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Technology Innovation Management: Topic Evolutions and Research Trends from 1968 to 2022

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Abstract

The technology innovation management (TIM) field attracts an increasing amount of attention. This paper takes a retrospective look at high-quality publication output in the TIM field over the 55 years from 1968 to 2022, revealing topics, their evolutions, and research trends. A total of 31,498 articles and proceeding papers published during this period are analyzed. The paper first extracts the fine-grained topic words using the tool ITGInsight. Then Linlog algorithm is used to cluster topics based on the co-occurrence of the topic words. Time is integrated within the topic cluster results so that topic evolutions and research trends are analyzed. The TIM field has four main topic clusters: *technology research, product research, firm research,* and *future research*. In every topic cluster, there are many fine-sorted macro-topics and micro-topics. There is an obvious increase in diversity in the topic clusters of *technology research* and *firm research*. Especially, the evolution of *technology research* has been closely connected with society. In contrast, *product research* has declined in its topic size. At the same time, *future research* maintains a certain stability of its scientific publications. The research predicts that all the four topics will retain their popularity, and play an important role in the TIM field. Among them, *technology research* will continue to expand and enrich the TIM field. The other three topics will deepen their research for a better development of the TIM field. The paper also proposes some advice for industry professionals, policymakers, and researchers.

Keywords

technology innovation management; word co-occurrence; topic cluster; topic evolution; research trend; ITGInsight;

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1. Introduction

Technological innovation is essential for economic development and the creation of wealth (Manigandan *et al.*, 2023; Taylor *et al.*, 2003). Both the government and the firm have realized and tried their best to achieve it (Dolfsma & Seo, 2013; C. Wang *et al.*, 2008). With the advancement of every new scientific and technological revolution, technological innovation occupies an important position in the game of great powers. Every industry revolution will bring new opportunities and challenges for countries (Morrar *et al.*, 2017). For example, the United States, without a long history as a country, has become the top competitive country, because it vigorously developed technological innovation in the wake of the industrial revolution to achieve its current position. Not a few latecomer countries have obtained the catch-up ability by taking advantage of the opportunity. Owning technological innovation capability can help a country seize the opportunity to push its competence to a higher stage. Technological knowledge together with its capability to generate innovation is one of the firm's main resources (Chen *et al.*, 2023; Galende, 2006). But only useful technological innovation leads to better firm performance (Koellinger, 2008). Breakthrough innovation has received a lot of attention because it allows companies to quickly gain a dominant position in the market. But the difficulty is that disruptive and incremental innovation needs different strategies to manage (Lopes *et al.*, 2016). So in order to make the right technological innovation, help firms form the core ability of technological innovation, and solve the problem of long-term development, the role of technological innovation management has become increasingly important (Xu *et al.*, 1998).

Now, policymakers in every country are concentrating on effective policies that can stimulate technological development (Dolfsma & Seo, 2013; Gong & Hansen, 2023) and help their countries become stronger. Managers in firms are in the same situation. So the field of TIM began to be appreciated by academia and industry. For scholars, using the scientific method to manage technology innovation brings great advantage for countries and firms. Since the nineteenth century, scholars have gotten to know the importance of TIM (Bright, 1969; Robertson, 1974; Utterback, 1971). In the information society, the literature explosion makes researchers feel confused. At the same time, TIM is an interdisciplinary field (Linton & Thongpapanl, 2004), and this makes it more difficult to analyze and evaluate than other fields. Most scholars start with the more practical aspects of the field, such as green technology innovation (Du , 2019), digital innovation (Llopis-Albert *et al.*, 2021), and disruptive innovation (Beltagui *et al.*, 2020). The TIM field is mentioned in different theories that include technological innovation (Dosi, 1982), process innovation (Tidd, 2001), open innovation (Huizingh, 2011), and new product development (Takeuchi & Nonaka, 1986). This is consistent with the definition of technology innovation management. Technology innovation management is a new combination of production factors and production conditions. And the field of technology innovation management refers to the research within the scope of technology innovation management. However, direct research in the TIM field is very scarce. As for research directly related to TIM topics, most insights are published in TIM journals. In 1999, citation analysis was used to rank five TIM journals (Cheng *et al.*, 1999). Then in 2004, citation analysis was also used to rank ten leading TIM journals (Linton & Thongpapanl, 2004). Through expert interviews and literature review, a review of the TIM field about the development status in the period from 2014 to 2019 is proposed and some key scientific problems are put forward (Jiao *et al.*, 2022). At present, there is a lack of an overview of the field's development to help countries and firms achieve better development and innovation. This paper fills this gap by conducting a bibliometric analysis. It uses word co-occurrence, topic cluster, and topic evolution techniques to demonstrate the development of the TIM field.

