place. Research into these issues benefits from new possibilities of empirically identifying firms' use of analytical, synthetic, and symbolic knowledge, brought about by the extension of existing microdata sources and the construction of innovation biographies…"

Reflective

Linking CKBs to complexity thinking opens a window for complexity studies in economic geography because this concept could reflect the type and relationships between knowledge components. Moreover, with the help of CKBs, a place- and sector-sensitive theory of complex knowledge evolution that is able to explore and understand both the actors involved in the production of knowledge and how they accomplish it and the policies and institutions supporting upgrading towards higher levels of complexity. The detailed elaboration is visible in the following sections in Chapter 2.

In the next section, we will explain why and how the CKB concept advances the understanding of cross-sector complex knowledge.

2.1.4 Advancing the understanding of complex knowledge from a CKB perspective

2.1.4.1 What is the motivation to develop a new understanding of complex knowledge?

Although the previous literature on knowledge complexity is valuable, the analysis of contextualization of complex knowledge is not sufficient. In regions with similar complex knowledge, processes and mechanisms of complex knowledge may have huge differences. Only context sensitivity analysis could help us to respond to the related questions:

* What are the characteristics of upstream-downstream interactions in the complex knowledge evolutionary process?

* Which do actors enter more complex activities, and how do they accomplish them?

* How can policy support upgrading towards higher levels of complexity?

Qualitative research is viewed as a complementary methodology for quantitative research in contemporary economic geography, enhancing the understanding of regional disparities. In qualitative research, context sensitivity is measured by reconstructing the theories from different paradigms or disciplines, such as evolutionary economic geography, complex science, institutional economic geography, and relational economic geography. In different regions and different industries, interactions between firm-level and system-level agents may differ. As Gong and Hassink (2020) stated, context sensitivity could help us better understand what we observe and reconstruct theories by considering more nuanced elements in relation to history, institutions, intermediaries, or firm attributes.

2.1.4.2 Why could CKBs help us to better understand complex knowledge in terms of contextualization?

I have developed a CKB-complex knowledge analytical framework. I regard the transition from individual KBs, either analytical, synthetic, or symbolic knowledge bases, to a combination of knowledge bases. The CKB concept could reflect the essential property characteristics of complex knowledge: (1) the diversity of knowledge components/subclasses from a CKB perspective and (2) the combinatorial information among components. The analytical framework is made up of these two characteristics.

Characteristic I: the diversity of knowledge components/subclasses from a CKB perspective

The diversity of knowledge components/subclasses can be identified from the typology of the knowledge bases combination. The diversity of knowledge components is often influenced by policies and firm-level actors' strategies, which refers to two questions:

(1) How do policies upgrade for complex knowledge production?

(2) How do firm-level actors engage in more complex innovation activities?

Question I: How do policies upgrade for complex knowledge production?

Complex knowledge production is characterized by complex interactions among multiple actors and cross-sector communication, whereas policy upgrading aims to accelerate complex knowledge production and cross-sector policy coordination. Based on the analysis, policy upgrading from a CKB perspective is to investigate interactions between public sectors and firms with different types of knowledge bases and coordination between public sectors with similar or complementary knowledge bases in different industries. The CKB is deeply embedded in the regional innovation system, so policy upgrading can be identified through knowledge-based policies. To explain more clearly how policy complexity in policy upgrading contributes to complex knowledge production from a CKB perspective, we elaborate on the concept of complex adaptive systems.

Although the evolution of regional systems is deeply rooted in the regional historical context, the adaptation and evolution of regional complex systems are fraught with uncertainty and unpredictability, which results from the adaptability of individual parts and subsystems (see Figure 2.2). The interaction is influenced by institutional changes (Hodgson, 2006). Policies' design, publication, and implementation reflect how individual components fit into each other and the subsystem. Interactions among multiple agents and cross-sectoral interactions are critical features of complex policies.

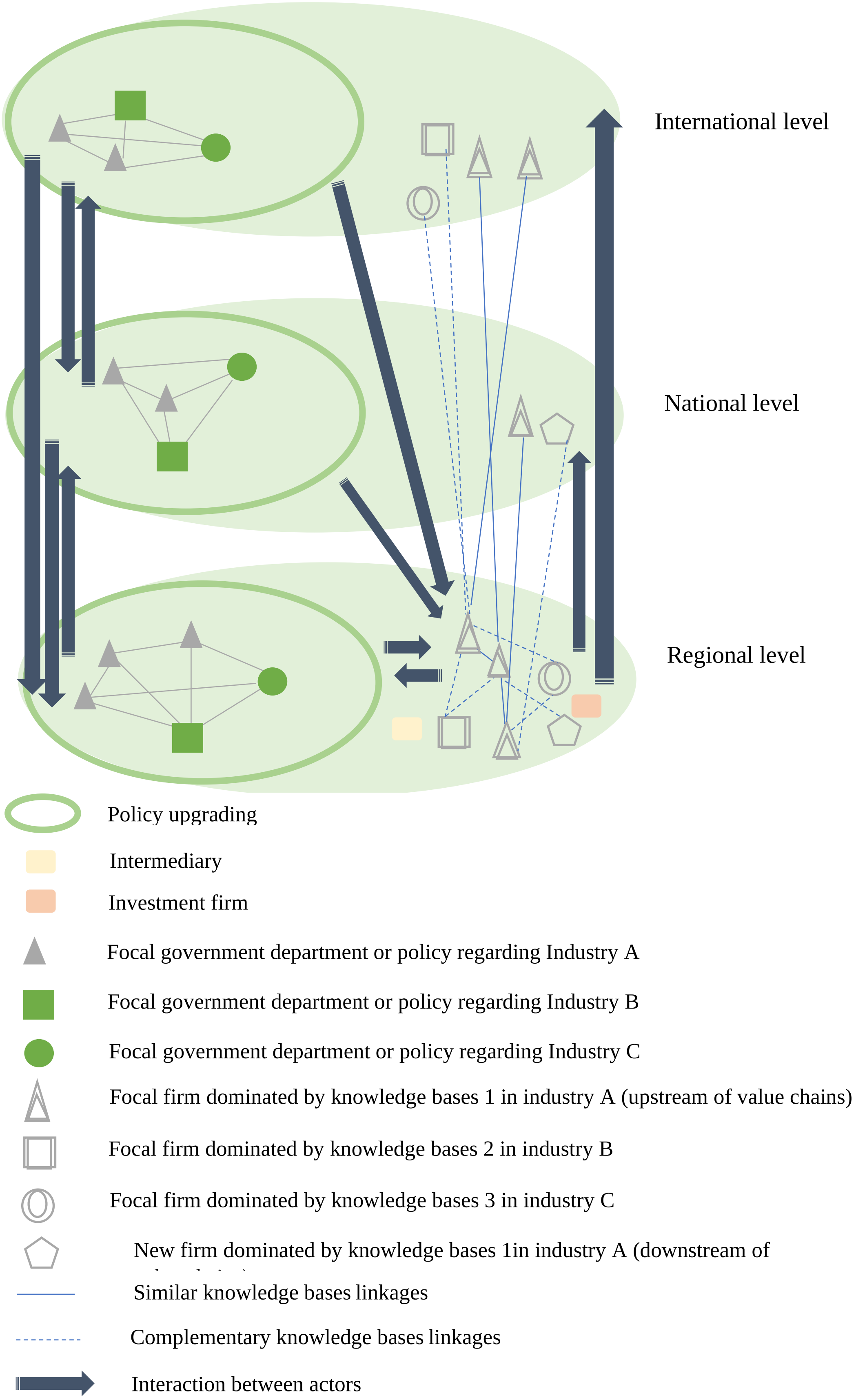

Figure 2.2. Complex knowledge production from a CKB perspective

Policy upgrading, i.e., the role of policy in regional complex knowledge production, has not been sufficiently discussed. For a long time, evolutionary economic geographers were much concerned with regional structure. Recently, economic geographers and regional researchers have shifted to the power of the agency in regional industrial path development and recombinant innovative activities. Grillitsch and Sotarauta (2020) identified three forms of agency, namely, Schumpeterian innovative entrepreneurship, institutional entrepreneurship and place leadership, potentially offering insights into the role of agency for knowledge creation and interaction in relation to different kinds of proximities. Innovative entrepreneurship concerns entrepreneurs "perceiving opportunities" within or outside the region and "striving to realize these opportunities" such as niche markets and new organizations (Grillitsch and Sotarauta, 2020, p711). Institutional entrepreneurship refers to the "change processes contributing to creating new institutions or transforming existing ones" (Grillitsch and Sotarauta, 2020, p711). Place leadership is linked to the collaboration between local actors, "revealing the types of social processes involved in 'making things happen' and in 'getting things done' (or not getting things done)" (Sotarauta et al., 2017, p188). Bristow and Healy (2014) suggested three factors to take into account to comprehend how agency affects system evolution: "how individual behavior adapts and change (acquisition of knowledge, learning processes, adaptation); how they translate into collective decisions and effects, through interactions in social networks, communities, and government; and how collective rules and governance systems constrain and enable evolution (institutional structures of governance, political power)" (Bianchi & Labory, 2019, p236, p237; Colander & Kupers, 2014; Sotarauta, 2017).

According to Borrás (2009), a broadening and deepening of innovation policy in various countries are visible. Broadening refers to the expansion of innovation policy action across sectors. For example, to develop a new industry A (a combination of three types of knowledge bases), the application of technologies from industry B (analytical knowledge base) and industry C (synthetic and symbolic knowledge base) to industry A may require some negotiation among public sectors. Public sector A, B and C may discuss new products' safety or testing standards of new technologies.

Deepening refers to the introduction of new and more complex policy instruments. The policy incentives for an industry move from direct policy incentives to indirect, diversified or related sectoral policy supports. Therefore, more significant effort is needed in studying "the complexity of contemporary innovation policy and its governance by highlighting the evolution and the learning and dynamic nature of innovation policy …" (Laasonen et al., 2022, p548).

Although governments are the main actors in policy implementation, other actors also contribute to policy changes. Gong and Hassink (2019) proposed that the co-evolution of regional industries and institutions needs to consider population. Hassink et al. (2019) also noted that multiple actors' interactions are central to regional policy changes. Top-down and bottom-up alternate or occur simultaneously in the regional industrial transformation process, remarkably in the communication between the public sector and companies with different types of knowledge bases. The development of electric vehicles, for example, involves interaction not only with the automotive sector but also with the internet sector.

Question II: How do firm-level actors engage in more complex innovation activities?

It is feasible to identify how firm-level actors are involved in more complex innovation activities through firms' knowledge bases and the relationship between firms (horizontal vs. vertical linkages).

"Horizontal linkages such as alliances are lateral relations between firms, specialized in similar value chain stages that are constructed with the primary purpose of obtaining complementary know-how" (Turkina et al., 2021, p765). Note that similarity in technology has a significant role in creating horizontal links. Companies view horizontal links as a means of acquiring knowledge (Galunic & Rodan, 1998). However, businesses prefer to create these connections when there is a medium level of technological similarity between themselves and other businesses (Nooteboom, 1999). The development of horizontal links is unattractive due to excessive technological similarity because the external partner has few innovative ideas to share with the focus enterprise. In contrast, a corporation may find it challenging to absorb the outside (Turkina et al., 2021).

Vertical links refer to "buyer-supplier relations between firms specializing in different value chain stages, with the main goal being to improve efficiency. An analysis of the main technological drivers of both linkage types is necessary to understand the formation of network communities in the context of co-located clusters" (Turkina et al., 2021, p765). For vertical connections, complementary knowledge of firms from an input-output perspective matters in the formation process (Turkina & Van Assche, 2019; Turkina et al., 2021).

Moreover, the exaptation concept also provides insight into how companies are organized to systematize scaling as an innovation strategy by unlocking it (Mokyr, 1998; De Noni et al., 2021). A more refined definition regarding knowledge exaptation is done by Dew et al. (2004). They attempted to accurately capture the natural attribute of exaptation by distinguishing similar concepts such as general knowledge (base) recombination and unexpected outcomes. From such a perspective, complex innovation activities can be classified into intentionally and unintentionally knowledge base-oriented combinations.

Characteristic II: the combinatorial information among components

The combinatorial information can be understood as dependencies between knowledge bases and correlations and irrelations between knowledge bases. The high level of dependency between knowledge bases can only be explicitly analyzed through specific objects.

Dependencies between knowledge bases may be reflected in patterns of collaboration. If there are strong dependencies between knowledge bases, two teams from different institutes work together daily in the same place. Frequent face-to-face communication is necessary for R&D relevant to CKBs, where communications among engineers specializing in electronics, software, and machinery prevail. Against this background, local buzz plays a decisive role in complex knowledge production. Additionally, regular collaboration communication is widespread, including collaborations among engineers from electronics, software, and machinery and collaborations between engineers and doctors. Concretely, both research strands occasionally make an in-depth report on CKBs, sharing their research progress and discussing and preparing a new plan for the next step.

In the process of knowledge base combination, a sector is generally linked to several technological innovation systems (TISs), and a TIS may have different agents from different sectors (Stephan et al., 2017; Andersen & Gulbrandsen, 2020). Highly dependent knowledge bases mean significant agent interaction and knowledge flows between TISs. These highly dependent knowledge bases are often located in the upstream position of the technology value chain and have very dense knowledge networks at advanced stages of the technology life cycle. Moreover, As Andersen et al. (2020 et al., p 348) stated, it is necessary to explore "how existing knowledge bases influence the direction and scope of transitions" as well as "attention to the diversity of sectors and firms involved in, and affected by, transitions through inter-sectoral linkages."

The characteristics of knowledge bases combinations prevailing in emerging industries may change over time from a technology lifecycle perspective. Technology develops following an S-shaped growth curve, similar to the industry or product life cycle (Achilladelis et al., 1990; Haupt et al., 2007). Although Asheim (2022) held that most knowledge bases combinations are unrelated, the discussion primarily zooms in on the emergence of emerging industries, namely the introduction and growth stages. For the maturity and decline stages, a related knowledge bases combination is possible because incremental innovation based on market feedback to improve novel products is expected in green industries, even in other emerging industries (Andersen & Gulbrandsen, 2020; Barbieri et al., 2020a; Barbieri et al., 2020b).

2.1.5 A summary of three measurements of complex knowledge

Complex thinking helps us to better understand the characteristics of complex knowledge. The diversity of subsets and the relationships between subsets are mapped out in the study of all three types of complex knowledge. By comparing the ontology, the object of study, the research strengths, the research weaknesses, and the intrinsic links between the three approaches to complex knowledge, I illustrate the need for advancing the understanding of complex knowledge (see Table 2.4).

Table 2.4. A comparison of three measurements of complex knowledge

Measurement	Place-based complex knowledge	Structure-based complex knowledge	CKB-based complex knowledge
Main Scholars	Balland and Rigby (2017)	Broekel (2019)	the author
Ontology	The non-universal nature of space, the complexity of place	Topology of knowledge structures	The combination of knowledge bases
Research Object	Patents	Patents	Recombinant knowledge in industrial upgrading or emerging industries
Research Method	Quantitative research, analysis of urban technology networks	Quantitative research, network diversity score	Qualitative research
Advantage	Accurate analysis of the complexity and spatial clustering characteristics of all patents	Accurate analysis of the complexity and spatial clustering characteristics of all patents	Context sensitivity of new knowledge; knowledge in culture and art domains
Disadvantage	Physical and geographical factors can affect calculation results; only focus on complex knowledge in polytechnical areas; limited contextual understanding of complex knowledge	Only focus on complex knowledge in polytechnical areas; limited contextual understanding of complex knowledge	Inability to compare the level of complexity and spatial clustering of specific knowledge
Complexity thinking	Diversity of components and relationships between components		
Potential relationship among these insights	The author’s understanding is complementary to the existing measurements in economic geography		

Sources: Balland and Rigby (2017), Broekel (2019), and the author

2. 2 Process and mechanism of complex knowledge production

2.2.1 Proximity and complex knowledge

2.2.1.1 Proximity

Multi-dimensional proximity have been developed in the last few decades. The literature on proximity started to grow in the 1990s to explore the coordination of industrial activities. The French proximity school first pointed out that, in addition to the geography of actors, a non-geographical dimension, namely organizational proximity, should be embodied in the proximity analysis (Bellet et al.,1993; Rallet & Torre, 1998). In their view, not only the physical distance between collaborators but also the close relationship of actors has the potential to facilitate or hinder knowledge collaborations. Over time, they added the institutional dimension to the proximity framework to explain how institutional environments affect, shape, and reshape knowledge interactions and innovative networks between agents (Carrincazeaux et al., 2001; Kirat & Lung, 1999). Additionally, other dimensions of proximity, such as social, cognitive, technological, and interpersonal proximity, have been receiving increased attention and are widely applied in economic geography as well as related social science domains (Agrawal et al., 2008; Guan & Yan, 2016; Sabbado et al., 2021).

Meanwhile, scholars have tried to summarize, integrate and compare different dimensions of proximity. Boschma (2005) summarized and integrated the above-mentioned literature by establishing a comprehensive analytical framework, where five types of proximities are included, i.e., geographical, organizational, institutional, social, and cognitive proximity. Moreover, some researchers have been concerned with the relationship between different dimensions of proximity, such as substitution and overlap (Hansen, 2015). Last but not least, Balland et al. (2015, 8) explored the co-evolution of proximity and knowledge network, elaborating that five types of dimensions may vary over time because of “the processes of learning, decoupling, institutionalization, integration, and agglomeration.” Overall, proximity provides an in-depth understanding of knowledge interactions and innovation networks (Boschma, 2005; Marek et al., 2017; David & Frenken, 2018; Mattes, 2012).

2.2.1.2 Proximity and complex knowledge: A CKB perspective

Knowledge similarities and heterogeneity between firms within the same industry lead to vertical and horizontal knowledge links (Turkina et al., 2021). One firm may participate in several innovative projects and have different knowledge linkages. The linkages contain up to seven types of CKBs, namely combinations of intra-synthetic, intra-symbolic, intra-analytical, analytical & synthetic, analytical & symbolic, symbolic & synthetic, and analytical & synthetic & symbolic knowledge bases (Asheim et al., 2007; Asheim et al., 2011).

In the same stage, the whole attribute of CKBs with codified and tacit characteristics in the same innovative project is vague. Little literature responds to the potential linkages between CKBs with codified and tacit characteristics and proximity.

Combinations of analytical and synthetic knowledge bases are highly agglomerated in metropolitan areas and industrialized regions (Strambach, 2017; Mewes & Balland, 2022; Balland et al., 2020). Firms benefit from strong and comprehensive innovation systems, a large-sized market and skilled labour, multiple position mobility (multiple working experiences in different organizations), and various innovation collaboration projects (Wagner & Growe, 2022; Balland et al., 2020; Broekel, 2019).

At the local level, geographical proximity plays a significant role in collaborations based on analytical & synthetic knowledge combinations because innovation activities, including synthetic knowledge, are done through face-to-face communication and local buzz (Asheim et al., 2017).

Knowledge interactions are a social-spatial process (Boschma, 2005), which means innovation processes regarding combinations of analytical and synthetic knowledge are also embedded in local social networks and institutional environments (Strambach, 2017; Wagner & Growe, 2022). Therefore, social and institutional proximities may matter in regional combinations of analytical and synthetic knowledge bases.

Note that the regional institutional environment reflects how complex innovation and the combination of knowledge (bases) are treated. Firm-level actors generally prefer to choose partners who follow the same rules, regulations, and policies (formal institutions) when these partners could offer related R&D requirements. In addition, if collaborators share common norms, values, and culture (informal institutions), they are also a top priority for firm-level actors.

At the non-local level, organizational proximity may be an essential alternative to geographical proximity for collaborations with synthetic and analytical knowledge.

On the one hand, establishing sub-organizations is beneficial to absorbing cross-region or cross-county synthetic knowledge because synthetic knowledge is very sensitive to geographical distances. On the other hand, the recombinant process of analytical and synthetic knowledge is always accompanied by high uncertainty (Bennat & Sternberg, 2020). If interacting collaborators are in the same organizational branches and follow the same organizational arrangements, they could work together with a high-level synergy and reduce uncertainties (Capone & Lazzeretti, 2018). In other words, organizational closeness has the potential to reduce the risk of non-local collaborations and accelerate knowledge combinations between subsidiaries.

At the non-local level, combining knowledge creation is also very cognitively demanding due to the complex R&D process for analytical knowledge and mutual technical support for synthetic knowledge. In such an innovation process, both interacting partners absorb knowledge from each other and finally contribute to recombinant knowledge across space.

Organizations in different metropolitan areas often interact mutually and complement each other and hence are the main contributors to knowledge combination and cross-space diffusion. These metropolitan regions may be in the same or different countries.

For cross-country CKB flows, social proximity may matter because social ties are linked to trust and friendship (Broekel & Boschma, 2012; Martin et al., 2017), which shape, strengthen, and solidify the combination of analytical and synthetic knowledge. Such a solid tie creates a greater sense of identity among actors in advanced knowledge-creation processes and more minor frictions than collaborations without social ties.

2.2.2 Institutions and complex knowledge

2.2.2.1 Institutions

As Strambach (2017) stated, the institutional context influences the cognitive framework, the perception of the actors, and the interpretation of the situation, thus promoting mutual understanding, social learning, and the generation of new knowledge (Nooteboom, 2010; Turvani, 2010). In other words, the institution can be understood as a driver determining the rate of knowledge production and variation of knowledge in time and space. Although the institution is like a ‘black box’ (Bathelt & Glückler, 2014) without a precise definition, there are two main aspects when it comes to the effects of institutions on industrial knowledge bases and innovation, namely formal and informal institutions. Informal institutions are associated with social culture, customs, values, habits, and codes, among others, whereas formal institutions are relevant to knowledge infrastructures, rules, regulations, and legislation, among others (Casson et al., 2010). Regional institutional characteristics, i.e., institutional lock-in (Hassink, 2010), institutional hysteresis, and emergent change, reflect how local knowledge innovations are understood and treated (Bathelt & Glückler, 2014).

The literature on institutional changes has started to grow since the 1990s, in which multiple actors, referring to inventors, investors, and policymakers are emphasized (Bathelt & Glückler, 2014; Gertler, 2010, 2018; Grillitsch, 2015). The new classifications, namely firm-level and system-level actors, are identified, helping us to better understand top-down and bottom-up approaches in multi-scalar institutional changes (Isaksen et al., 2018). Institutional changes aim to stimulate new knowledge generation via the reconfiguration of infrastructures, the introduction of financial tools, and the legitimacy of technology at different spatial levels. To enhance the acceptance degree of innovation, new knowledge and technology are often linked to existing organizations, intermediaries, and regional industries (Bathelt & Glückler, 2014).

2.2.2.2 Institutions and complex knowledge: A CKB perspective

On the one hand, it concerns the relationship between system-level actors and complex knowledge. Complex knowledge is generally the result of multi-scalar institutional interactions, which refers to "multi-level governance and regional autonomy" (Moodysson et al., 2017, p385). Therefore, coordinating organizations at different spatial scales is critical in fostering local industrial innovation and creating complex knowledge, which is sometimes called holistic institutions (Edquist, 2014; Schröder & Voelzkow, 2016). Generally, the successful alignment of institutions at different spatial scales means that they are reinforcing and complementary. In contrast, failed coordination among multi-scalar institutions may lead to barriers to knowledge base combinations and industrial development (Manniche et al., 2017).

Moreover, the formation of four essential resources (i.e., knowledge creation, technological legitimacy, financial support, and market formation) highly depends on system-level actors' strategies. The four resources directly or indirectly affect the speed and quality of complex knowledge production in emerging industries. For example, Binz et al. (2016) addressed three cases in the on-site water recycling sector, finding that only Beijing experienced the development of a substantial on-site water recycling technology (OST) in China, even under very limited initial conditions. They proved that anchoring four resources by system-level actors in the early stage of industrial development is crucial.

In qualitative research, although the process and related mechanisms of knowledge-centered emerging industrial development are emphasized, the existing literature primarily zooms in on the role of policies and institutions within a single industry. However, the coordination of cross-sector institutions has not been sufficiently explored. For example, multiple sectors' interactions in the technology value chain are extended from the firm level to the system level (i.e., regime and institution). Phirouzabadi et al. (2022, p175) employed a mathematical model for dynamic simulation to analyze internal combustion engine, hybrid, and battery-powered automobiles in the American market between 1985 and 2050. They found that, "innovation policy mixes can possess a triple nature of 'creation', 'destruction' and 'accumulation' for interacting TISs through positive and negative internalities and externalities." Furthermore, inter-sectoral knowledge interaction and technology innovation system studies have dominated the regional sustainability transition. However, there is a limited understanding of system-level inter-sectoral interactive processes (Mäkitie et al., 2022; Glaa & Mignon, 2020). Sectoral interactions at the system level, in practice, are beneficial for policymakers to make innovative schemes and strategies.

In quantitative research, a range of studies examined the role of policies in patent application and innovation output. However, most policies are very general rather than having distinctive industrial characteristics. For example, in Yu et al. (2021)'s study, an inverted relationship between government subsidies afterwards (GSA) and financial performance is perceived in China; meanwhile, a positive U-shaped association between government subsidies beforehand (GSB) and financial performance is uncovered by addressing China's financial data. They also pointed out that digital transformation can enhance the efficiency of GSA and mitigate the adverse impacts of excessive GSA. Ruan et al. (2014) examined how different types of policies, such as promotional and restrictive policies, shaped breakthrough innovation and environmental transformation by tracing the trajectory of China's electric vehicles, providing a nuanced argument for catching up on innovation strategies. Jin and McKelvey (2019)'s empirical analysis has indicated that Hangzhou's public policies, in relation to the sharing market of electric vehicles, stimulated market formation rapidly, which actuated technical niches because manufacturers aim to enhance technological skills to reduce costs in this context.

On the other hand, the concept of firm-level actors is vague. Firms with different knowledge bases may enter the same emerging industries. Due to the differences in organizational factors, firms exhibit varying levels of innovation performance even in the same regional institutional context. As Manniche and his colleagues (2017, p11) stated, "it may indeed be equally contingent on organizational factors such as firm size, age, country, key individuals' networks and professional experiences, and a range of other organizational constraints and incentives to which the CKB approach does not pay attention. Such characteristics, not directly related to knowledge dynamics per se, may be strongly decisive for the actual organization of innovation processes…." Recently, Zhu et al. (2018) analyzed regional diversification in terms of technological relatedness, firm heterogeneity, and regional institutions, illustrating "the role of micro-level firm heterogeneity in terms of internal resources, capabilities, assets, and organizational structures" and "impact of macro-level regional variation of institutional contexts on the formation of new industries" (p70).

I see the need to investigate how inter-sectoral institutional changes stimulate complex knowledge-centered emerging industrial development. In the next paragraphs, I will construct an analytical framework for institutions and complex knowledge evolution.

Institutional changes aim to stimulate complex knowledge production and industrial transformation via knowledge creation, technology legitimacy, financial investment, or market formation (see Table 2.5). To enhance the acceptance degree of innovation, new knowledge and technology are often linked to existing organizations, intermediaries, and regional industries (Bathelt & Glückler, 2014).

Table 2.5. Four dimensions in institutional changes

Dimension	Definition
Knowledge creation	Activities that create new technological knowledge and related competencies (e.g., learning by searching, learning by doing, activities that lead to exchanging information among actors, learning by interacting, and learning by using networks).
Technology legitimation (legitimacy)	Activities that embed new technology in existing institutional structures or adapt the institutional environment to the needs of the technology.
Financial investment	Activities related to the mobilization and allocation of basic financial inputs such as bank loans, venture capital, or angel investment.
Market formation	Activities that contribute to the creation of protected space for the technology, construction of new market segments by tax regimes, subsidies and others.

Sources: Combine Karakaya et al. (2018, p654) and Binz et al. (2016, p181)

Most modern technologies have value chains that traverse many sectors, necessitating cross-sector knowledge spillovers (Stephan et al., 2019; Malhotra et al., 2019). The value chains of these technologies usually link various sectors that provide the varied knowledge bases and industrial skills needed for manufacturing (Jacobsson & Bergek, 2011; Stephan et al., 2017). Note that for the complex industrial chain, advanced technologies are usually influenced by different sectors located in different positions of the industrial chain. This implies that new technologies may emerge when institutional changes affect sectors in either the downstream or upstream positions of the industrial chain.

In other words, understanding the inter-sectoral dynamics of how a technology arises, changes, or declines as part of transitions requires a knowledge of the nature and interactions of these varied sectors engaged in the value chain.

For example, as Figure 2.3 shows, when multi-scalar institutional changes and technological breakthroughs influence sector A, sector B, located in the downstream position of the industrial chain, also has more opportunities to undergo transformation or upgrade through technology pull. Furthermore, when sector B is developed via technology legitimacy, financial investment, knowledge creation, and market formation, inter-sectoral linkages may lead to sector A's participation in related innovative activities.

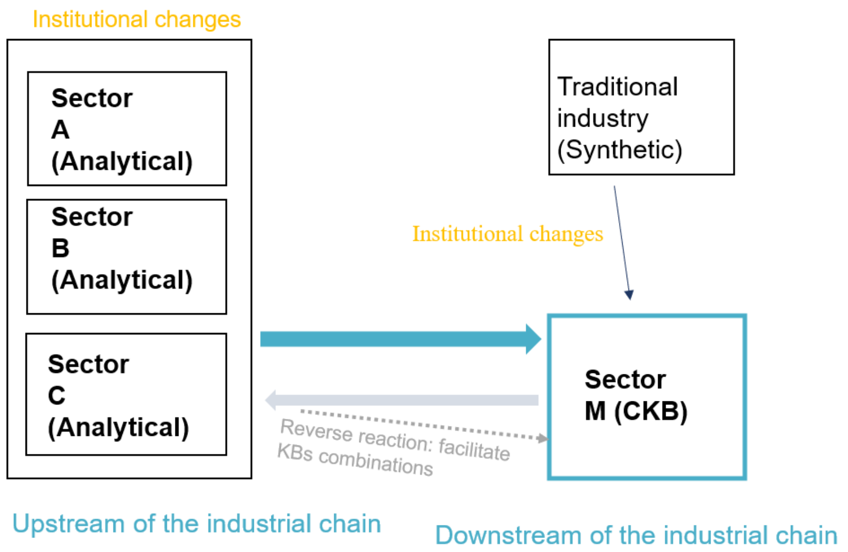

Figure 2.3. The analytical framework for institutions and complex knowledge evolution

Particularly in different transition contexts, the inter-sectoral dynamics may become more complex. This study analyzes how resources at different spatial scales and multiple actors contribute to the complex knowledge evolution in a twin transition in which inter-sectoral dynamics are emphasized.

2.2.3 Innovation system reconfiguration and complex knowledge

2.2.3.1 Innovation system reconfiguration

Innovation systems offer insights into the spatial agglomeration of innovative activities (Asheim et al., 2016; Binz et al., 2016; Isaksen et al., 2022). In economic geography, scholars are likely to explain the geography of innovation with the help of a regional innovation system (RIS) or technological innovation system (TIS). The RIS primarily consists of institutions, networks, and actors in which the institutional infrastructures mutually complement or reinforce and may be supported by institutions at different spatial scales (Asheim & Coenen, 2005; Asheim et al., 2016). The TIS can be understood in terms of six system elements (i.e., knowledge creation, entrepreneurial experimentation, market formation, resource mobilization, legitimacy, and search guidance) accelerating regional industrial upgrading and transformation (Binz et al., 2016; Miörner & Trippl, 2019). Differ from the RIS, which reflects how regions treat innovation, the TIS considers more industrial environmental factors (i.e., market side) and concrete approaches in the innovation process (i.e., resource mobilization and guidance of the search) and goes beyond the spatial limitation of the region, and is therefore widely applied in innovation studies.

The innovation system reconfiguration aims to facilitate the combination of cross-field knowledge, enhancing regional industrial competitiveness (Asheim et al., 2016; Miörner & Trippl, 2019; Miörner, 2022). To achieve such a goal, regional actors take different reconfiguration modes (how). For example, Miörner and Trippl (2017) identified three modes of ISR in Scania's digital game industry by creating new elements alongside old regional innovation systems. The first mode is layering, which involves the introduction of new institutions (such as Nordic Game Conference, Game Assembly, and Game City supported by policymakers, private entrepreneurs, and cluster organizers) and the establishment of new education infrastructures (including a vocational training school in Malmö) to facilitate the structural adjustment of Scania's digital games industry. The second mode is adaptation, which involves changes to existing informal and formal institutions in Scania's digital game industry, such as modifications to the goals of NGC (Nordic Game Conference) due to potential lack of support from policymakers for the establishment of new organizations. The third mode involves the novel application of existing institutions and resources, which may also benefit other sectors in Scania. For example, the City of Malmö and Region Skåne, a regional government body, invested in the Nordic Game Conference instead of creating a new support structure.

In addition to creating new elements, innovation systems may be reconfigured by adjusting or repositioning the existing system elements. Miörner and Trippl (2019) addressed the effectiveness of three modes of ISR (namely, the intra-regional system functions developed and system functions assessed and transplanted in the outer regions) according to the geography and functions of system elements (six elements in the TIS) in the self-driving car industry in West Sweden. The first model concerns the developing system functions within the region. The interaction between Chalmers and the local automotive companies resulted in the adjustment of education schemes associated with university software education and related research forums. The second model involves accessing system functions elsewhere. The coordination and critical linkages between existing initiatives and new networks (Swedish Transport Administration) offer opportunities to go to SAFER, Lindholmen Science Park, and Test Site Sweden. The third model is transplanting system functions from elsewhere, such as the inflows of automotive and IT firms, a Chalmers University campus and technological service organizations in West Sweden.

Furthermore, Miörner (2022) investigated the process and mechanisms of ISR by contextualizing agencies in the automotive industry in Western Sweden and the digital game industry in Scania. They constructed a regional imaginaries-power relations-directionality framework. Concretely, in Scania, public actors categorized the game industry as part of Media Evolution, loosely anchoring this industry to regional imaginaries characterized by post-industrial, diversified-cultural, and innovative regions. To develop the game industry, private actors actively initiated a program to address youth unemployment through the diversity of this industry instead of establishing new support organizations. Although the public actors paid more attention to media activities, they did not issue concrete incentives in this aspect and point out specific directions and guides (weak directionality). Moreover, although regional automotive manufacturers and official staff in Western Sweden expected to develop sustainable automotive technologies, national-level formal regulations limited their actions. It led regional actors to “adopt a more ‘thematic’ than ‘industrial’ focus, developing a supportive system around ‘SDCs’ defined broadly”, namely sustainable transport systems rather than specific automotive technologies (Miörner, 2022, p600). Because of this direction, an open RIS has been established, where broad participants such as IT firms, stakeholders in other sectors, and marginal actors are included.

Although these studies have elaborated on the role of multiple actors in the ISR process in terms of spatiality, private-public attributes, and dominant sectors, the definition of actors and cross-sector complex interactions among actors are vague. Particularly, the analyses of actors in non-dominant or interconnected sectors and the coordination among multiple public departments are not satisfactory. For example, in medical device and automotive industries, semiconductor, new material and digital sectors, located in the upstream of the industrial chains, are playing a more and more role in high-end medical device products and electric vehicles. It means more actors from different sectors and official departments participate in ISR in the complex industries. Therefore, identifying the detailed attributes of actors/organizations and their role in ISR could help us to better understand the complex knowledge production process, i.e., how it happens and why it is successful or failed.

2.2.3.2 Complex knowledge production and ISR: A CKB perspective

As has become clear in the previous sub-section, complex knowledge evolution involves the transition from DKB to CKB. Successful transitions are conditioned by innovation system reconfigurations at several scales. These reconfigurations are, in turn, affected by institutional evolution, dynamic capabilities of entrepreneurs and governance complexity, which will be dealt with below.

Institutional evolution

The co-evolution of regional knowledge institutes that are linked to distinct knowledge bases plays a crucial role in the production of cross-sectoral complex knowledge. The evolution of these institutes toward different knowledge bases can either be similar or differ. Common approaches include establishing new knowledge infrastructures, offering new courses, forming new departments, or creating affiliated entities such as labs for the application of foundational knowledge (Asheim et al., 2011). When the co-evolution is well-coordinated, it tends to drive the transformation of the regional economy. Conversely, if the evolution is disorderly or the development of institutes is fragmented, it can impede regional industrial upgrading.

Dynamic Capabilities of Entrepreneurs

The process of cross-sectoral complex knowledge production involves inherent uncertainties due to the novel combinations it entails (Manniche et al., 2017). Only firms with strong dynamic capabilities are able to engage in recombining innovative activities. In other words, diverse entrepreneurs serve as the gatekeepers of ISR involved in cross-sectoral complex knowledge production.

The consistency of dynamic capabilities highlights the importance of firms from interdependent sectors aligning their sensing and seizing of opportunities for cross-sectoral ISRs (Roundy & Fayard, 2019). While entrepreneurs may simultaneously sense business opportunities based on customer demands, adjusting firm-level innovative strategies and investing in new innovative projects may not always be in sync. Achieving consistency in dynamic capabilities involves the reconfiguration and integration of R&D resources across sectors, enabling firms to mutually facilitate each other's innovation efforts.

Governance complexity

To promote cross-sectoral complex knowledge production, policy broadening and deepening around upstream and downstream sectors are needed (Laasonen et al., 2022; Borrás, 2009). The sector located in the downstream position of the industrial chain is developed via sectoral governance per se on the one hand, but on the other hand, it is also influenced by other sectoral governances in the upstream position. "… How actors in upstream sectors respond to those change signals can impact both the direction and pace of the transition. An inter-sectoral linkage perspective provides a nuanced view of the sectors and firms engaged in a particular technology. It can connect those changes in upstream sectors to transition processes in a focal sector ..." (Andersen et al., 2020, 349-350).

The interwoven sectors along the industrial chain and cross-sectoral complex knowledge interactions lead to governance complexity in ISR. For example, policymakers have to calculate direct and indirect effects of sectoral governance on other sectors. The participation of official staff from different public departments or the increased scope of regulation by existing governing authorities can lead to multiple interactions at the national and regional levels when policies are introduced, multiple processes are analyzed or regulations are enacted.

The need for innovation system reconfigurations can occur both in a context of single-sectoral knowledge production or in a cross-sectoral complex knowledge production process. In the latter case, the ISR shows more attributes and features in institutional evolution, dynamic capabilities of entrepreneurs and governance complexity (see Table 2).

Table 2.6 A comparative analysis for two modes of regional ISR

Perspective	Regional ISR mode for single-sectoral knowledge evolution	Regional ISR mode for cross-sectoral complex knowledge evolution
Institutional evolution	Establish new knowledge infrastructures, new courses, new departments, or new affiliates such as labs for applications of basic knowledge	Co-evolution of regional institutes related to complementary knowledge
Dynamic capabilities of entrepreneurs	Sensing and seizing opportunities; Sensing means identifying and pursuing opportunities according to customers' demands; Seizing means investing in key innovative projects to establish sustainable business opportunities	Diverse entrepreneurs and the consistency of dynamic capabilities
Governance complexity	Introduce rules, regulations and policies regarding R&D, investments and marketization; multi-scale governance	Policy broadening and deepening around interdependent sectors (located in different positions of industrial chains)

Sources: Arthur (2009), Miörner (2022), Miörner & Trippl, (2017), Mäkitie et al. (2022), Markard and Hoffman (2016), Asheim et al. (2011), Manniche et al., (2017), Roundy & Fayard (2019), Laasonen et al. (2022), Borrás (2009), and the authors.