Topic extraction, or topic detection, is widely used in field analysis. It mainly includes two types, the

first research uses LDA-related method to extract the topic, and the second research uses the topic cluster method to extract the topic. LDA is the most successful and famous method. It has been improved for scholars' purposes for many times. The most famous improved methods are DTM (Blei & Lafferty, 2006) and ATM (Rosen-Zvi *et al.*, 2012), which integrate time and author elements into the LDA model respectively. The topic cluster includes vector-related methods and network-related methods. The vector-related method generates topics by grouping topic words with similar meanings together. The network-related method usually uses social network theory and generates word relationships. And word co-occurrence method, also called the co-word method, is the most used method. It belongs to the bibliometric method, which is a useful method for exploring and analyzing large amounts of scientific data (Donthu *et al.*, 2021). Word co-occurrence is an established method that has been developed early (Peters & van Raan, 1993). In the actual operation process, natural language processing and text mining methods are applied to identify meaningful terms, then a two-dimensional map is used to visualize the terms and their relationships (Mohammadi & Karami, 2022). This method has been widely used in different fields (Ding *et al.*, 2001; Hu *et al.*, 2013; Peters & van Raan, 1993; Rip & Courtial, 2005).

Topic evolution starts with discovering topic trends in temporal documents. Topic evolution has three main aspects: topic intensity evolution, topic status evolution, and topic content evolution (Zhu *et al.*, 2022). In our research, we use a new annual ring topic evolution figure to describe the topic evolution. It can show the topic cluster's holistic and subdivided evolution, which can help to reveal the research trend. Through analyzing topic evolutions, research trends can be identified. Research trends are very important in field review because policymakers and firms not only care about what happened but also what may happen in the future. Different from forecasting technology, research trend analysis is just analyzing the current topic's features, through increasing and decreasing trends to judge the topic's development. In temporal analysis, research trend usually has reliable results.

The aims of this paper are twofold. First, we provide a retrospective look at the TIM field by exploring its topic evolutions and research trends. It is important because, through the analysis of evolutions and trends, advice could be proposed for better development. To the best of our knowledge, no analysis has been dedicated to the TIM field for its years of development. Second, we can gain a better understanding of not only the most important topic in a specific phase but also the evolution and trend of a specific topic by using text analysis and data visualization for temporal documents. By studying the topic's importance and how the topic has changed in the past, science and technology management departments of firms or governments can better grasp the future development priorities. The paper is organized as follows: Section 2 introduces the data and method, including data, the fine-grained topic word generation, phase division, and topic cluster and visualization. In Section 3, the research results are obtained and analyzed in detail. Section 4 gives the conclusion of this paper. The flowchart of our method is shown in Fig. 1.

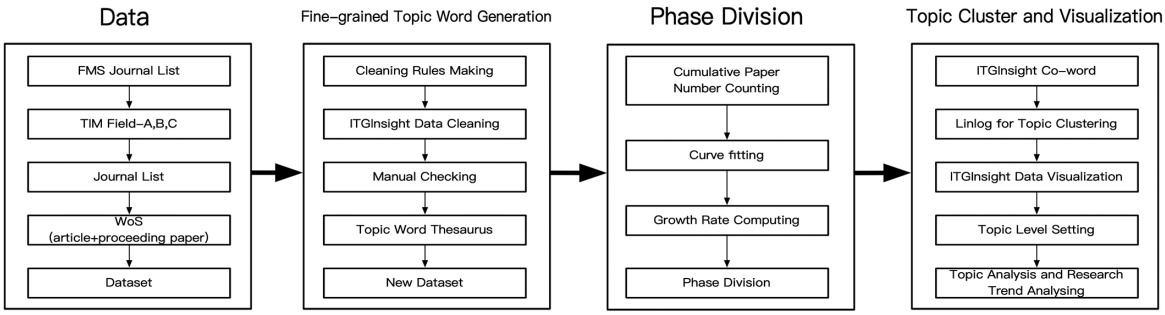

Fig. 1. Method flowchart.