Overall, by combining combinatorial knowledge bases and innovation system reconfiguration, we develop a theory of complex knowledge evolution (Figure 1). The three pillars of innovations system reconfiguration, namely institutional evolution, dynamic capabilities of entrepreneurs and governance complexity affect the transformation from knowledge bases to a combination of knowledge bases. The theory is able to analyse, understand and explore complex knowledge trajectories in regional economies. The analytical power of the proposed theory will be illustrated with qualitative empirical work on complex knowledge evolution in two emerging industries in Shanghai, namely the medical device and automobile industries, in the next Section. We consider qualitative methods as essential doing research with this theory, because complex knowledge evolution is a highly qualitative process that can only be partly understood by looking at structures and relatedness of industries in regional economies.

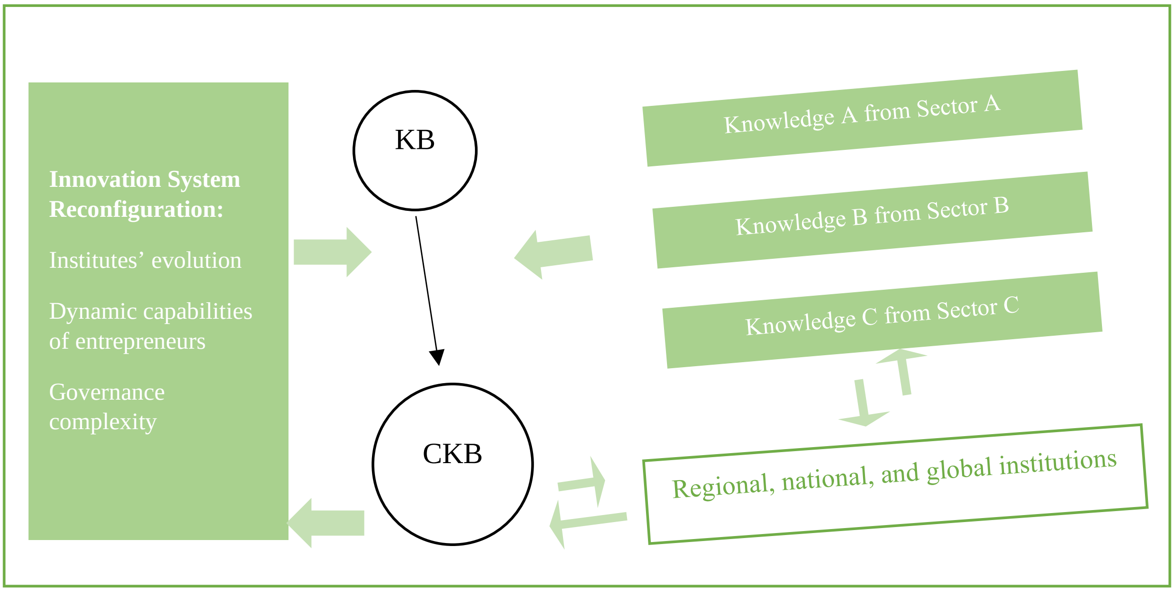

Figure 2.4. ISR and complex knowledge production

2.3 Complex knowledge evolutionary process and mechanism: towards a comprehensive theoretical framework

Knowledge complexity is a crucial issue for the core questions mentioned above in economic geography. While the existing studies are insightful into agglomerative spatial patterns of complex knowledge production and have made significant advancements in measurement and metrics (Hidalgo, 2021), they offer a limited understanding of certain critical questions in economic geography, such as why do some regions, despite having similar industrial structures, have a stronger concentration of knowledge complexity than others? Or why do regions differ in their complex knowledge evolution over time? These are questions related to processes and mechanisms of complex knowledge evolution, which have been insufficiently dealt with in current complex knowledge theorizing in economic geography.

The comprehensive theoretical framework (see Figure 2.5) addresses this problem. First, it advances the understanding of complex knowledge from a CKB perspective, in which knowledge bases reflect the components of complex knowledge. Secondly, it explores how proximity, institutions, and innovation system reconfiguration facilitate the evolutionary processes of complex knowledge: (1) In proximity analysis, it employs multiple dimensions to analyze the drivers of complex knowledge evolution at different spatial scales; (2) In institutional research, it uncovers the effects of upstream-downstream interactions on knowledge base combinations in green and green digital transitions. (3) In ISR research, it highlights institutional evolution, entrepreneurs' dynamic capabilities, and governance complexity that accelerate the evolution of complex knowledge in the innovation system reconfiguration process. The three research strands answer three questions about how policies upgrade, how upstream-downstream interactions take place and how actors engage in more complex activities, providing strong pieces of evidence for a contextual interpretation of complex knowledge. Note that a multi-scalar perspective, a multi-dimensional analysis, and multiple actors are emphasized in analyzing context sensitivity.

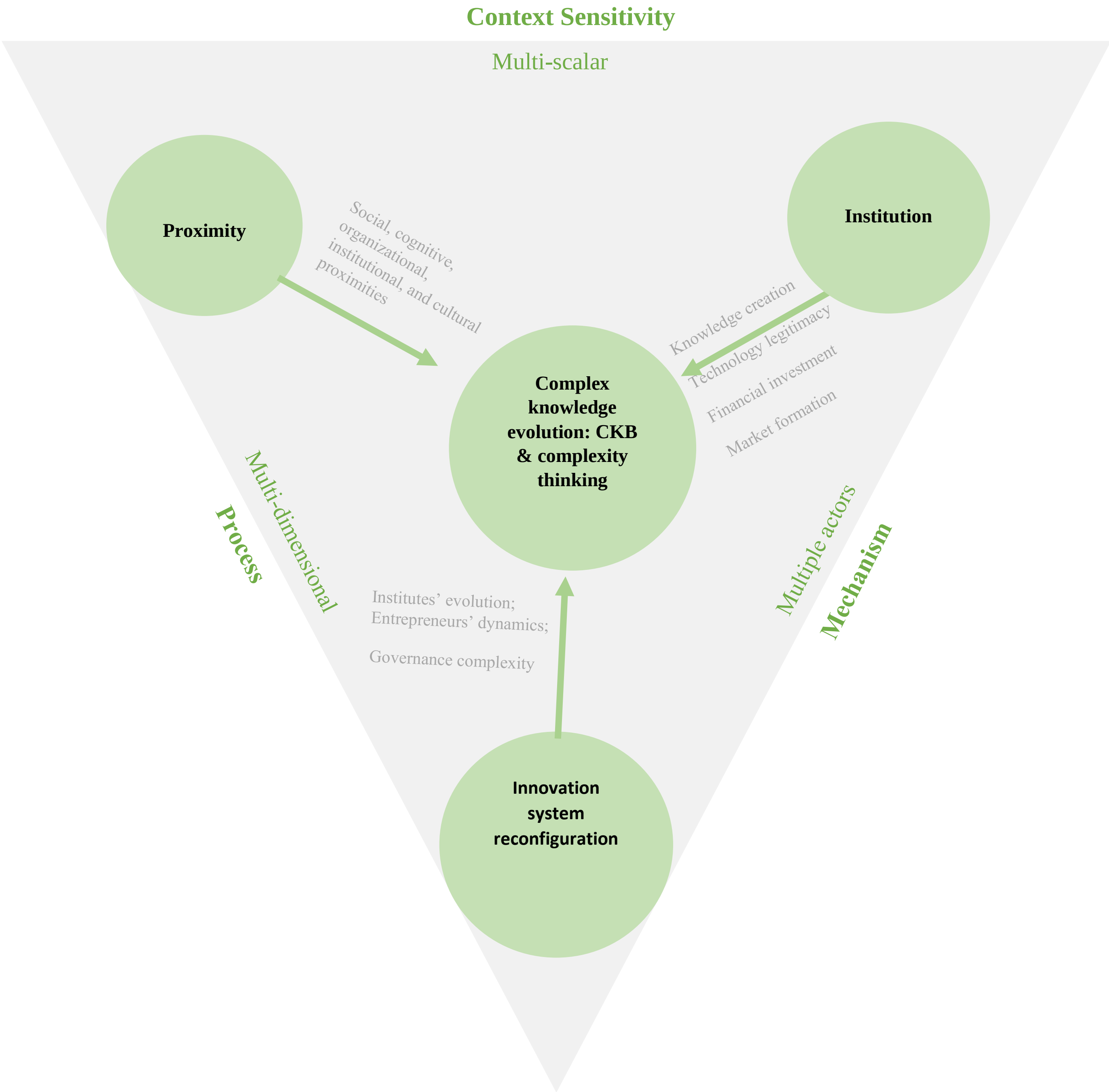

Figure 2.5. A comprehensive theoretical framework

2.4 This chapter's summary

In the field of evolutionary economic geography, complexity and knowledge have played prominent roles. Apart from the comprehensive theoretical contribution by Martin and Sunley

(2007), until 2018, very few economic geographers did empirical research on complexity (for an exception, see Weig (2016)). Boschma and Frenken (2018) hardly mentioned complexity in their overview of the conceptual and empirical state of the art in the field of evolutionary economic geography. However, despite its relative unpopularity until 2018, in recent years, inspired by Hidalgo (2018), there has been a sudden upsurge in the quantitative and empirical literature related to complexity in the context of knowledge and networks (Balland & Rigby, 2017; Balland et al., 2020; Broekel, 2019; Mewes & Broekel, 2022; Pinheiro et al., 2022). However, the recent literature neither makes reference to complexity theory nor to complex adaptive systems, nor does it significantly advance theories.

As Gong and Hassink (2020) stated, the context sensitivity could help us better understand what we observe and reconstruct theories by linking to more nuanced elements in relation to history, institutions, intermediaries, or firm attributes. Furthermore, the examination of knowledge complexity predominantly centers on analytical knowledge within science-based sectors, overlooking various other knowledge domains. For instance, knowledge encompassing art, design, and culture exhibits substantial spatial clustering. Aesthetic design and high-precision engineering technology in specific manufacturing sectors have emerged as critical factors in market competitiveness. It is imperative to delve into complex knowledge that transcends the boundaries between different knowledge domains.

Exploring complex knowledge from a CKB perspective is a visible approach. Such an approach could help scholars to better understand the context sensitivity of complex knowledge because policy upgrading and actors’ interactions toward more complex activities are easier to observe from a CKB perspective. As Asheim (2022, p 52) stated, the DKB approach "supports an active role of policymakers in stimulating novel combinations of differentiated knowledge bases, which shows its roots in the (regional) innovation systems tradition. As such, the knowledge base approach is closer to an institutional than to an evolutionary way of reasoning. The policy dimension with a focus on intentional actors and agencies requires a social ontology as a foundation to understand and explain how emerging industries and new path developments, which often result from public policy interventions and innovative entrepreneurs, take place. An evolutionary approach cannot fully make sense of such new developments…"

Then, I analyze the context sensitivity of regional complex knowledge evolution from a CKB perspective. Proximity, institutions, and innovation system reconfiguration are introduced as the primary lens to unravel the process and mechanisms of complex knowledge production. In the proximity lens, I address how five dimensions (i.e., institutional, cognitive, organizational, social, and geographical proximities) influence the combination of knowledge bases at regional, national, and international levels, providing insights into complex knowledge evolution at multiple scales. In the institutional lens, I explore how different types of firms in the multi-scale institutional changes actively interact with system-level actors, which in turn leads to regional innovation outputs. A common assumption in both lenses is that multiple actors are the driving forces for complex knowledge evolution. Strategic changes of multiple actors are an essential influence in technological changes and knowledge (base) combinations. Based on such a common assumption, I use the lens of innovation systems to examine how different actors adjust strategies in the innovation system reconfiguration and regional economic evolutionary process, in which institutional evolution, entrepreneurs' dynamic capabilities, and governance complexity are identified.

In summary, the chapter discusses the context sensitivity of complex knowledge from a CKB perspective, which can be seen as a complementary understanding of existing measurements. In addition, this chapter has provided a theoretical framework for the empirical analyses, which will follow in chapters 4.1, 4.2, and 4.3.

3. Methodology

After introducing the theoretical section, I specify how I conducted my research under scientific guidance. I present the ontology and epistemology of critical realism, the research strategy and methodology, the case selection, and the research process (see Figure 3.1).

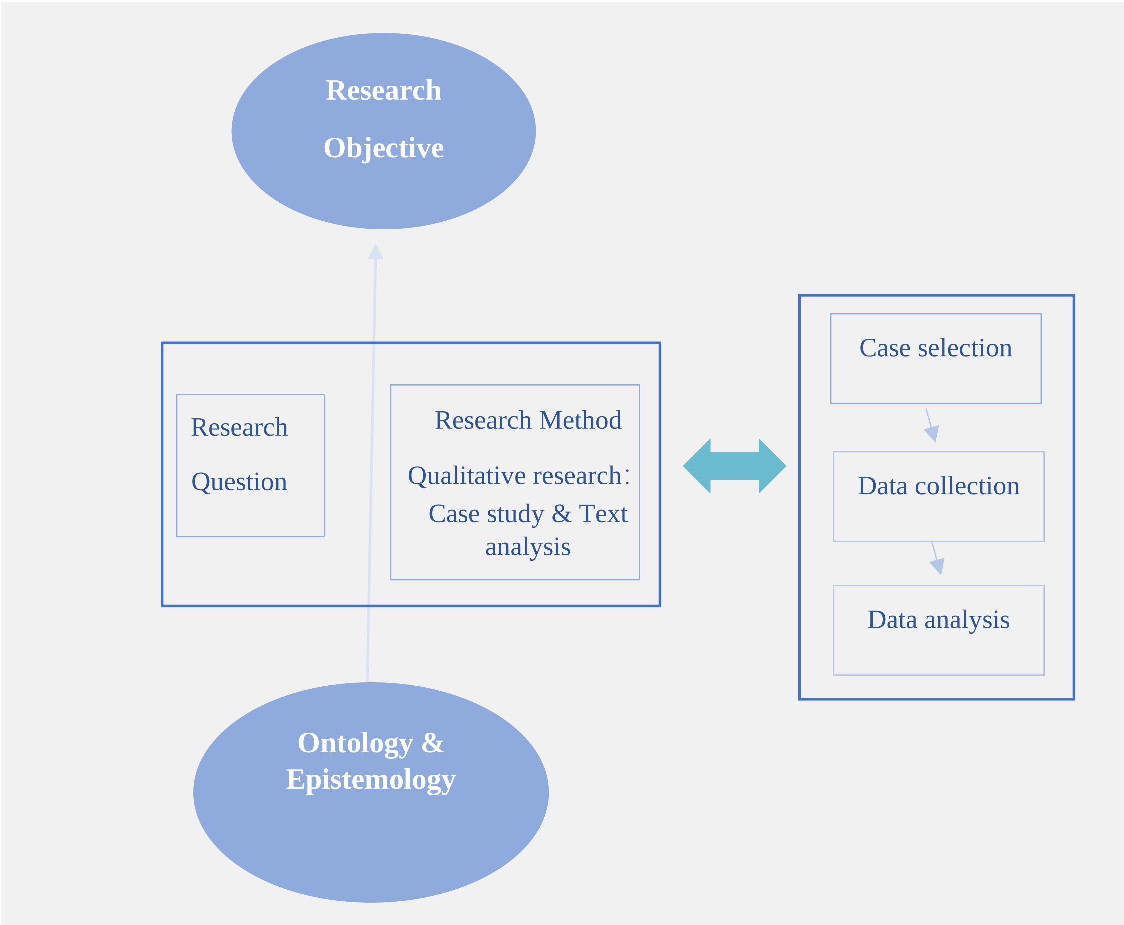

Figure 3.1. Research design

3.1 Philosophical methodology

Like the central role of grammar in language, philosophy has a macro-directive role in research and makes it more scientific (Graham, 2013). In human geography, “space is relative and variable, and this makes context king” (Rodríguez-Pose, 2011, p352). This subsection aims to clarify how ontology and epistemology in criticism contribute to the research goals.

Bhaskar (1975) first introduced critical realism as a philosophical idea in the 1970s, emphasizing the vital role of context in the development of human society (Bhaskar, 1998). Andrew Sayer applied critical realism to human geography to answer the question, “how far, or at what depth, are social structures and processes context-dependent?” (Sayer, 1989, p 255). Following Sayer’s argument, several human geographers have opened up a deeper level of inquiry. On the one hand, space is a fundamental disciplinary attribute of human geography and is, therefore, widely considered in applying critical thought. For example, a regional industrial path takes place in specific countries, regions, and specific institutional frameworks (Tanner, 2016; Hassink et al., 2019; Jolly et al., 2020), whereas studies of related diversity have been criticized for ignoring the context sensitivity and contingent conditions in the existing literature (Gong & Hassink, 2020). On the other hand, critical thinking has led to a constant reinterpretation of causal forces in the practice of theorizing. For example, knowledge bases are considered an excellent example of the application of critical thinking to economic geography, as a more sophisticated and complex alternative to CKBs for DKBs has recently been established (Asheim et al., 2017; Manniche et al., 2017; Gong & Hassink, 2020).

Yeung (1997) blends in realism epistemology with realist ontology, offering essential guidance for theorizing economic geography. In his view, this “celebrates the existence of material reality independent of human consciousness (realist ontology), ascribes causal powers to properties/potential in objects and human reasons and their activation through generative mechanisms such ad enduring social structures (realist ontology), rejects relativism in social and scientific discourses (realist epistemology), and orientates the social sciences towards its emancipatory goal (realist epistemology)” (Yeung, 1997, p52).

This study’s philosophy of critical realism provides a scientific guide to my research topic. Specifically, system-level actors at different spatial scales have developed several strategies for complex knowledge production. Complex knowledge’s context sensitivities and contingent conditions must be adequately explained. As Chapter 2 shows, the CKB concept offers a nuanced insight into the ontology of complex knowledge evolution. Following such an argument and scientific guide, I designed a research strategy and questions, as described next.

3.2 Research strategy and methods

Qualitative research interprets complex practices (Marshall & Rossman, 2014; Qu & Dumay, 2011). It can reveal tensions and conflicts resulting from the constant shift of internal and external factors due to their historical shape (Patton, 2005; Hennink et al., 2020). Qualitative researchers firmly believe in the value of a detailed description of the social world. By contrast, quantitative researchers pay little attention to such detail because they focus on positions and universal laws. More importantly, quantitative researchers are likely to ignore such rich descriptions deliberately because such detail disrupts their process of generalizing profiles.

This study aims to analyze the driving mechanisms behind complex knowledge and answer three questions: (1) What are the characteristics of upstream-downstream interactions in the evolution of complex knowledge ? (2) How do actors engage in more complex innovation activities? And (3) how can policies be upgraded to facilitate complex knowledge production. These three questions require an in-depth contextual analysis for the actors' interactions. Hence, I choose the qualitative method. Specific research methods include case studies and text analysis.

3.2.1 Case study

Case studies have two advantages. Firstly, case studies are well-placed to answer research questions about how and why. By describing phenomena, researchers can dig deeper into the driving mechanisms behind them (Flyvbjerg, 2011; Gerring, 2004; Tellis, 1997). Secondly, case studies map out natural, objective phenomena, and these social observations are solid material and evidence to enhance and refine theories (Gong & Hassink, 2020; Flyvbjerg, 2011). Using a case study as a starting point for a scientific study can increase the validity of the research.