2. Data and Method

2.1. Data

In order to better represent the TIM field, science, technology and innovation management field in the FMS (Federation of Management Societies of China) Journal Rating Guide is used. This Rating list is created using scientific methods. The journal rating list has referred to several major and authoritative journal lists, such as UTD 24, FT50, ABS, ABDC, CNRS, and VHB. And then experts' opinions are combined. So the selection of high-quality journals and the ranking of journals are carried out from a comprehensive perspective. Only high-quality journals will be on this rating list. Thus this journal rating is reliable and meaningful. Each field has four journal ratings: A, B, C, and D. The rating represents the experts' opinion of the journal in the current field, A is better than B, by parity of reasoning, and D is the last recommendation for high-quality journals made by experts. Then we select the TIM field journals in this list for research. In China, science and technology innovation management almost can be treated as technology innovation management. We choose 22 journals with the levels of A, B, and C (D-rated journals are missing from most mainstream journal ranking lists, indicating that these journals are not currently representative of research in the TIM field, so they are not selected). The chosen journals are listed in Table 1.

Table 1
Journals.

Rating	Journals
A	Journal of Product Innovation Management; Research Policy
B	Industrial and Corporate Change; Technological Forecasting and Social Change; Technovation; R & D Management; Science, Technology & Human Values; Journal of Technology Transfer
C	Futures; Industry and Innovation; Research Technology Management; Science Technology and Society; Evaluation; Economics of Innovation and New Technology; International Journal of Technology Management; Journal of Engineering and Technology Management; Technology Analysis & Strategic Management; Research Evaluation; Creativity and Innovation Management; Science and Public Policy; Innovation-Organization & Management; European Journal of Innovation Management

All literature data used in this research is retrieved from the Web of Science (WoS) platform. WoS includes a wide variety of journals, thus it is chosen to be the data source. We use journals in this journal list as the target journals. The earliest journal included in WoS core collection is *Futures*, it was first included in 1968. So the search years are controlled to be between 1968 and 2022, and publication types are articles and proceeding papers. The search date is February 1, 2023. As the result, 31498 papers are retrieved. Then we retain their titles and abstracts as the research data.

2.2. Fine-grained topic word generation

We use ITGInsight to generate topic words, it is a useful software for data processing and data mapping (Wang *et al.*, 2022). First, ITGInsight is used to generate the topic thesaurus. After using the thesaurus to handle research data, ITGInsight is used to generate the topic clusters and visualize them. To describe the topic better, phrases are used in this research. Although keywords are often used in topic evolution analysis, their length usually is one or two, which could not precisely express the topic well. So in this research, phases are defined as fine-grained topic words and chosen to help analyze

the topic of the TIM field. Fine-grained topic words are extracted from titles and abstracts. The title is the core information of the paper, it can intuitively summarize the paper's research question and sometimes reflect the methods used in the paper. The abstract is the paper's condensed expression. By reading the abstract, the key information of papers can be known. The length of the fine-grained topic words is manually set to 2 to 6 words according to the expert's opinion. The data is put into ITGInsight, using the data cleaning function to compute the TF-IDF values of the topic words. TF-IDF value 20 is chosen to ensure topic words will not show up too little, and the phrases are meaningful. Then topic words that have similar meanings are merged using ITGInsight and manual processing. Through repeatedly operating, and having experts handle the phrase lists, only meaningful phrases are remained and called fine-grained topic words. These fine-grained topic words are gathered into the topic thesaurus for further topic clusters. The thesaurus has 1544 topic words. According to statistics, there are 26,294 papers that contain topic words, accounting for 83.48% of the total. When processing the research data, only words in the thesaurus will be retained. Based on this information, a detailed analysis can be carried on.

2.3. Phase division

There are 55 years from 1968 to 2022. Different from traditional research that uses fixed year section, this research uses dynamic literature growth rate as the phase division method. This method is used based on the life cycle theory. The literature cumulative number is shown in Fig. 2, the fitting curve equation is shown in equation (1). The number develops slower than the estimated value in the early 30 years, and the development is in line with the fitting curve in the later 25 years.

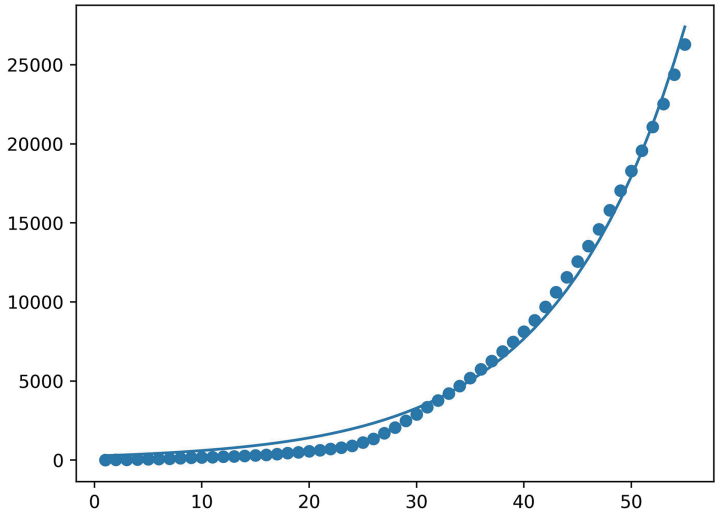

Fig. 2. The fitting curve of literature cumulative number.