This dissertation uses comparative case studies. Unlike most comparative case studies emphasizing different regions in the same industry, this dissertation reveals the characteristics and driving mechanisms of knowledge combination across sectors by comparing the complex knowledge evolutionary processes of different industries in the same region. I selected three cross-sectoral knowledge flows that are currently receiving the most attention in two emerging industries. Gong (2019, p52) emphasizes the important relationship between theory and case selection: “Theoretical sampling simply means that cases are selected because they are particularly suitable for illuminating and extending relationships and logic among constructs. In other words, cases are only sampled for theoretical reasons” (Eisenhardt & Graebner, 2007). Based on this, the research workload of this study was enormous, as it involved knowledge flows across six sectors.

3.2.2 Text analysis

Text analysis is an essential complementary approach for case studies (Kuckartz, 2013). In qualitative research, texts consist mainly of documents such as industry assessment reports, local newspapers, conference proceedings, books, press releases, and survey data. The central contribution of these documents to this study is that, firstly, they provide a history of the development of the regional industry and policy documents. This provided me with essential knowledge before entering the field and helped me to ask in-depth questions during the interviews. Secondly, these texts provided support and evidence for specific findings in the empirical analysis, which enriched and expanded my interpretation of the research phenomenon. Thirdly, the papers provided me with a deeper understanding of the challenges faced by regional industrial innovation activities. With them, I could help the interviewers address existing or potential problems by sharing academic examples.

3.3 Case selection and investigation process

3.3.1 Why did I choose Shanghai?

Shanghai ranks fifth in the world, according to GaWC 2020, where complex knowledge is highly agglomerated. Many disruptive breakthroughs and crucial technological innovations in China occurred in Shanghai because of its rich, innovative sources such as advanced knowledge infrastructure and many research institutes. In Shanghai, manufacturing industries comprise the electronic and information sector, the automobile industry, petrochemicals and fine chemical manufacturing, refined steel manufacturing, biopharmaceuticals (including medical devices), and industrial machining. According to the Shanghai Bureau of Statistics, in 2021, these six key manufacturing industries contributed to nearly 24 trillion yuan in industrial output, accounting for more than 68.3% of the city's total. Service industries primarily include the internet, financial, trade, and creative cultural industries. Over the last two decades, and particularly in the last 10 years with the development of internet technologies, Shanghai's digital economy has expanded quickly. By the end of 2020, it accounted for over 50% of the city's total GDP. Overall, complex knowledge production prevails in Shanghai.

The medical device and electric vehicle industries have developed quickly in the last 20 years. Table 3.1 shows a sharp increase in the number of firms and patents, and in the amount of knowledge infrastructure.

Table 3.1. The regional industrial context

Name	Automobile Industry in Shanghai	Medical Device Industry in Shanghai
The number of firms	7181 in 2000; 52392 in 2021	1568 in 2000; 38963 in 2021
The type of firms	State-owned, private, and joint firms in 2000; The emergence of foreign firms in 2018	State-owned, private, and foreign firms
Leading firms and size	SAIC (State-owned), Azera (private), Tesla (foreign) Volkswagen in Shanghai (joint firms)	Shanghai Precision Instrument Manufacturing Factory (state-owned) Siemens in Shanghai （foreign）
The influence of cluster	National-level Innovation Park: Zhangjiang Hi-Tech Park	National-level Innovation Park: Jiading Auto Park
The related public R&D institutes	About 30 in 2000; More than 50 in 2021	About 13 in 2000; More than 46 in 2021
Main related sectors in the complex knowledge production	Internet sector, Material sector, and Semiconductor sector	Internet sector, Material sector, and Optical sector

Sources: Fieldwork in China

3.3.2 Why do I choose the medical device industry?

The medical device industry is a multi-disciplinary, knowledge-intensive industry (Davey et al., 2011; Zhao et al., 2018), which refers to, among others, mathematics, physics, biology, computer, engineering, and electronics. Therefore, in the R&D process, cross-disciplinary collaborations are the primary way of product innovation.

3.3.3 Why do I choose the electric vehicle industry?

The electric vehicle industry is knowledge-intensive, referring to diversified disciplines such as engineering, electronics, and computer science. In other words, in this industry, complex knowledge is visible, and knowledge base combinations and recombinant innovation activities are easier to observe. Moreover, the electric vehicle industry is characterized by high risk and uncertainty. As such, it is primarily supported by the state, particularly in its early developmental stage (Antonson & Carlson, 2018; Skjølsvold & Ryghaug, 2020). Recently, with the market expansion of electric vehicles, this sector has seen more and more social capital or venture capital inflow. Last, green knowledge and digital technologies are central to regional electric vehicle industrial development. Green knowledge creation, as the first race of innovation competition, is primarily associated with the battery, motor, electric control and other vital components and parts, whereas digital innovation refers to automated technologies, AI, and digital management of electric vehicles (Lee, 2020; Sovacool et al., 2019).

3.3.4 Investigation process

The fieldwork was conducted in Shanghai from August 2020 to August 2022. Table 3 shows that I visited 77 interviewees by stratified random sampling and snowballing (see Table 6). I contacted these interviewees through my former colleagues, classmates, friends, and family. A few of the interviewees were contacted by me via email. I found senior R&D staff or project managers in the medical device and electric vehicle industries from a Business Card All-in-One app. All the interviewees I selected had at least four years of working experience.

I first communicated with scholars and experts (SE) to determine the main characteristics of knowledge evolution and regional industrial histories, as well as the role of institutions in the application of the sectors located in the upstream and downstream positions of industrial chains. Based on the communication, critical knowledge flows were identified across sectors concerning automobiles and medical devices. Then, semi-structured interviews were conducted with CEOs, research staff (CS), and official staff (OS) from the Shanghai electric vehicle industry, Shanghai medical device industry, semiconductor industry, new materials sector, internet sector, and optical sector. In the fieldwork, communication primarily revolved around knowledge infrastructure, entrepreneur behavior, and policy upgrading. The interviews lasted, on average, 45 minutes.

In addition to the interviews, I attended several conferences organized by Tongji University, Shanghai Jiao Tong University, the Jiading government, and the Shanghai International Medical Equipment Fair in 2020 and 2021. Some forums were supported by universities, where CEOs were invited to present their new products and discuss some of the opportunities and barriers they or the industry faced, such as digital opportunities in the electric vehicle industry, the relationship between intelligent transportation and electric vehicles, and charging facilities. At the meetings organized by the government, official staff explained the related assets led by them and solicited opinions from industrial associations and firms. Furthermore, the original data were complemented with secondary documents from various sources, such as industrial reports, mainstream media reports, and academic papers.

Table 3.2. The interviewees

Automobile Industry		Medical Device Industry	
CEOs and research staff (CS)	Automobile firms: 4 CEOs and ten research staff	CEOs and research staff (CS)	Medical device firms: 4 CEOs and 12 research staff
	Internet firms: 3 CEOs and five research staff		Internet firms: 3 CEOs and four research staff
	Material firms: 2 CEOs and two research staff		Semiconductor firms: 2 CEOs and two research staff
	Semiconductor firms: 2 CEOs and two research staff		Optical firms: 2 CEOs and two research staff
Scholars and experts (SE)	Three scholars and experts	Scholars and experts (SE)	Four scholars and experts
Official staff (OS)	Four official staff	Official staff (OS)	Five official staff

Sources: Fieldwork in China

3.4 Data analysis

There were four main steps to the data analysis. In the first step, I imported all the data into Nvivo and organized the data by developing codes, selecting codes, and attributing codes. After the basic coding was completed, I tried to rethink the validity of these codes and the fitness between theoretical and conceptual elements, and then I adjusted some of the codes. I attempted to link the modified codes through storytelling in a second step. Some information was eliminated, added, and supplemented in this description process. In the third step, I carved out the core driving mechanisms through some software assistance, such as the second-degree retrospective process. In addition, I reviewed relevant studies, finding research results and classical comments closely related to the coding to indirectly compare the reliability and veracity of the existing data analysis. For some contrary phenomena found, I explained and proved this study's reliability via in-depth context sensitivity. In the fourth step, I carried out a backward extrapolation, i.e., from empirical evidence to theory, examining reliability and trustworthiness of the whole study.

3.5 Summary

This chapter elaborated on why and how I conducted the fieldwork. First, I described how my research follows scientific guidelines and highlighted the advantages of case studies and text analysis. As Figure 3.1 shows, critical thinking regarding complex knowledge is the starting point for research, and the specific research methods (i.e., case study and textual analysis) are the process. Secondly, I explained why the Shanghai medical device and electric vehicle industries are suitable cases for this thesis. Cross-sector knowledge base combinations and strong industrial bases were crucial for selecting cases in my research. Finally, I detailed the data processing process, including developing codes, selecting codes, and attributing codes, modifying these codes through storytelling, carving out the core driving mechanisms through software assistance, and examining the data as reliable and trustworthy. In the next chapter, I conduct an in-depth empirical analysis.

4. Cross-sector complex knowledge evolution: A comparative study in Shanghai

Based on the theory in Chapter 2 and the methodology in Chapter 3, I study complex knowledge evolution in Shanghai's medical device and electric vehicle industries. Firstly, I use the concept of proximity to analyze the combination of knowledge bases in the Shanghai medical device industry at regional, national, and international levels, with the goal of identifying the key drivers operating at different spatial scales. Secondly, I use the concept of institutions to analyze how policymakers in the development of Shanghai's electric vehicle industry encourage actors to engage in more complex innovation activities in green and green digital transitions. Finally, I compare the key factors driving the evolution processes of complex knowledge in these two industries, highlighting both their similarities and differences. I construct a framework for the innovation system reconfiguration, in which institutional evolution, entrepreneurs' dynamic capabilities and governance complexity are emphasized.

4.1 The Shanghai high-end medical device industry

In the following, we will present the results of our empirical analysis. The empirical analysis is introduced based on three spatial scales, namely, intra-Shanghai, Shanghai-other cities in China and Shanghai-global studies. According to the data statistic analysis, we found that the proportion of collaborators from Shanghai, other cities in China and international cities are about 3:1:2, which means Shanghai's high-end medical device development is highly dependent on local and local- global sources. Detailed collaboration analyses are as follows.

4.1.1 Intra-Shanghai analysis

After the end of the 20th Century, the central government has paid more attention to the development of medical devices and encouraged enterprise innovation through a related set of industrial policies (SE2; OF1). Partly because of this support, the number of medical device companies has been growing in Shanghai, locating in new districts, such as Pudong, Minhang, Fengxian, and Songjiang. Moreover, the number of public research institutes increased rapidly, significantly supporting industrial development.

These preconditions pay the way for national policy upgrading to develop the high-end medical device industry since 2013. National policies and regulations primarily refer to opinions on deepening the reform of the review and approval system to encourage innovation in drugs and medical devices (issued in 2017), the Twelfth Five-Year Plan for the Medical Device Technology Industry (work from 2011 to 2015) and Special Plan for Scientific and

Technological Innovation of Medical Devices in the Thirteenth Five-Year Plan (work from 2016 to 2020).

Within Shanghai, there are by now about 50 universities, colleges and research institutes that refer to related disciplines or technologies, including biotechnology, medical science, artificial intelligence, mechanical engineering and electronics. The disciplines or technologies primarily relevant to analytical and synthetic knowledge (Cheong et al., 2020; Wu, 2007).

Among these, the R&D collaborations of the high-end medical device industry mainly include software engineering, electronic engineering and human factor engineering characterized by the combination of synthetic and analytical knowledge bases (CR1-CR17). Space agglomeration characteristics of this type of CKB are mostly influenced by high geographical embeddedness and tacit features of synthetic knowledge bases (CR2, 4, 8, 10, 15, 16, 17; SE1).

Geographical proximity facilitates knowledge interactions concerning software engineering, electronic engineering, and human factor engineering. An essential prerequisite for planning the Shanghai high-end medical device industrial park is its proximity to relevant universities, research institutes, and university-affiliated hospitals in Shanghai. Integrating industry, academia, research, and medicine provides favorable conditions. Given the requirement for face-to-face interaction in composite CKBs, companies tend to prioritize industrial parks near their partners, such as universities and research institutes (2019 Shanghai High-End Medical Device Industry Report).

“Knowledge interaction between software engineering and electrical engineering is crucial for CKB-related R&D during collaboration, necessitating frequent face-to-face communication. The two research groups typically provide detailed reports on CKB, share research progress, and discuss and prepare new plans for the next phase,” explained the R&D staff. Geographical proximity is vital in reducing unnecessary time costs for collaborators and contributes positively to local synergy.

“During R&D collaborations in human factors engineering, the primary purpose of communication between engineers and doctors is to enhance medical devices. Physicians document user needs, and occasionally, they may propose their solutions. As engineers, we evaluate the feasibility of the doctors’ proposed solutions, or we propose solutions based on user feedback and subsequently assess their feasibility with the doctor,” explained the two engineers from the startups (CR1, 10).

“In this industry-academia-research-medicine collaboration, doctors working in hospitals and academics affiliated with universities and research institutes usually serve as the authors of research papers, while the company applies for the patents. Sometimes both partners become co- authors of the paper and co-holders of the patent,” explained a well-known team from Shanghai Jiaotong University (SE2).

Moreover, Shanghai’s institutions reflect how the combination of analytical and synthetic knowledge bases in the high-end medical device industry is treated (see Figure 2). On the one hand, Shanghai's inclusive innovative culture (informal institutions) plays a positive role in cross-domain R&D activities regarding software engineering, electronic engineering and human factor engineering (Action Plan for Promoting the High-Quality Development of Shanghai's Biomedical Industry) (CR1, 2, 7, 8, 13; OF 3). Against this context, inventors are encouraged to do it whereas CEOs invest heavily in these fields.

On the other hand, preferential policies, regulations and relevant rules (formal institutions) given by cluster organizations or parks have become key advantages for Small and Medium enterprises (SMEs), large firms and start-ups to explore how an analytical knowledge base is combined with a synthetic knowledge base (CR17). In other words, institutional proximity is key in the process of knowledge base combination.

For example, "The China (Shanghai) Pilot Free Trade Zone (CSPFTZ), to which many enterprises would like to move, gives key advantages concerning a reduction of import fees, financial subsidies of enterprise income tax, and value-added tax and individual tax adjustment, to medical device companies with CKB", an official staff explained (Meng & Zeng, 2019).

Fudan Fenglin Science Park is another park giving advantages to SMEs and start-ups (Wu, 2007). According to the CEO of a firm located in Fudan Fenglin Science Park said, "Our company produces advanced combinatorial knowledge, received specialized financial subsidies, 300,000 yuan, from the Shanghai government and Fudan Fenglin Science Park in 2020, for being successfully listed as a Shanghai high-tech enterprise in 2020. According to him, being based in Fudan Fenglin Science Park helped us to receive such a big financial subsidy” (CR7).

Last, social ties reflect innovation cooperation networks, where social embeddedness based on trust and friendship contributes to the combination of inter-knowledge base. Interviewees specializing in products’ R&D acknowledged that “finding reliable partners with similar cognitive levels through acquaintances can effectively reduce the risk of collaboration” (Sabbado et al., 2021) (CR1, 7 10, 14, 15, 16).

An expert from Fudan University added, “Most CEOs and managers grew up or studied in Shanghai. Their friends, alumnus or relatives working in hospitals or engaging in high-end medical device industries provided some related knowledge resources in joint R&D and production. It means that social proximity facilitates CKB in the Shanghai high-end medical device industry. It is worth noting that collaborators are often very familiar with one type of knowledge base, such as analytical or synthetic knowledge base. Through mutual discussions and communications, both of them progress together and CKB is developed and then patented” (SE3).

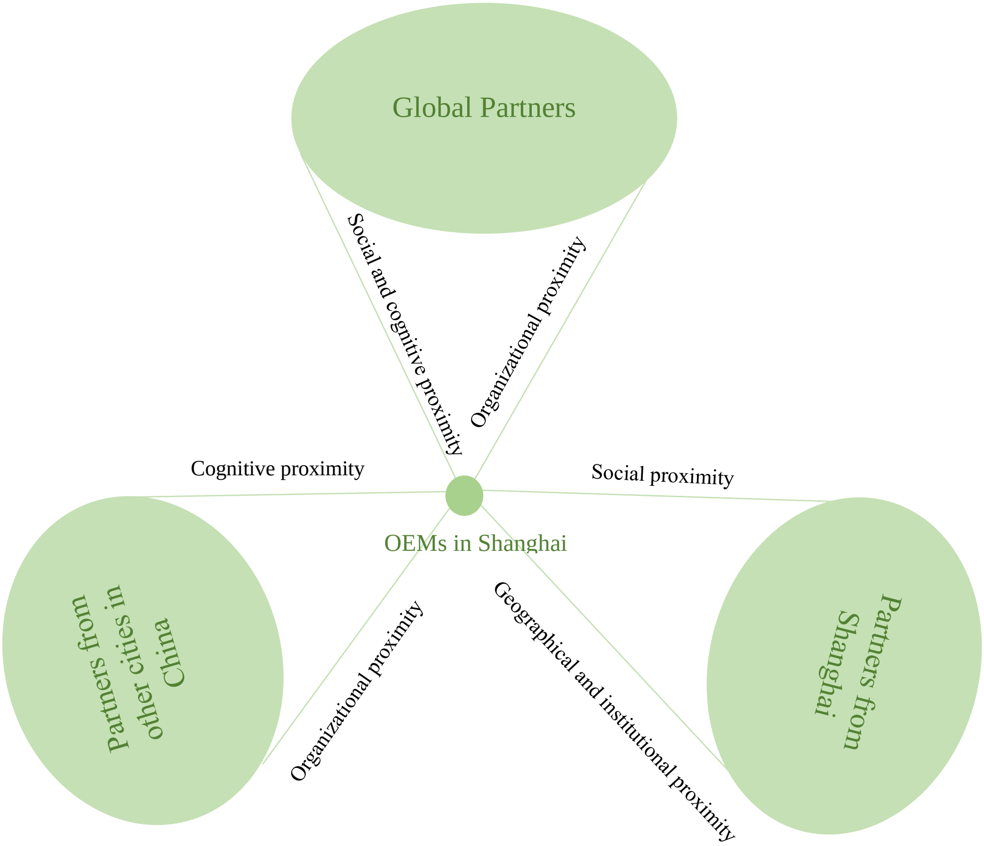

Figure 4.1 Proximity and CKBs characterized by combinations of analytical and synthetic knowledge

4.1.2 Shanghai-other cities analysis in China

In order to utilize R&D sources of other cities in China to resolve problems relevant to implantable medical devices and diagnostic equipment mainly based on the combination of analytical and synthetic knowledge, the Shanghai high-end medical device industry actively seeks collaborations with firms or organizations outside the Shanghai area in China (SE1, 2, 3).

In such a process, high organizational proximity is viewed as a significant driver. KB combination is always accompanied by high risks and uncertainties, which can be reduced if partners follow the same organizational arrangements (CR5, 16, 17; SE 3; OF2, OF4).

One R&D manager from Weichuang Co., Ltd. explained that "we have to choose intra-firm collaborations if those branches could meet their R&D requirements. Especially for large companies in Shanghai, it is a very common way to acquire some related medical device companies in other Chinese cities as their subsidiaries, thus promoting intra-company cooperation regarding CKB" (Shanghai high-end medical device industry report in 2019). He added, "For example, in 2012, Weichuang, a medical device company located in Zhangjiang High-Tech Park, Pudong, Shanghai, specializing in orthopedic and implantable medical devices acquired D-Pulse Medical (Beijing) Co., Ltd. with patents related to the stent" (Wang et al., 2021) (CR16).

Note that at this level, regular communication and sending people to the cooperation unit for longer periods are easier to observe. Concerning the allocation of R&D benefits, it also follows the three forms observed within Shanghai mentioned above.

In addition, cognitive proximity makes the combination of analytical and synthetic KB possible. Highly qualitative products with CKB are easier to create if actors have decreased cognitive distances because of the same industrial and knowledge background (CR5, 8, 9, 16, 17).

For example, the Shenzhen Lianying High-end Medical Equipment Innovation Institute, established in 2019, is a private, non-profit organization jointly sponsored by Shanghai Lianying Medical Technology Co., Ltd. and the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences. It contributes to Shanghai Lianying's R&D on software engineering and electronic engineering characterized by combinations of analytical and synthetic KBs (CR12).

"Although the geographical location of most collaborators predominantly refers to Shanghai, Beijing, Tianjin, Zhejiang Province, Jiangsu Province and Guangdong Province, geographical proximity varies, which means cognitive proximity is more important than geographical proximity at this level", an expert working in the medical device consultation department summarized based on her rich consultation experiences (SE1).

4.1.3 Shanghai-global cooperation

Although the Shanghai high-end medical device industry has recently developed quickly, medical device products from America, Germany, Japan, Switzerland and the Netherlands have been imported to Shanghai and China for a long time. In specific fields, Shanghai's industrial development has depended highly on international sources (Shanghai high-end medical device industry report in 2019).

Research staff specializing in R&D of high-end medical devices acknowledged that"Shanghai-international interactions primarily include optical engineering (optical engineering consists of a combination of analytical and synthetic KBs) and electronic engineering. Concerning optical engineering, collaborators mainly come from cities in Germany, Japan and Switzerland, which have advanced optical engineering knowledge in this aspect, while American collaborators are the biggest partners in R&D in electronic engineering, as they are renowned in this field" (Wang, 2008) (CR1, 5, 9, 12, 13, 16, 17).

In these international interactions, social proximity and cognitive proximity are often linked to each other and matter together in R&D projects regarding optical and electrical engineering. "The social relationships are primarily built via universities where we once studied, as well as previous institutes where we worked. The same education background and working environments lead to similar cognitive levels", CEOs of medical device companies explained. To some extent, cognitive proximity can be replaced by social proximity (CR4, 7, 13).

Earlier collaborations or peer recommendations play an important role in facilitating current interactive learning. If the behavior of both partners is in line with their mutual expectations during earlier collaborations, they usually continue to work together in the future.

Entrepreneurs with overseas studying backgrounds acknowledged that "Collaborating with alumni, laboratories and universities via regular communication and sending people to collaborating organizations where they once studied is a common interactive mode. Note that collaboration at the international level is fundamentally based on the communication between optical engineers, electronic engineers and mechanical engineers, referring to concrete technical resolve schemes, whereas the doctor-engineer collaborations are few".

In addition to cognitive and social proximity, the international level also plays a role in organizational proximity. For example, in 2013, Weichuang acquired Wright’s OrthoRecon business, which consists of hips and knee implant products, and set up Weichuang’s global orthopedics headquarters in Arlington, Tennessee, USA. Then it acquired the stent-related assets of Johnson & Johnson Cordis in 2014. The organizational integration aims at building technological relatedness between Shanghai headquarters and branches. Furthermore, “the dual-embeddedness cooperation mode also prevails, which means the subsidiaries actively collaborate with other companies or institutes in their geographic scope and hence get the patents relevant to CKB and then offer help for R&D activities in Shanghai headquarters”, one scholar specializing in International R&D activities. “This approach is breaking a ban on the export of cutting-edge technology from several countries (i.e., the USA) to China. Optical devices and electronics are the main objects of the export ban”, he added.

4.1.4 Discussion

For Shanghai, an advanced city in developing countries, OEMs in the high-end medical device industry are highly dependent on innovative sources within the city and international collaborators. At these two spatial scales, three aspects are compared.

> First, a comparison concerning the role of proximity in collaborations based on combinations of analytical and synthetic knowledge. The similarity is that both cognitive and social proximities contribute a lot to combinatorial knowledge interaction at these two spatial scales. The differences are also observed as geographical and institutional

proximity only has a positive impact on the R&D of this kind of CKB within Shanghai, whereas organizational proximity plays a role at the international level.

Secondly, comparing the knowledge interaction entities and allocation of benefits. In addition to working together every day, regular communication and sending people to the cooperation unit at these two spatial scales, establishing strategic partners is also a significant pattern of international cooperation of this kind of CKB.

Thirdly, comparing the identification of collaborators. The communication between engineers of different organizations takes place at these two spatial scales while the knowledge interaction between firms and hospitals is primarily maintained in Shanghai. Moreover, the correspondence between the engineers within Shanghai only refers to R&D of electronics, software and machinery, but joint R&D at the international level is predominantly about electronic and optical engineering.

Furthermore, some innovative advantages of other cities in China have been developed into affiliates of Shanghai headquarters. Because of this, organizational proximity at this level strongly affects combinatorial knowledge interaction in the Shanghai high-end medical device industry. Moreover, cognitive proximity matters, knowledge interaction patterns, and allocation of benefits are similar to those seen in Shanghai.

4.2 Electric vehicle industry

The market-for-technology strategy in the automobile sector was proposed in the 1980s in China. The strategy stipulated that any international automotive giant wishing to enter the Chinese market must establish a joint venture with a Chinese company. Joint ventures include Shanghai Volkswagen, Shanghai General Motors, Shanghai BMW, and Shanghai Audi. These joint ventures absorbed cutting-edge technologies from the R&D centers of international giants in the US and Europe, contributing to Shanghai’s traditional automobile development.

4.2.1 Shanghai electric vehicle development in a green era: Downstream facilitates upstream

4.2.1.1 Shanghai electric vehicle development: Green innovation (2001-2009)

Technology legitimacy

In the early 21st century, China embraced the electric vehicle era via a top-down approach (Konda, 2022). Intense administrative interventions and policy-oriented industrial features played a significant role in driving the industrial development of electric vehicles in China. By providing strong policy support for the production and sale of electric vehicles, the central government aimed to enhance recognition of the potential benefits of environmental protection, realize technological catch-up, and accelerate economic growth (SE1; OF2). Various policies and initiatives included tax incentives, subsidies, and investment in charging infrastructure.

Shanghai is one of the earliest pilot cities in China to develop electric vehicles. Shanghai followed the central government's call, implementing and refining national policies to promote regional electric vehicle development actively. From 2001 to 2013, Shanghai authorities also offered R&D subsidies for electric vehicle companies, establishing charging infrastructure and other organizations for electric vehicle R&D, inspection, and testing facilities, and encouraging universities such as Tongji University and Shanghai Jiaotong University to cultivate related graduates (SE1; OF1). In other words, Shanghai had no regional-specific assets in this period.

Shanghai's traditional automobile OEMs are primary lobbying targets by the Chinese and Shanghai governments, due to their state-owned enterprise status and role in the early development of electric vehicles (CR1-5). This unique status positioned them as strong supporters of the Chinese government's decisions and initiatives, making them pioneers in driving the implementation of China's electric vehicle strategy. As industry leaders, they have actively reshaped the industrial chain, promoting the environmental benefits led by using electric vehicles (CR2, 5). Additionally, Shanghai's automobile joint ventures, influenced by corporate headquarters and the Chinese policy environment, have begun developing technologies for electric vehicles and actively introducing advanced technologies from their headquarters (CR7-10). The strategic adjustment of these state-owned enterprises and joint companies has reshaped the upstream and midstream of the automobile industry chain as companies move towards green technologies.

Financial investment

During the transition towards environmentally sustainable mobility, most traditional automobile manufacturers continue to produce fuel-powered vehicles and fund the development of electric vehicles through profits generated by traditional automobiles (CR1-3, 5, 7, 9, 10). In addition to this, external financing options, such as bank loans and government initiatives aimed at promoting electric vehicle development and production, are available with lower interest rates. Despite the availability of diversified financing support, which includes targeted bank loans at the national, regional, and industrial levels, such assistance is only marginally helpful.

Knowledge creation

Shanghai's existing knowledge infrastructure has established new departments, courses, and branches dedicated to electric vehicle R&D. These institutions include the School of Automotive at Tongji University and the School of Electronic Information Technology at Shanghai Jiaotong University. These establishments have designed courses and research topics regarding electric vehicle chips (SE3), environmentally friendly materials, and mechanics. They are committed to conducting rigorous R&D and training talented individuals to meet the demand for expertise in these fields. The outcomes of smaller-scale experiments in electronics, mechanics, physics, and materials have shown considerable progress (SE1, 3).

The co-evolution of national and regional institutes played a significant role in promoting Shanghai electric vehicle industrial development. Leading institutes such as the Harbin Institute of Technology, Tianjin University, and the Tsinghua Suzhou Automotive Research

Institute—all located outside Shanghai—have been critical collaborators in the development of electric vehicle power systems (i.e., batteries, motors, and electric controls).

Harbin University and Tianjin University have been essential partners in Shanghai's traditional automobile development and have improved their innovation capabilities in hybrid motors and motor controller projects. Meanwhile, Tsinghua University's Suzhou Automotive Research Institute, which was established in 2011, is the first specialized institute for a specific industry under Tsinghua University and is a comprehensive electric vehicle industrial research institute. It has established six business platforms: Technological R&D, Testing, Fintech, Talent Training, Technology Transfer, and Business Incubation. These platforms enabled the institute to conduct cutting-edge research, develop high-quality talent, and promote the commercialization of electric vehicle technologies.

At the international level, new materials and electronic chip companies, as well as research institutes in the US, EU, and Japan, have played a critical role in fostering the development of electric vehicles in Shanghai (CR3, 5, 7-14). Collaborations between these entities, local companies, technology giants, and leading knowledge facilities have been prevalent.

4.2.1.2 Shanghai electric vehicle development: Market formation (2009-2013)

Influenced by national policies and rules, the Shanghai electric vehicle market can be categorized into three significant events. First, pilot demonstrations and electric vehicle promotion took place in 20 cities (e.g., Shanghai), focusing on public services. For example, during the 2010 Shanghai World Expo period, all public buses in the Expo Park were electric vehicles (OF1). Second, pilot subsidies for the private purchase of electric vehicles were introduced in seven cities (OF2). Third, in September 2013, four government ministries and commissions at the national level claimed that electric vehicle promotion and application were fully implemented for public services and personal use in 40 regions (e.g., Shanghai and Beijing).

The market formation of Shanghai's electric vehicles was highly dependent on key government initiatives, including pilot demonstrations, subsidies for private purchases, and corporate tax breaks. These efforts were implemented in different stages, with the first phase occurring between 2009 and 2012 and the second phase beginning in 2013 with the release of a national initiative. Despite Shanghai's positive response to the initiative, there was lack of significant results. In 2013, for example, only 515 vehicles were promoted.

4.2.1.3 Downstream pulls upstream: Semiconductor and new materials sectors

From 2001 to 2013, cultivating Chinese semiconductor and new materials companies was the main goal of the central government and Shanghai authorities via tax relief and R&D subsidies. During this period, companies mainly engaged in low-value innovation activities.

These two sectors are embedded in many industrial chains and related technological innovation systems, such as electric vehicles, medical devices, and aviation. Firms in these two sectors have diversified choices in specializing in which kind of business and industrial chains. The limited issued policies for knowledge creation and financial investment do not directly affect chips and energy-efficient and environmentally friendly materials in the electric vehicle industrial chain.

However, market signals mattered quickly in the semiconductor and new materials sectors in the upstream position of the electric vehicle industrial chain (see Figure 4.2). The interviewees said, “Rules, regulations, and policies regarding market formation made us more confident for self-R&D of electric vehicle batteries, motors, electric control and other vital components, and hence we are willing to dedicate more production lines to automotive chips and new materials” (CR4, 23).

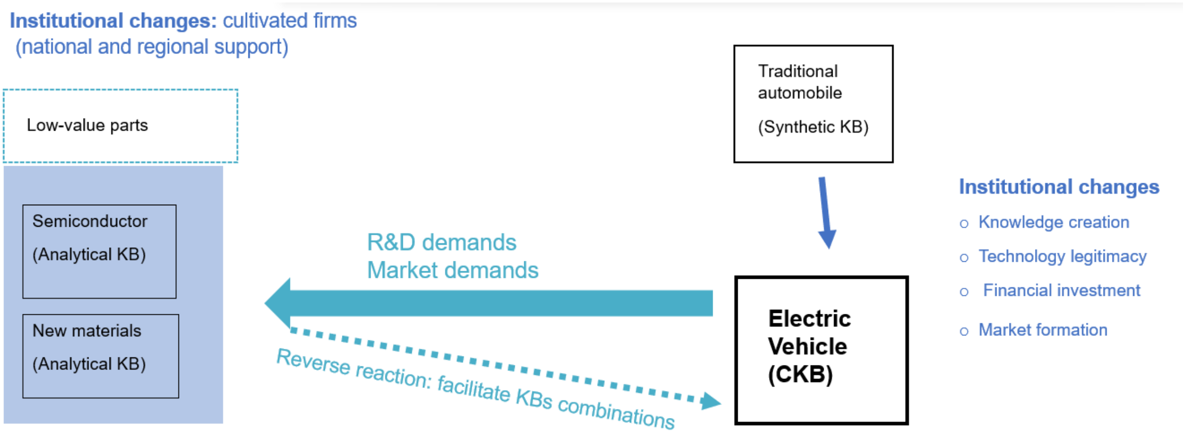

Figure 4.2 The sector in the downstream position pulls sectors in the upstream position into the green transition

4.2.2 Shanghai electric vehicle development in a green digital era

4.2.2.1 Upstream fosters downstream via technology push (2014-)

(1) Digital opportunities in Shanghai

A project of city informatization from 1999 to 2001 was introduced in Shanghai, which facilitated the development of internet technologies. Next to the informatization project, the “Digital City Shanghai” strategy was adopted in 2003 to establish the city’s information infrastructure and systems (OF4). In the next few years, the applications of digital innovation in city construction and other industries were visible. Because of this strategy, Shanghai’s Fintech, digital media, intelligent transportation, etc., developed sharply between 2003 and 2013. Note that digital innovation was mainly applied in service industries during this period (OF4).

Since 2013, mobile internet development has provided new opportunities for manufacturing industries in Shanghai. Thanks to improved knowledge infrastructures and preferential policies, the mobile internet sector in Shanghai has experienced rapid growth and has played a vital role in facilitating the application of AI and automation technologies in traditional manufacturing sectors.

This integration of analytical knowledge with manufacturing sectors represents a significant shift from the dominance of synthetic knowledge in the past. As a result of mature digital technologies, the digital legitimacy of electric vehicles has become possible, contributing to the region’s green growth (OF2; OE3). Figure 4.3 and Figure 4.4 illustrate the impact of these changes on market formation and the overall development of the Shanghai mobile internet sector.

CKBs regarding digitalization in Shanghai's electric vehicle field are mainly visible in charging piles, the three electrical components (TEC, including battery system, motor system and control system) system, automatic driving, and intelligent cockpits (Llopis-Albert et al., 2021). Specifically, the digitization of charging piles improves the safety of charging devices, while the digitization of the TEC system contributes to the digital management of batteries, etc. (CR5, 13, 15, 16, 17, 18, 20). These innovative projects make the core equipment or components of products more reliable and efficient. By contrast, the emergence of autonomous driving and intelligent cockpits is directed at meeting the needs of consumers and expand the electric vehicle market. For example, digital controls could help users to reduce driving fatigue. An intelligent cockpit is also a critical application scene of digitalization (CR 17). Experts and R&D staff said the current user demand for cockpit functions would gradually shift from essential to emotional needs (CR18; SE1, 2). Through digital scene optimization, the company accurately screens user needs for functional innovation points to create various personalized cockpit mobile spaces, achieving an immersive experience.

The digitalization of electric vehicles is primarily taking place in Shanghai and advanced regions in Europe or North America. For example, Tesla's sub-organization construction was completed in Shanghai in 2018, with production starting in December 2019. Schwabe (2020, p1117) investigated Shanghai Tesla, finding that "Tesla is generally willing (and implicitly expected) to engage and train local suppliers in order to enable them to meet the technical requirements of Tesla and, thus, gradually develop a local value chain not only for the battery, but also for other components specific to electric vehicles such as electric engine, battery management system, or battery temperature regulation" (the application of digitalization in electric vehicles) (CR 14). Moreover, Azera has established an innovation center in Berlin to develop intelligent cockpits, autonomous driving, and energy technologies. Azera Energy Europe's plant in Pest, Hungary, is the European manufacturing center, service center, and R&D center for Azera Plus products. It has completed the rollout of its first exchange plant. The Berlin Innovation Centre will work with the Azera Energy Europe factory and the Azera Oxford and Munich R&D and design teams on all aspects of research and development.

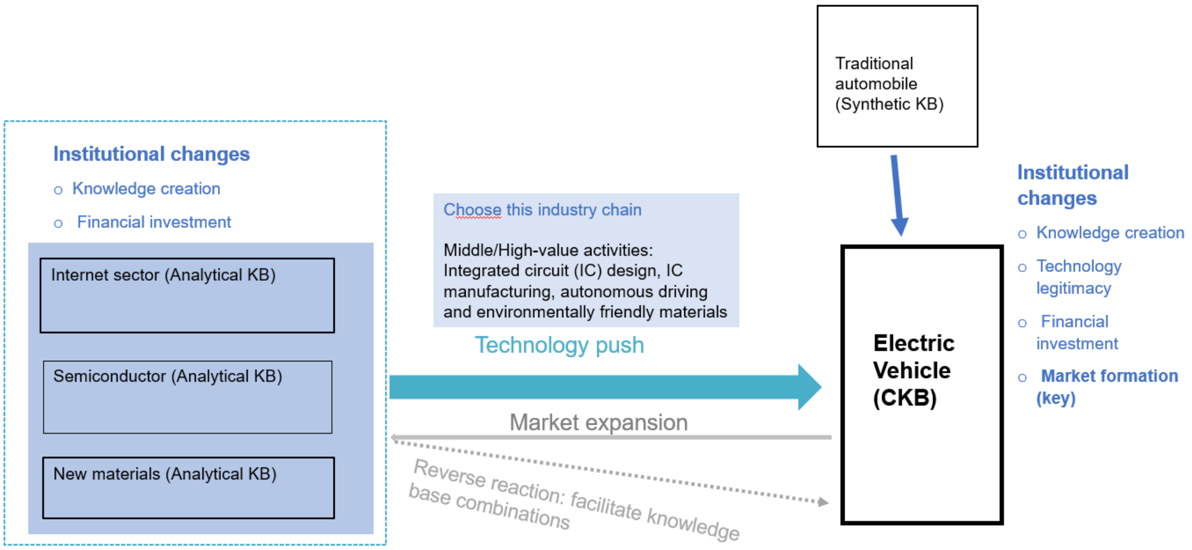

Figure 4.3 Interactions between sectors in the downstream and upstream positions in the green digital transition

(2) Semiconductors and new materials

Since 2014, China's central government has placed the development of semiconductors and new materials at the national strategic level, providing strong policy support to companies specializing in integrated circuit (IC) design, IC manufacturing, and new materials that focus on advanced manufacturing-related components (OF1, 3; SE1). The government has identified key research directions for these technologies in sectors such as electric vehicles, as evidenced by the documents published by the central government (see Figure 4.4). In response to this national call, the Shanghai Municipal Government has issued over 20 critical documents encouraging R&D and process innovation in semiconductors and new materials. Formal institutions at national and regional levels include extending preferential tax policies for these companies, establishing laboratories for semiconductors and new materials, and opening up green channels for bank loans (OF3; SE1). These formal institutions enhance Shanghai's innovation capacity and regional competitiveness in semiconductors and new materials and support innovative activities closely related to developing core components for electric vehicles in Shanghai, thereby accelerating the application of these two sectors in the electric vehicle industry (Stephan et al., 2019).

Specifically, on the one hand, electronic automotive chips can be categorized into application processors (such as in-vehicle infotainment and microcontroller units), power semiconductors (such as the Automotive Megatrends Platform and insulated gate bipolar transistors), sensor chips (such as tire pressure monitoring systems), and separation devices based on their application areas (CR25). These R&D activities are commonly conducted at prestigious academic institutions, including Tongji University and the School of Electronic Information at Shanghai Jiao Tong University, as well as at specialized chip research centers such as the Shanghai Smart Chip R&D Centre and chip companies located in technology parks such as Zhangjiang Software Industry Park and Xuhui Caohejing Technology Park (CR27; SE2).

Since 2016, the Shanghai electric vehicle industry has significantly focused on research fields and related policies to stimulate innovation and development within the automotive chip sector. To this end, the "Automotive Semiconductor Supply and Demand Matching Manual", "Intelligent Vehicle Innovation Development Strategy", and "Medium- and Long-term

Development Plan for the Automotive Industry" have been established, providing explicit and comprehensive market prospects for the automotive chip industry, as well as a favorable production and operational milieus for enterprises (CR26, 28; SE3). This supportive environment has facilitated the creation of knowledge and financial investments in semiconductor technology, as evidenced in Table 4.2.

On the other hand, there has been a growing trend of utilizing novel materials in electric vehicles, predominantly in three distinct fashions. Firstly, polymer composites, exemplified by aluminum alloys and carbon brazing, yield considerable benefits, such as augmented vehicle durability, lightweight designs, and increased safety. Secondly, procuring rare earth elements is pivotal for producing new energy vehicle drive motors, which mitigates the carbon footprint of automobiles. Thirdly, exploring new materials in new energy vehicles has become crucial for research institutions such as Shanghai University of Technology, Shanghai Tongji University, and Shanghai Jiaotong University.

Against this background, related technological breakthroughs in China's and Shanghai's electric vehicles are visible. For example, materials, electronic chips, electric drives, and charging advancements have significantly reduced prices in Shanghai and China. Specifically, three major components of pure electric vehicles—batteries, motors, and electronic controls—comprise about 50% of their cost. The cost of batteries, which accounts for around 40% of the total cost, has decreased in recent years. Additionally, the technical maturity of electric motors and electronic controls has increased, leading to a decrease in prices from 15% to 7% of the total cost. The cost of a complete set of electric motors and electronic controls for pure electric passenger cars is now around 10,000 yuan. Prices of power batteries have also fallen by 20% (China Electrical Vehicle Industry Report). Such significant achievements partly result from regional and national support for the establishment of knowledge infrastructure and cross-regional innovation collaboration. For example, Shanghai's public R&D service platform, collaborations between Jiaotong University and Ningde Times, and international key component giants such as BOSCH have contributed to territorial technological catch-up (CR18).

Table 4.1 Upstream of the electric vehicle industrial chain

Sectors in the upstream position of the EV industrial chain	Institutional changes	Performance
Shanghai internet sector (analytical knowledge base)	Knowledge creation	More than 30 Universities and Research Institutes in Shanghai specialize in computer science; these institutes collaborate with other organizations in other cities within or outside China.
	Market formation	The preferential tax rate of 15% applies to high-tech enterprises, and software enterprises can enjoy the preferential policy of "two exemptions and three reductions of 50%" and the preferential tax rate of 10% directly for key software enterprises.
Shanghai semiconductor (analytical knowledge base)	Knowledge creation	Key institutes: School of Microelectronics at Shanghai Jiao Tong University, School of Microelectronics at Fudan University, School of Electronics and Information Engineering at Tongji University, Shanghai Institute of Microsystems and Information Technology at Institute of Microtechnology Industry at Chinese Academy of Sciences, College of Information Science and Technology at East China Normal University, Shanghai Institute of Advanced Studies at Chinese Academy of Sciences.
	Market formation	Tax credit for large companies, from 8% to 15%, while the tax credit benefit for SMEs will increase from 16% to 25%; two-stage special investment funds. The fund in the first phase was primarily invested in the midstream of the semiconductor sector, including manufacturing, design, packaging, and testing of leading enterprises. In contrast, in the second phase, the leading investment objectives are upstream and downstream, especially the leading companies specializing in high-precision equipment production, essential materials to improve chips' performance, and other weak points.
Shanghai new materials (analytical knowledge base)	Knowledge creation	More than eight universities and research institutes (i.e., the School of Materials at Shanghai University)
	Market formation	Subsidies for enterprise projects: technology-based small and medium-sized enterprises, high-tech enterprises, specialization, first loan subsidies, technology centers, research and development centers Enterprise business transformation: technological transformation, large equipment purchase and sale, first equipment purchase, intelligent and innovative manufacturing, integration of two, patent industrialization, subsidies for various support policies after the epidemic, etc. Investment and development: innovation platform construction, e-commerce platform, science and technology innovation platform, cultural tourism construction.

Sources: rules, regulations, and policies from China and Shanghai authorities

Table 4.2 Electric vehicle developmental trend

Electric vehicle development trend (analytical, synthetic, and symbolic knowledge bases)	Autonomous
	Connected
	Shared
	Electric driving

Sources: Accenture Strategy, 2020

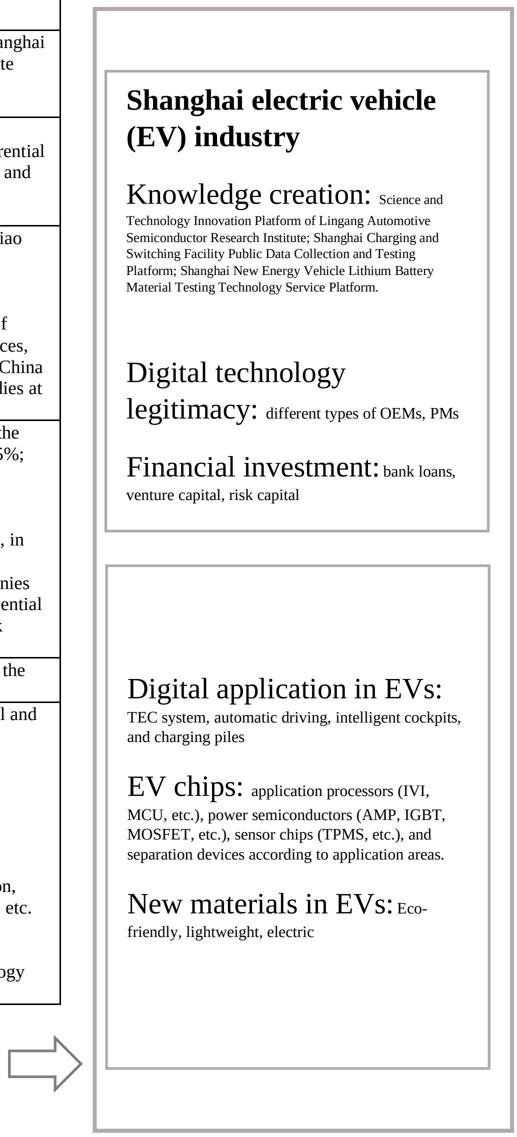

Figure 4.4 Combinatorial knowledge dynamics in the electric vehicle industry

(3) Mobilizing multiple sources for the digitalization of electric vehicles

Technology legitimacy

The digital legitimacy of electric vehicles in China also refers to a top-down process. Despite more mature technologies in China's electric vehicles and the formal rollout phase of electric vehicles since 2014, the development of the electric vehicle industry in Shanghai still needs to improve at expanding the market. Inspired by Tesla's software-defined cars, the China Development and Reform Commission and the Chinese Ministry of Industrial Information commissioned public institutes such as the China Development and Reform Institute to report the future industrial development trends of electric vehicles, considering consumer needs, the technological advancements of international leaders, and current industry developments in China, particularly with regard to the feasibility and necessity of digitalization in China's electric vehicle industry. After careful investigation and consideration, the national government issued its first policy in 2014 to expand the electric vehicle market by accelerating the digitalization of electric vehicles. Shanghai has positively followed this policy and implemented it through various formal and informal forums and initiatives. The Shanghai High Tech Cluster and the Automotive Industry Park emphasized that companies involved in digitalizing electric vehicles will receive generous benefits and preferential treatment regarding rent and the admission process (OF1).

Traditional automobile manufacturers have quickly accepted the lobby for digitalizing electric vehicles. In their view, the digitalization of electric vehicles has two advantages. On the one hand, the digital management of the TEC system will make electric vehicles safer, a general trend in green innovation (OF1; SE1). On the other hand, Chinese users pay much attention to intelligent cabin seating and artificial driving (CR20). Functional upgrading and added value enhance the domestic market competitiveness of electric vehicles. Therefore, they are actively recruiting digital talent or cooperating with internet companies.

In this context, Chinese internet entrepreneurs are known for their willingness to establish new companies across various industries for R&D, particularly in major cities like Shanghai, Beijing, Hangzhou, Shenzhen, and Guangzhou (SE2). When the national policy for the digitalization of electric vehicles was introduced, internet firms such as Baidu, Tencent, and Huawei actively participated in the electric vehicle sector, with innovative projects focusing on autonomous driving, the digital management of electric vehicles, and exploring new business opportunities (CR15, 16, 19). They believe that digital innovation is crucial for electric vehicles to remain competitive in the coming years and see this as an opportunity to enter the industry. As a result, these internet entrepreneurs quickly accepted digital licenses for electric vehicles without a significant lobbying process.

Some internet-born entrepreneurs in China have taken the opportunity to start new companies specifically focused on the digital production of components for electric vehicles or as OEMs for electric vehicles. Examples of these companies include Azera Motors, founded in Shanghai in 2014 with its headquarters and R&D department, and Qidian, founded in Shanghai in 2016 (CR 14). Moreover, Xiaopeng was founded in Guangzhou in 2015, with its R&D facility in Shanghai. There are reportedly several other companies of this type, with a significant number of them having their headquarters or R&D facilities based in Shanghai (CR 13). Some internet entrepreneurs emphasized that the massive potential of the future electric vehicle market and the application of digitalization in the electric vehicle sector are the main reasons for their entry into this industry—and not government subsidies, which have decreased gradually since 2014.

Financial investment

Venture capital and angel investment are the primary financing forms for emerging companies in the electric vehicle sector. Venture firms are mainly from Shanghai, Beijing, and overseas institutions. Investment firms include internet giants (e.g., Tencent, Baidu, and Alibaba) and venture capitalists (e.g., Redshirt Capital, Warburg Pincus, and High Tide Capital). In the last two years, local governments such as in Hefei and state-controlled enterprises have also started investing in these new powerhouses.

These companies often establish partnerships with OEMs with traditional automobile production experiences to reduce risk and uncertainty and gain investor trust. Such a strategy gives new firms with robust internet technologies more time and energy to work on a digital electric vehicle ecosystem, a capability that traditional automobile manufacturers lack (CR14, 16, 17). To investors, companies with cutting-edge digital technologies are particularly well suited to navigate the digitalization of products. Furthermore, financing abilities and social connections are central in Chinese business. On the one hand, several electric vehicle OEMs with internet backgrounds possess the stronger financing abilities than traditional OEMs. For example, the speed at which these companies can go from business plan to roadshow, or from CEO presentation and business plan showcase to contacting investors, is notably faster than traditional manufacturing companies (CR 14). On the other hand, they could discover new partners and potential investors by participating in international or Chinese electric vehicle exhibitions and other business events, such as the electric vehicle forum organized by the Jiading government (SE3). Supposing that they have strong social networks in these industry-specific events organized by various institutions, they may find it easier to find investors because social ties often play a significant role.

4.2.2.2 Downstream fosters upstream via market expansion (2014-)

(1) Electric vehicle market expansion in institutional changes

Since 2014, national, regional, and local governments' subsidies for electric vehicles have been withdrawn. Still, the free license plate policy of Shanghai's electric vehicles has become a critical incentive for the industry, particularly for combining digital technologies and existing knowledge in electric vehicles (i.e., charging piles, the TEC, automatic driving, and intelligent cockpits). The Shanghai government classified Shanghai license plates into different types to relieve traffic congestion. Only the "license A" cars can travel throughout Shanghai at any time, whereas other license plates are limited to certain areas and times. The office staff explained that getting a "license A" is tough, and a report claimed that the probability of getting a Shanghai A license is very low (OF2). However, after 2014, anyone could get a license similar to "license A" by buying an electric vehicle and having never owned other cars. Due to this particular policy, the market of electric vehicles has been expanding since 2014. All CEOs and investors said that such a policy means a good market formation, giving them enough confidence to participate in the digital innovation of electric vehicles because Shanghai is the central consumption place of China's electric vehicles. In other words, this policy is favorable for their product sales and operations.

Although the state has introduced the Science and Technology Board Listing to encourage firms to increase the proportion of R&D, this policy only matters to some companies because the R&D requirements need to be lowered for Chinese firms (OF3). The policy claimed that companies must meet two R&D requirements to successfully apply for the Star Market, namely that they must have spent more than 5% of their operating revenue on R&D in the past three years or more than 60 million yuan on R&D in the past three years, and that the ratio of R&D staff to the total number of employees in the year be no less than 10%.

(2) Business expansion

These rules and policies regarding market expansion mean a promising market in the future. In the PMs' view, the improvement of the automobile industrial environment in recent years, highly technological barriers regarding chips and new materials, and potential markets make them more confident to stick to the original position (CR 22, 23, 27, 28). They said, "In 2021, average electric vehicles in China required more than 1,000 chips—twice as many as traditional automobiles 20 years ago! The number of chips for every electric vehicle will increase in the future." and "Demand for new materials also continues to rise!" Therefore, business expansion and growth in the number of companies are visible (Kumar & Alok, 2020) (CR 21).

4.3 A comparative study of Shanghai’s emerging industries

In this section, I present medical device and automobile industries and subsequently draw comparisons between them across three dimensions: institutional evolution, entrepreneurial dynamic capabilities, and governance complexity.

4.3.1 Medical Device Case

4.3.1.1 Institutional Evolution

The territorial institutional changes and international technology embargoes have accelerated complex knowledge production in Shanghai's medical device sector and related industries. Such changes have been achieved by applying optical knowledge, chip knowledge, and digital technology (OF1). The territorial institutional changes (i.e., China's Advanced Manufacturing 2025 strategy) aim to replace imported medical devices with high-end domestic products (Li, 2018). The international technology embargoes entail bans on the sale of photolithography and Electronic Design Automation (EDA) to mainland China, as stipulated in the chip bill prohibiting the sale of high-quality chips to China by the United States (OF4).

The success or failure of complex knowledge production is affected by the development of digital, semiconductor, and optical institutes. On the one hand, a critical way in which institutes evolve is through the creation of new courses, professions, and colleges (SE2, 3). In the case of the chip industry, thirty years ago, there was a chip manufacturing major in the

School of Electronic Information at Fudan University in Shanghai. However, the chip major initially received less attention. In recent years, however, to achieve “Advanced Manufacturing 2025” and break the foreign technological embargo, the semiconductor sector has received unprecedented attention. Shanghai Jiaotong University and Fudan University have reintroduced chip design-related courses, such as the new-type semiconductor course at Fudan University (SE2; CR24).

Moreover, curricula on digitizing medical information, artificial intelligence, and photovoltaic technology have been established, reflecting an interdisciplinary approach (CR 20-23). The School of Physics and the School of Computer Science, among others, have also joined the relevant curricula adopted by more than eight universities and research institutes in Shanghai, including Shanghai College of Health Sciences, Shanghai Jiao Tong University, Medical Device Research Institute at Fudan University, Tongji University, Shanghai University of Traditional Chinese Medicine, and the Chinese People’s Liberation Army Navy Military Medical University. According to an expert (SE1), “Masters and Ph.D. students are the main cross-domain talents and key players in research projects.”

On the other hand, despite digital science, chips, and optics belonging to analytical knowledge, constant experimentation is still required in the application process (Liefner & Hennemann, 2011; Zhang et al., 2021). Therefore, the establishment of affiliates, such as university laboratories, technology translators, incubation centers, and cross-discipline labs, is crucial. However, few public affiliates in Shanghai specialize in optics research for medical devices, and most related affiliates are still under construction (SE1; CR29, 31). As a result, the application of basic knowledge to the medical device sector has not been successful. Two developers specializing in optical design pointed out that “the optical devices we produce do not meet the standards of medical devices, which results from the lack of affiliates” (CR1, 5).

Furthermore, the evolution of institutes regarding digitalization has been successful due to the strong internet industry. In contrast, chip institutes have received heavy investment since 2018, and Shanghai now aims to achieve stable production of 3nm chips, which is a high level in China (SE3; OF4).

To conclude, Shanghai's internet and semiconductor sectors have contributed to the digitization, intelligence, and safety of medical devices in Shanghai (Figure 2), which has been facilitated by successful curriculum alignment and the establishment of affiliations. However, due to interrupted scientific research and the foreign technology embargo, the semiconductor sector has provided limited support for producing high-precision chips for medical devices. Moreover, although optical knowledge has received significant attention in Shanghai's basic research, the number of university affiliations has been limited. These affiliates have not focused on applying optical knowledge in medical devices, leading to failed evolution of universities and research institutions.

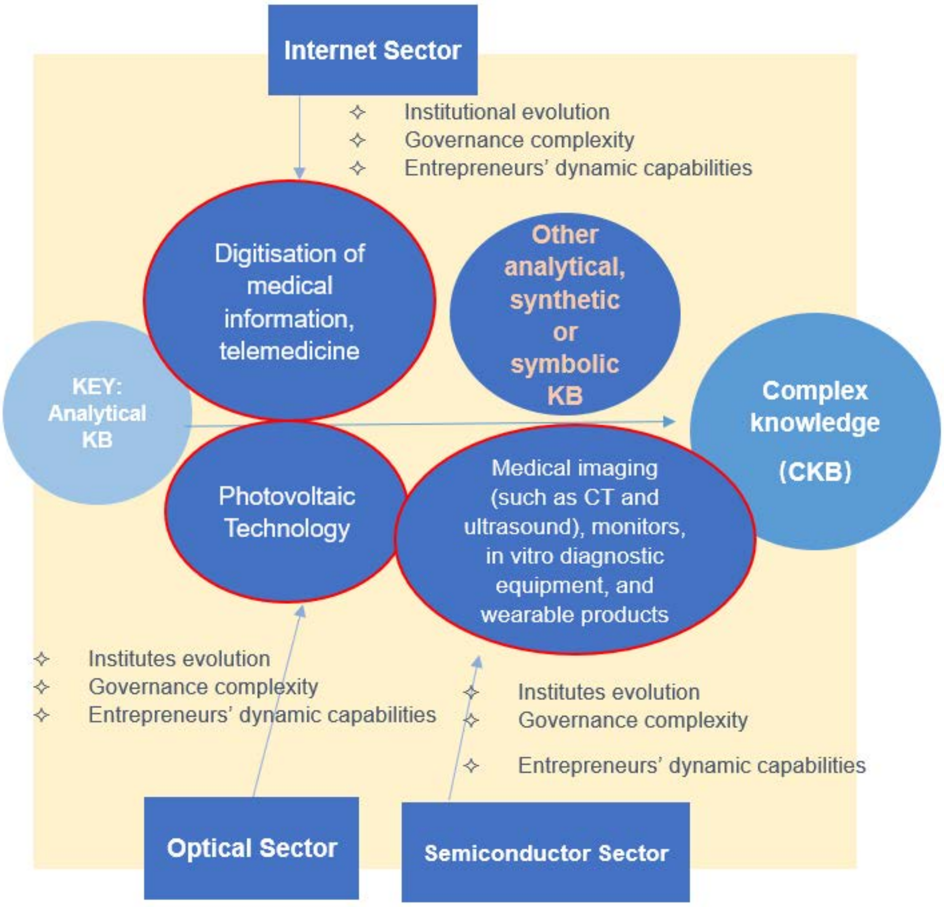

Figure 4.5. The key knowledge evolutionary process (knowledge base combination) in the medical device industry

4.3.1.2 Entrepreneurs' dynamic capabilities

Differences in entrepreneurs' dynamic capabilities in different sectors have been observed. Entrepreneurs from the medical device sector are able to perceive potential opportunities arising from macro-scale institutional changes (such as the National Innovative Call) and micro-scale policy support (CR1-17). They engage in complex innovation activities related to high-end medical devices. Large-sized firms, such as Weichuang and Lianying, have been committed to becoming major players in the production of complex medical device knowledge in Shanghai and even in China since 2005. To achieve this goal, they have acquired and merged with many overseas companies and actively opened overseas R&D institutes according to the strategic needs of firms (CR12, 16). These entrepreneurs are the main contributors to the rapid development of medical devices in Shanghai and China.

Returnees are likely to live and work in Shanghai because of the city’s rich innovation resources, diversified venture firms, and a high degree of internationalization (CR 1, 4, 5, 9, 13, 17). In particular, returnees from European and American universities or institutes with high levels of education and international medical relations start their businesses in Shanghai, setting up small and medium-sized companies and engaging in cutting-edge R&D activities related to medical devices. Despite being start-ups, these entrepreneurs have made significant achievements in the medical device industry due to their high levels of expertise and rich international innovation resources. Tiefeng Hu is a typical case. He graduated from China Medical University as an undergraduate and then pursued his master’s degree at Yale University in 1987. After graduating from Yale University School of Medicine and the New Jersey Cancer Center, he entered the medical technology business in 1996. He led technical R&D, management, and the commercialization of new products, respectively, at Guidant and Johnson & Johnson (Cordis) in Silicon Valley (CR4). In 2005, he returned to China to start his own business. Core partners of his team are world-renowned experts in the industry such as Dr. Randy James Lee, Professor of Cardiology at the University of California, San Francisco (UCSF) and Dr. Farrell Mendelsohn, Director of the Cardiovascular Regeneration Research Center at Birmingham Medical Center, as well as international medical technology entrepreneurs such as Dr. Brad Hubbard, a preclinical research expert who is one of the creators of animal experimental models for cardiovascular interventional product development, and Dr. Eveleen Tang, an expert in polymer research.

Entrepreneurs from the internet sector are also very active. They probably entered the medical device market in 2016 because of the replacement strategy initiated by the state. They primarily focused on the domestic consumption market and user demands. Their greatest strength in complex R&D activities regarding original equipment manufacturing is their ability to attract venture capital and the digital advantage of medical devices. As said by CEOs specializing in digitalizing electric vehicles (CR18-19), “venture capital and angel investments are the two main channels that help us achieve our car dreams.” They added, “because of prior working experience, we know how to make a persuasive pitch that impresses investors and shows our company's value and capacity.”

Entrepreneurs in the optics and semiconductor sectors aim to become component manufacturers of medical devices (CR24-31). Due to the failure of institutional evolution, embargoes of related technologies, and very high technology accumulation requirements, entrepreneurs specializing in optics and high-precision chips actively collaborate with overseas universities and foreign firms. Collaborations across sectors and the slow innovative speed cannot keep up with the companies’ production needs, which is one of the biggest challenges for these entrepreneurs.

Overall, unlike entrepreneurs from other sectors who typically focus on the production of parts and components related to digitalization, internet entrepreneurs are actively engaged in the R&D of OEMs while also responding to the government’s call for domestic products to replace international medical devices. The technical and financial advantages of internet entrepreneurs constitute their core capabilities and are essential to the success of incoming OEMs. By contrast, entrepreneurs from the optics and semiconductor sectors act primarily as component suppliers and as a transition into foundries in cases where the technology is not yet mature. Despite facing challenges in collaboration and mass production, these entrepreneurs continue to collaborate with overseas universities and foreign firms to stay competitive in the market. The introduction of the Marketing Authorization Holder policy has provided some relief to the issue of mass production.

4.3.1.3 Governance complexity

Coordinating multiple departments

In the top-down policy implementation process (Feng et al., 2021), the national-level public departments include the China Food and Drug Administration, China Development and Reform Commission, China Medical Devices Department, China Industry Department, China Ministry of Science and Technology, which often collaborate across sectors in several ways. Shanghai-level public organizations are primarily involved in the Shanghai Development and Reform Commission, the Shanghai Science and Technology Commission, and the Shanghai Drug Administration (OF1). These departments and commissions are interwoven, constructing complex governance networks, in which often the regional entities follow the national ones.

National policies are often mentioned by several departments in Shanghai. For example, one significant national policy, titled Marketing Authorization Holder (MAH), is key to China's medical device institutional changes. The role of MAH is to unbound product registration and production license (Xu et al., 2019), which positively affected the high-end medical device industry in Shanghai. Firms that cannot research highly complex knowledge benefit from this policy, as they can focus on mass production through collaboration with firms with related patents (OF3).

Broadening and deepening of the innovation policy

The Chinese 13th Five-Year Plan (2016-2020) and the Shanghai 13th Five-Year Plan (2016-2020) provided cross-sectoral policies supporting large-size (e.g. 12") silicon single crystal polished wafers and Cloud Computing regarding high-end medical devices. The 14th Five-Year Plan (2021-2025) in Shanghai and China have also emphasized crucial technological breakthroughs with high value for advanced CKBs in the regional industrial competitiveness, such as insulated gate bipolar transistors (IGBTs), high-end micro control units (MCUs), chemical mechanical polishing materials, and encapsulation materials (OF2-3; SE3).

These macro industrial policies offer guidelines for regional industrial R&D subsidies, tax relief, and incentives for innovative companies. In addition to the general policies, which are enjoyed by firms in these four sectors, nearly all specific policies at the Shanghai, district and industrial park levels prioritize firms specializing in the cutting-edge fields (CR1-17).

To support the advanced CKBs, a range of rules and regulations are introduced. First, some strengthen the role of angel investment and venture capital guiding funds, and optimize the operation mode of the funds (OF1). Secondly, the Star Market initiative goes deeper into the implementation of the Pujiang Light Initiative, aiming at improving the construction of a reserve pool of companies listed on the Science and Technology Venture Board, and promoting more enterprises in strategic emerging industries to be listed on the Board (OF4). Thirdly, some policies continue to promote preferential interest rate long-term credit policies to further reduce financing costs for enterprises in strategic emerging industries (OF1). Fourthly, some policies focus on further promoting the establishment of technology sub-branches by financial institutions and on exploring the establishment of professional technology insurance companies (SE2, 4).

On the one hand, the increased scope of regulation by existing governing authorities has accelerated the speed of the combinations of analytical and synthetic knowledge bases in the high-end medical device industry. For example, in the past, only registers of medical devices had the quality to produce the products (CR6, 9). In other words, Innovative outputs were not translated into benefits promptly and directly invested in new innovative projects from the benefits obtained from other innovative activities (CR14, 17). Instead, organizations had to get benefits via market sales, which increased organizations' innovative burdens and became a hindrance to knowledge base combinations. Policy broadening and deepening in medical device R&D and production, particularly the introduction of MAH, prioritize the organizations' R&D benefits, facilitating knowledge base combinations in the high-end medical device industry.

On the other hand, the increased scope of regulation and the coordination of multiple public departments have hindered the transition toward CKBs. For example, the coordination of several public departments has led to the low application speed of CKBs, which indirectly influences optical and new material knowledge flow (OF5). Medical devices with CKBs primarily involve Class II and Class III medical devices. Reviewing Class II medical devices, characterized by relatively safety and effectiveness, generally takes 60 working days, and registering this kind of medical device takes nearly one year (Excludes clinical trial time). Reviewing Class III medical devices, which are potentially dangerous to the human body, generally takes 90 working days and registering this kind of medical device takes nearly two years and a half (Excludes clinical trial time) (Kramer et al., 2012).

4.3.2 Automobile Case

4.3.2.1 Institutional Evolution

Global climate change, the energy crisis and the globalization strategy of Chinese automobiles have accelerated unrelated knowledge (base) combinations in the Shanghai electric vehicle industry. In the last decade, an evolutionary trajectory towards analytical knowledge (i.e., digital knowledge, semiconductor, and optics) has prevailed in the Shanghai automotive sector, which can be reflected in regional institutional evolution.

In Shanghai, about 12 universities and research institutes participate in the digitalization projects of automobiles, primarily including intelligent cabins, the digitalization of charging piles, and the digitalization of the TEC systems to improve the efficiency and safety of automobiles (Lee, 2020; Lee & He, 2021) (SE 2; CR 10, 12, 16, 17).

Moreover, the Shanghai Public Digital R&D Platform promotes Industry-Academia-Research collaboration. The Shanghai public R&D service platform for SMEs, which was established in 2004 to reduce R&D costs, where literature search, science infrastructures, technical services and inspection, as well as testing, are provided for SMEs (small- and middle-sized enterprises) of EVs, biomedicine, and electronic information. After 2014, digital sources in the EV sector have been included in this platform's technical services, contributing to green digital development in Shanghai. For example, a CEO of a middle-sized firm explained that his company once encountered an R&D problem with Assisted & Automated Driving in 2016. He has two choices to resolve it through this platform (CR6). One is through free literature search offered by this platform and another is to seek the platform's R&D help. Finally, he chose the R&D help, spending less money than what he should pay because the platform shared a coupon for these middle-sized firms.

Automobile chips accompany the evolution of six universities and research institutes, including the School of Microelectronics at Shanghai Jiao Tong University, the School of Microelectronics at Fudan University, the School of Electronics and Information Engineering at Tongji University, Shanghai Institute of Microsystems and Information Technology at the Institute of Microtechnology Industry at Chinese Academy of Sciences, College of Information Science and Technology at East China Normal University, and the Shanghai Institute of Advanced Studies at Chinese Academy of Sciences (Wu, 2007; VerWey, 2019). Although R&D and production activities towards automobile chips in Shanghai benefit from its strong electronic information industrial base, the lack of core chips is a serious problem in Shanghai and worldwide because of geopolitical tensions (CR25, 27, 28).

Material science is widely applied in energy-saving parts, rare metals, or chips to improve the performance of chips. Until now, more than 20 universities and research institutes (i.e., the School of Materials at Shanghai University) carry out material R&D. Overall, applying digitalization, new materials, and chips in Shanghai automobiles is relatively successful because of the strong internet, electronic, and material industrial bases and the related smooth evolution of the public institutes, which contributes to the innovation system reconfiguration (see Figure 4.6).

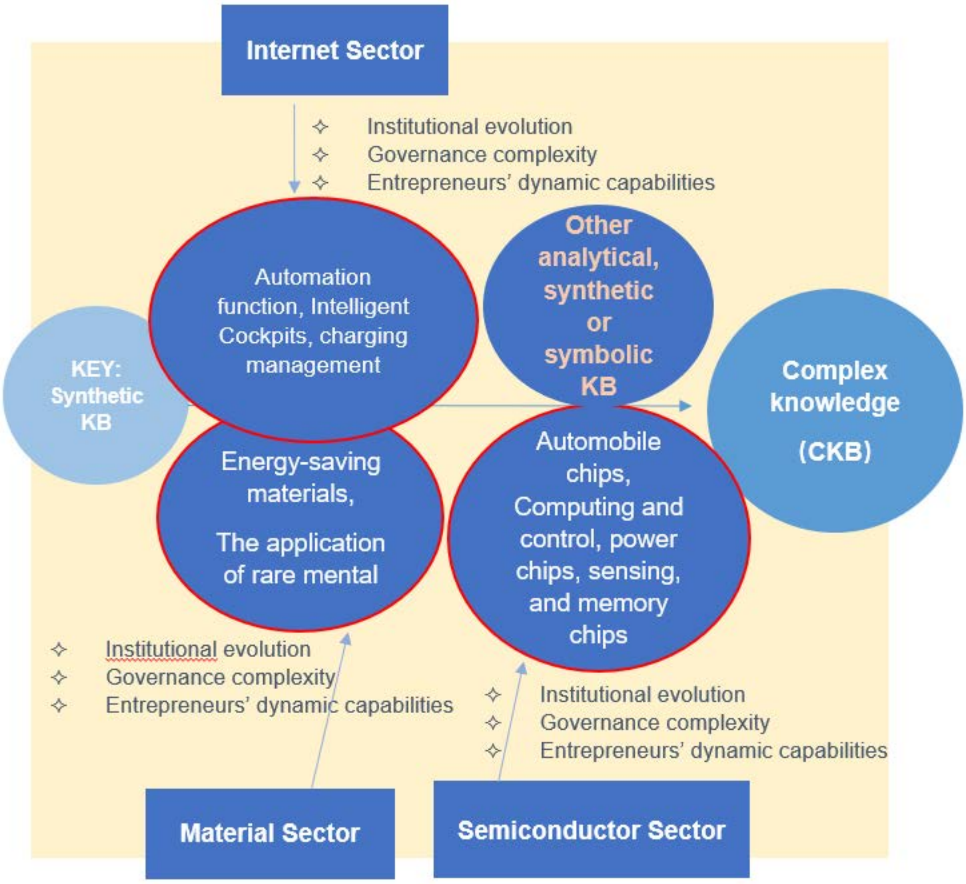

Figure 4.6 The key knowledge evolutionary process (knowledge base combination) in the automobile industry

4.3.2.2 Entrepreneurs' dynamic capabilities

There are important differences in the dynamic capabilities of entrepreneurs in different sectors. Since the 21st century, entrepreneurs from the automobile sector have perceived the huge market potential of electric vehicles in the next few decades in terms of international, national, and regional institutional changes. They first shift to R&D activities associated with the TEC system and other key parts. Chips and new materials are given much attention by OEMs and PMs of automobiles (CR24; SE3). Related R&D collaborations are therefore subject to considerable investment. In 2014, the state introduced a policy called the digital legitimacy of automobiles, which led to the application of digital knowledge in automobiles. Before 2013, Shanghai automakers specializing in original equipment manufacturing consisted mainly of Sino–foreign joint ventures and state-owned enterprises.

Entrepreneurs from the internet sector have also positively responded to the digitalization of automobiles and established more than nine new firms (private firms) in Shanghai between 2014 and 2015 (SE2). The purpose of these entrepreneurs is not only to participate in digital projects but also to produce automobiles. The CEOs explained that the "maturation of clean technologies means low risks and uncertainties in this aspect (CR12-13). We mean, we can directly enter the new competitive race, our biggest advantage, that is, digital technologies." They added, "In addition, the plate license policy regarding electric vehicles helps us to see a quickly expanding market in the next years because the license A is so hard to obtain in Shanghai. Many people have applied for several years but still do not have one. We believe these people may switch their focus to electric vehicle plate licenses by buying an electric vehicle."

However, “several OEMs with strong internet technologies went bankrupt after 2017 because of reduced or shifting subsidies” (from prepayment to post-sale re-payment), the experts and CEOs added. The most successful case is the Azure automobile, established in 2014 in Shanghai, which made profits in 2019. Their products are not only popular in China but also sold overseas. Because this firm has not had the ability to produce automobiles, Azure’s automobile production was handed over to JAC in Hefei. In 2020, Azure moved its headquarters to Hefei, the capital of Anhui Province, but its research base and marketing department are still in Shanghai (CR14).

Key PMs from the internet sector also contribute to digital knowledge creation around electric vehicles, serving regional traditional automobile manufacturers but also providing help to international firms. For example, Tencent set up the first Smart Car Cloud in Shanghai. Tencent provides essential support for Bosch’s China automobile driving R&D platform in storage, computing, and networking. It supports the need for hundreds of petabytes of storage and hundreds of the latest GPU cards for large-scale distributed training, promoting cost reduction and efficiency in autonomous driving R&D (CR18).

Entrepreneurs from the material and semiconductor sectors acknowledged that they are likely to specialize in the components of automobiles instead of being OEMs (CR21-28). In their view, the improvement of the automobile industrial environment in recent years, high technological barriers regarding chips and new materials, and potential markets make them more confident to stick to the original position. As they said, “In 2021, electric vehicles on average in China required more than 1,000 chips—twice as many as traditional automobiles 20 years ago! In the future, the number of chips for every electric vehicle will increase.” and “Demand for new materials also continues to rise!”

The dynamic capabilities of entrepreneurs contribute to Shanghai's automobile industrial development. Among these, automobile entrepreneurs are the prominent supporters of the intuitional changes. Because of their wise selection, entrepreneurs from other sectors dare to participate in related innovative activities. Although entrepreneurs with digital working experiences enter the original equipment manufacturing of electric vehicles, complex knowledge, high risks, and changing policies are significant hindrances for them. Only a few firms have survived until now.

4.3.2.3 Governance complexity

Since 2010, China and Shanghai governments have paid more attention to technological breakthroughs in the semiconductor and new materials sectors. On the one hand, national and regional policy supports and diversified actions (a broadening and deepening of innovation policy) for the Shanghai automobile industrial evolution are visible in more and more sectors.

In the automobile sector, national and regional governments introduced a range of policies to foster knowledge base combinations towards electric vehicle development, particularly tax preferences for all automobile firms, green and digital legitimacy, R&D subsidies for key PMs (battery, motor, and electric control) and OEMs, as well as sale subsidies for OEMs (Yuan et al., 2015).

In the semiconductor sector, the policymakers emphasize that the emergent research task is to develop high-value automobile chips with high computing power in terms of tax incentives and two-stage special investment funds (VerWey, 2019). The funds in the first phase were primarily invested in the midstream of the semiconductor sector, including manufacturing, design, packaging, and testing of leading enterprises, whereas in the second phase, upstream and downstream, especially the leading companies specializing in high-precision equipment production, essential materials to improve chips' performance, and other weak points, are the main investment objectives (OF1; SE2; CR22, 26).

In the new material sector, governments encourage environmentally friendly materials and the effectiveness of rare metals in automobile innovation primarily via tax incentives and R&D subsidies.

In the internet sector, the state introduced the first policy regarding the digital legitimacy of electric vehicles in 2014. All firms specializing in digital management and innovative activities of electric vehicles could enjoy the same preferential policies offered by electric vehicle firms (CR11, 19, 20).

Recently, a market-oriented policy change to enhance firm innovation performance has been visible in the three sectors. A special policy is Star Market (namely, Sci-Tech Innovation Board) (Li et al., 2023). Xi Jinping delivered a keynote speech announcing the establishment of the Science and Technology Innovation Board on the Shanghai Stock Exchange and the pilot registration system in the opening ceremony of the first China International Import Expo in early November 2018. Star Market started to operate in 2019. In comparison to general listing regulations, Star Market pays more attention to the R&D capacity of the firm and thus is viewed as a special selection for high-tech companies in electric vehicle, medical device, new materials, optical and semiconductor sectors (SE1; OF3).

On the other hand, at the regional level, the Shanghai Development and Reform Commission and the Shanghai Industry and Information Technology Commission enhance the coordination of related public departments. Essential coordination among these sectors primarily zooms in on critical parts (i.e., TEC) involving four shortage chips (computing and control chips, sensing chips, and memory chips), the digital management, and the related selective materials (i.e., rare materials and special polymers to enhance sensitivity). The cluster organizers and the managers of industrial parks revolve around critical coordination to identify the related firms to offer convenient services in financing and renting plants. Although multiple actors and complex linkages are observed, governance primarily occurs in the manufacturing sector instead of the internet sector (OF2, 4; SE3).

Beneficial from policy broadening and deepening and the coordination of multiple public departments, more and more institutes and firms have been likely to participate in high-value innovative activities around the digitalization and electrification of electric vehicles. It has contributed to critical technological breakthroughs, which reduced production costs in materials, electronic chips, electric drives, and charging advancements. Particularly, the three primary constituents of pure electric vehicles (EVs) – namely, batteries, motors, and electronic controls – constitute approximately 50% of the total cost of EVs. The cost of batteries, representing approximately 40% of the overall expense, has observed a recent decline. Moreover, the technological maturity of electric motors and electronic controls has surged, leading to a reduction in their contribution from 15% to 7% of the total cost. Presently, a complete set of electric motors and electronic controls for pure electric passenger cars stands at approximately 10,000 yuan. Furthermore, there has been a 20% decrease in the prices of power batteries.

4.3.3 A comparative study of medical device and automobile sectors in Shanghai

Knowledge base combinations across sectors for medical devices are lower than for automobiles. One key reason is that scientific knowledge is relatively widely applied in the automobile industry because of the relatively successful institutional evolution, whereas in the medical device sector, most optical institutes are under-constructed (see Table 4.3).

Table 4.3. Cross-sector complex knowledge evolution: A comparative study of Shanghai automobile and medical device sector

A comparative study		Medical Device Industry	Automobile Industry
Knowledge base combinations across sectors		Internet, Optical, and Semiconductor sectors	Internet, Material, and Semiconductor sectors
Innovation System Reconfiguration	Institutes' Evolution	+++	+++++
	Entrepreneurs' Dynamic Capabilities	+++++	+++++
	Governance Complexity	++++++	+++++

Sources: The author

Moreover, entrepreneurs' dynamic capabilities are similar. Both in the medical device and automotive sectors, there exist strong alignments of dynamic capabilities between OEMs and PMs. OEMs actively share user information and feedback with PMs, fostering collaborative discussions regarding future investments and initiatives. Note that internet entrepreneurs are very positive in automobile and medical device development; some try to become OEMs, while others aim to be PMs.

Finally, although Shanghai-related sectors contribute more to regional automobile development than medical devices, China's strict rules and regulations in the inspection, testing, and review of medical devices are visible. That is why there is higher governance complexity in the medical device industry than in the electric vehicle industry. The latter is primarily influenced by the multiple actors and the coordination among sectors.

4.4 Summary

In this chapter, I propose proximity, institutions, and the innovation system reconfiguration as lenses for illuminating the process and mechanisms of cross-sectoral complex knowledge evolution. First, I explored how the five dimensions (i.e., institutional, cognitive, organizational, social, and geographical proximities) affect the combination of knowledge bases at regional, national, and global levels in the Shanghai high-end medical device industry. Secondly, I investigated how upstream-downstream interactions affect knowledge base combinations in the Shanghai electric vehicle industry in green and green digital transitions from an institutional perspective. Thirdly, I examined how multiple actors contribute to regional complex knowledge evolution in the regional innovation system reconfiguration process in the two industries, where institutional evolution, entrepreneurs' dynamic capabilities, and governance complexity are highlighted.

Based on the empirical analyses regarding complex knowledge evolution, I summarize the main findings, contributions, limitations, and a research agenda. The detailed information is elaborated on in Chapter 5.

5. Conclusions and Outlook

This chapter summarizes the main findings of the empirical cases and related research contributions. Notably, it highlights different actors' strategies, the characteristics of upstream-downstream interactions, and policy upgrading approaches in the complex knowledge evolutionary process. Based on the research results, I propose several policy recommendations regarding complex knowledge evolution. Also, I propose a research agenda associated with the next stage of economic geography and complexity research.

5.1 Main findings and contributions

The Shanghai medical device industry has gradually evolved from an analytical-led knowledge base to a combination of analytical and synthetic knowledge bases. Typical cases of CKBs include software engineering, electrical engineering, and optical engineering and they are essential to the R&D activities of high-end medical devices. By contrast, the Shanghai automobile industry has gradually evolved from a synthetic-led knowledge base to a combination of analytical and synthetic knowledge bases. The digitization of electric vehicles, chips, and new materials dominates the evolutionary process.

5.1.1 Three research questions and related findings

Research Question 1: What are the characteristics of upstream-downstream interactions in the complex knowledge evolutionary process?

Shanghai's high-end medical device industry

(1) Interactive intensity: relatively weak upstream-downstream interaction

Since 2013, innovative OEMs in Shanghai's high-end medical device industry have emerged on a large scale, meaning that these companies have been established relatively recently. These established OEMs do not play a significant role in driving the development of Shanghai's high-end medical device industry chain. Instead, relatively innovative OEMs have developed products mainly by mobilizing innovative resources at different spatial scales. In other words, upstream-downstream interactions in this industry are primarily based on the innovation capabilities of different companies in the short term. Multi-dimensional proximities play a decisive role in upstream-downstream interactions. Moreover, local high-end medical device brands have a limited presence in the domestic market in China. Foreign companies make up a 80% of China's high-end medical device market.

(2) Interactive approaches: Interactions between OEMs and multi-scalar sources for the complex knowledge evolution

CKBs in Shanghai's high-end medical device industry depend heavily on innovative sources within the city and on international collaborators (Moodysson, 2008). Within Shanghai, geographical, institutional, and social proximities are central. By contrast, cognitive and organizational proximities play a decisive role in the knowledge interactions between Shanghai and other cities in China. In addition to cognitive and organizational proximities, social ties are crucial for local-global cooperation.

Some innovative advantages of other cities in China have developed into affiliates of Shanghai headquarters. Because of this, organizational proximity at this level strongly affects combinatorial knowledge interaction in the Shanghai high-end medical device industry (see Table 5.1).

Table 5.1 Approaches of upstream-downstream interactions

Cases	Approaches of upstream-downstream interactions	
Shanghai's high-end medical device industry	Intra-Shanghai OEMs and partners	Cluster initiatives and industrial parks provided a sound collaboration environment (geographical proximity); Cluster organizations and industrial parks provide preferential policies and R&D services (institutional proximity); Social connections (guanxi), such as old colleagues or partners with similar knowledge bases, are significant sources for CEOs' knowledge interactions (social proximity).
	Shanghai OEMs and partners in other cities in China	Knowledge interactions are mainly based on intra-firm organizations (organizational proximity); Jointly established institutes fostered cognitive proximity at the national level (cognitive proximity).
	Shanghai OEMs-global collaborators	Germany, Japan and Switzerland have advanced optical engineering knowledge, while America is renowned as cutting-edge electronic engineering (international cognitive proximity); Earlier collaborations or peer recommendations play an essential role (international social proximity); Mergers and acquisitions (M&A) and new sub-organizations (organizational proximity).
Shanghai electric vehicle industry	A green era: Downstream facilitates upstream (2001-2013)	OEMs (influenced by knowledge creation, green technology legitimacy, financial investment, and market formation) contribute to sectoral development in the upstream position of the electric vehicle via R&D and market demands;
	A green digital era: Upstream fosters downstream (2014-)	Influenced by institutions regarding knowledge creation and market formation, Shanghai internet, semiconductor and new materials sectors in the upstream position have engaged in high-value components and parts of electric vehicles;
	A green digital era: downstream fosters upstream (2014-)	Influenced by digital technology legitimacy, financial investment, and market formation, OEMs promote the business expansion of upstream sectors.

Source: The author

Two modes—the M&A mode and the dual-embeddedness cooperation mode (Raziq et al., 2021; Davy et al., 2021)—exist in local–global organizational proximity. Both models promote the creation of CKBs by reducing risk and uncertainty. The M&A mode is often discussed in research on intra-firm collaboration. By contrast, the dual-embeddedness cooperation mode should be given more attention in organizational proximity studies, although the mode itself prevails in economic geography.

Shanghai electric vehicle industry

(1) Interactive intensity: Relatively strong upstream-downstream interactions

Developing electric vehicles has been a national industrial strategy in China for two decades, and policy support for upstream and downstream companies in the Chinese electric vehicle industry chain has been strong. Shanghai's electric vehicle industry has undergone large-scale research, development, and production. OEMs specializing in traditional automobiles have expanded to include the development of electric vehicles. Moreover, the increased recognition of domestic electric vehicle brands in the domestic market has indirectly strengthened the interaction between upstream and downstream companies.

(2) Interactive approaches: Upstream-downstream interactions (see Table 5.1)

Downstream sectoral development primarily promotes knowledge creation in the upstream sectors via R&D and market demands for green transition. By contrast, upstream sectoral development primarily speeds up the pace of innovation downstream through technological linkages in the green digital transition, such as market-oriented industrial environment development and the digitization and electrification of vehicles. For example, mobile internet development directly opens the doors for manufacturing industrial upgrading, whereas semiconductors and new materials contribute to developing chips and TEC systems for electric vehicles.

Note that the organizational attributes of OEMs significantly determine resource mobilization and assignment approaches in the electric vehicle industry: (1) Environmental innovation is the starting point for the first group of OEMs and the primary contribution of the Shanghai CKB. These OEMs are likely to utilize their power in the automobile industry to promote related sectoral transformation, and this in turn will accelerate cross-sectoral knowledge flows and knowledge base combinations. (2) The second group of OEMs is more concerned with digital innovation, such as autonomous driving and the digital management of TEC systems, which play a significant role in the transition to sustainability. This group is sensitive to new and popular elements, producing electric vehicles with a strong sense of modern science and technology. This finding aligns with the argument by Manniche et al. (2017): "…equally contingent on organizational factors such as firm size, age, country, key individuals' networks and professional experiences, and a range of other organizational constraints…Such characteristics, not directly related to knowledge dynamics per se, may be strongly decisive for the actual organization of innovation processes…"

Research Question 2: Which actors enter more complex activities, and how do they accomplish them?

Institutes, entrepreneurs, and governments are crucial actors for promoting the evolution of complex knowledge. These three actors show different regional innovation system reconfiguration strategies in the two cases (see Table 5.2).

Compared to the Shanghai electric vehicle industry, cross-sector knowledge base combinations are relatively weak in the Shanghai high-end medical device industry. Due to the creation of relatively successful institutes, scientific knowledge is implemented broadly in electric vehicles, whereas most optical institutes have evolved slowly in the medical device industry.

Furthermore, the dynamic capabilities of entrepreneurs are similar in these two cases. In both the medical device and automotive industries, there are strong alignments of dynamic capabilities between OEMs and PMs. OEMs actively share user information and feedback with PMs, fostering collaborative discussions regarding future investments and initiatives. Whereas Shanghai companies face more challenges than international giants in terms of accumulating technology, these entrepreneurs in Shanghai strive to enhance their product offerings and innovation capabilities.

Finally, although Shanghai-related sectors make a larger contribution to regional automobile development than medical devices, China has strict rules and regulations for inspecting, testing, and reviewing medical devices. This is why there is more governance complexity in the medical device industry than in the electric vehicle industry. The latter industry is influenced by the multiple actors and the coordination among sectors.

Table 5.2 Crucial actors in the regional innovation system reconfiguration

Cases	Institutional evolution	Entrepreneurs' dynamic capabilities	Governance complexity
Shanghai's high-end medical device industry	Shanghai's internet and semiconductor sectors: the successful curriculum alignment and establishment of affiliated entities; Shanghai semiconductor sector provides limited help in producing high-precision chips for medical devices; The number of university affiliations is very limited.	OEMs: Large-sized medical device firms, returnee entrepreneurs, and entrepreneurs from the internet sector; PMs: internet, semiconductor, and optical sectors.	The coordination across multiple public departments; The complexity of governance is still high due to the very strict medical device-based regulations and policies.
Shanghai electric vehicle industry	Shanghai's internet, new materials, and semiconductor sectors industries: institutional evolution contribute to the ISR regarding Shanghai electric vehicles;	OEMs: OEMs of traditional automobiles and entrepreneurs from the internet sector; PMs: internet, semiconductor, and new material sectors.	A broadening and deepening of innovation policy; The coordination of industrial chains.

Source: The author

Research Question 3: How can policy support upgrading towards higher levels of complexity?

What follows is a comparison of the similarities and differences in policy upgrading in these two cases.

(1) Similarities

From a spatial scale perspective, national institutional changes have played a decisive role in the evolution of complex knowledge. The Shanghai government follows the state's call in implementing national policies, and this has contributed to developing the two industries. Moreover, in terms of the industrial chain, policies have been implemented to maximize the coverage of upstream and downstream sectors and related companies. These policies include R&D subsidies for OEMs, market subsidies, tax incentives, technical support, and market promotion. Additionally, technical support and financial investment from component manufacturers have further encouraged the development of the industries.

(2) Differences

The level of policy support for electric vehicles is considerably higher than for high-end medical devices in terms of the number and diversity of policies and their effectiveness (see Table 5.3). This disparity is primarily attributed to the crucial role played by electric vehicles in China's socioeconomic development. Additionally, policy upgrades have emphasized companies upstream of the electric vehicle industry chain, from early-stage R&D to the application of technologies.

Table 5.3 Similarities and differences in policy upgrades in both industries

Similarities	Differences
Spatial scale: National institutional changes play a decisive role; regional policy support upgrading is also crucial.	The power of policies for the Shanghai electric vehicle industry is higher than the power of policies for the Shanghai high-end medical device industry.
Industrial Chain: Upstream-downstream policies and rules.	Policy upgrading pays more attention to firms in the upstream position of the electric vehicle industry chain than that of the high-end medical device industry.

Source: The author

5.1.2 Theoretical Feedback and Contributions

Theoretical feedback

By analyzing cross-sector knowledge base combinations in the Shanghai medical device and electric vehicle industries, I identify different actors' strategies, characteristics of upstream-downstream interactions, and policy upgrading approaches. These research findings respond to the discussion in the context sensitivity of complex knowledge. Particularly, I summarize a theory of regional complex knowledge evolution by linking CKBs to innovation system reconfiguration. By applying the theory in the two cases, I prove that the theory is feasible, reliable, and effective.

Contribution

This dissertation makes four main contributions. First, it advances the understanding of complex knowledge from a CKB perspective, providing a complementary approach for complex knowledge research in economic geography. Secondly, it introduces a nuanced and context-sensitive theory of complex knowledge evolution by linking CKBs and innovation system reconfiguration concepts. Thirdly, it examines upstream-downstream interactions of the Shanghai medical device and electric vehicle industrial chains, refining complex knowledge research at the different spatial scales and transition contexts. Fourthly, it draws on a recent empirical study of the Shanghai medical device and automobile industries to illustrate the theory and shed light on complex knowledge trajectories and related linkages and coordination among multiple sectors at the regional level.

5.2 Policy implications for cross-sector complex knowledge evolution

5.2.1 Policy implications for Shanghai

Policy implication 1

Shanghai's optics sector faces significant challenges in terms of applying scientific knowledge, particularly analytical knowledge, primarily due to the slower pace of development in university-affiliated institutes. In this regard, incubators, laboratories, and technology transfer institutes are pivotal for regional science and technology translation. To promote the flourishing of the upper echelons of Shanghai's complex industrial chain, policymakers in Shanghai should prioritize the application of analytical knowledge bases across sectors in ongoing R&D activities and provide relevant policy support.

Policy implication 2

The complexity of governance in Shanghai pertains primarily to the introduction of policy. However, the effectiveness of such policies is not consistently communicated to the multiple government departments and original policymakers, resulting in a lack of reliable governance. In the future, Shanghai should establish a dedicated process or monitoring group to provide regular and timely feedback on the outcomes of complex governance to the various government departments involved, thus improving the effectiveness of governance and promoting greater accountability.

5.2.2 Policy implications for other cities in China or other countries

Policy implication 1

Internet entrepreneurs have a positive attitude to applying digital technologies to electric vehicles and medical devices because some of them shift to OEMs. This phenomenon is seen not only in Shanghai but also in Beijing, Guangzhou, Shenzhen, and Hangzhou, as well as in other emerging sectors such as the smart wearable sector. This reflects the dynamic capabilities of internet entrepreneurs with Chinese characteristics.

The Chinese government should give adequate attention to the dynamic interplay between internet companies and other emerging industries in China. In appropriate cases, national and regional governments should introduce specific cross-industry incentives to stimulate entrepreneurial activities in complex knowledge. For instance, the government should closely monitor the initial stages of internet companies entering the OEMs of electric vehicles or high-end medical devices. Practical approaches include additional R&D subsidies, tax reductions, and incentives to accommodate research staff in these companies.

Policy implication 2

Industry-oriented policies, rather than new technologies per se, mostly lead to governance complexity in combining new technology and existing knowledge bases (Stephan et al., 2017; Jacobsson & Bergek, 2011; Stephan et al., 2019). Policymakers should pay more attention to industry-oriented policies to facilitate the rapid upgrading of industries. More importantly, coordination among related sectors is crucial in the evolution of knowledge.

Policy implication 3

Regional policymakers should prioritize the identification of sectors in the industrial chain and clearly define the starting points for complex knowledge production across sectors. This is crucial because it directly affects the interaction of upstream and downstream sectors. For instance, policymakers should proactively evaluate whether to commence from an upstream or downstream segment of the value chain. If the region comprises industries with extensive supply chains, the transformation or upgrading of the sector downstream of the supply chain can stimulate the development of the upstream sector through R&D and market demand. As the downstream sector and the associated technologies mature, technological breakthroughs in the upstream position of the industrial chain will emerge as a crucial driver for knowledge base combinations.

5.3 Limitations and outlook

The dissertation has several drawbacks, and several intriguing elements for further exploration. At this point, I remark on the research limits while highlighting five directions for further study.

First, I only examined the context-sensitive theory of the evolution of complex knowledge in developed regions of emerging economies. In the future, this theory should be applied to the peripheral regions of China and to industrialized countries to compare the results and generalize the theory for a deeper understanding of the underlying mechanisms of the evolution of complex knowledge across sectors.

Second, the dissertation emphasized the interactions between sectors at different industrial chain positions, neglecting the interaction between sectors in the upstream position (Andersen et al., 2020). The interviewees explained that the semiconductor, internet, and new-materials sectors are embedded in each other's technological innovation systems. The transformation of one sector may affect or be affected by the other sectors, and this relationship should be considered in the future.

Third, the dissertation offered a limited understanding of how international sources affect the evolution of complex regional knowledge. A more nuanced approach is needed. For example, how do international sources influence regional institutional evolution, the dynamic capabilities of entrepreneurs, and governance complexity in the ISR process? And which actors and which sectors establish the connection with international giants? By answering these questions, the "active genes" of actors in different sectors can be identified, to better exploit regional advantages based on existing regional sources.

Fourth, I examined three types of interactions that contribute to the evolution of complex knowledge across sectors (namely, system–firm-level actor interactions, firm–firm-level actor interactions, and system–system-level actor interactions) but I did not consider the intrinsic link between labor mobility and knowledge mobility. In the Shanghai medical device industry, I found that cross-disciplinary research often necessitates the collaboration between companies in different sectors, but I did not gather statistics on the proportion of the workforce in different types of knowledge bases in these companies. The ratios between these knowledge bases and their impact on the flow of knowledge across departments may be complementary or synergistic. Hence, an essential element of intrinsic causality must be considered at the system level when introducing policies in the ongoing innovation system reset. By tracking the rate and proportion of cross-sectoral labor flows in the process of complex regional knowledge evolution, we can predict the stage and speed of knowledge evolution and formulate appropriate policies to promote the evolution of complex knowledge.

Finally, the dissertation examined the evolution of complex regional knowledge across sectors based solely on two case studies, with an emphasis on their processes and mechanisms. However, a quantitative analysis of knowledge base combinations across sectors is warranted. Therefore, existing models should be applied or developed to explore the characteristics of knowledge flows and convergence in both time and space (Wu, 2022).

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