$$y=e^{0.08486268x+5.55066519} \quad (1)$$

Then the literature growth rate curve is shown in Fig. 3. The whole field is divided into four phases: from 1968 to 1990, 1991 to 2005, 2006 to 2016, and 2017 to 2022, respectively. These four phases are named the emergence phase, the oscillating-development phase, the stable-development phase, and the take-off phase respectively.

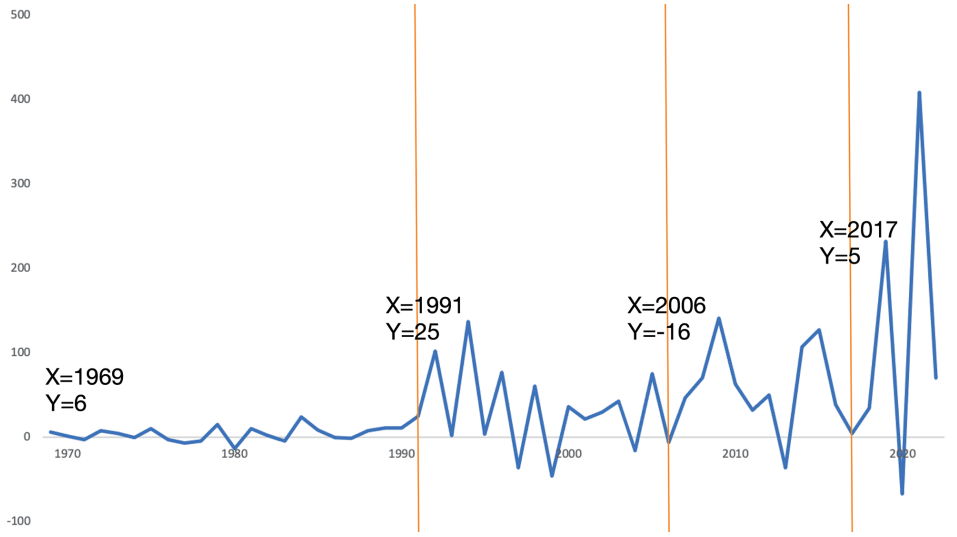

Fig. 3. The phase division.

2.4. Topic cluster and visualization

After phase division, fine-grained topic words are used to generate the co-occurrence relationships. Node will appear big when its corresponding term has a large word frequency. To distinguish between different clustering categories, the Linlog algorithm in ITGInsight is adopted as the topic cluster model. In the emergence phase, the paper numbers and topic word numbers are small, so all fine-grained topic words are shown in the cluster figure. In the other three phases, the topic word that can be analyzed and shown in the cluster figure is controlled to show up above 50 times. In the process of visualizing topic word co-occurrences, it is found that in the stable-development phase and take-off phase, due to numerous nodes and their complex relationship in the network, the topic words gathered into four clusters will lead to a low explanation. So we continue to cluster data using Linlog algorithm, which makes topic words in one cluster split into several clusters. In order to distinguish these different results, a four-level classified topic is created. The first level is topic clusters, which represent the overall topics. The second level is macro-topic, which expresses the main meaning of topics. The third level is micro-topic, which precisely expresses the topic. The fourth level is topic words, topic words are fine-grained topics, as well as the minimum and independent meaning of the analysis topics. These four levels are all topics, their relationships are shown in Fig. 4. In our study, the topic words are retained for analysis in the emergence phase. The fine-grained topic word is defined to be topic word. They will be matched with the topic words in the four types of topic clusters in oscillating-development phase to identify their topic clusters. In the oscillating-development phase, the four topics obtained by clustering are defined as the four topic clusters. In the stable-development and take-off phases, the results of the first clustering by Linlog algorithm are topic clusters, and the results of the second clustering are macro-topics. In the analysis part, micro-topic is used. Micro-topic is a part of macro-topic, which has obvious clustering effect. Micro-topic consists of topic words. We use four different colors to represent four topic clusters. We can easily associate the topic clusters generated in the stable-development phase and the take-off phase with the topic clusters in the oscillating-development phase by the high-frequency topic words. The macro-topics, the micro-topics and topic words use the same color system as the corresponding topic clusters.

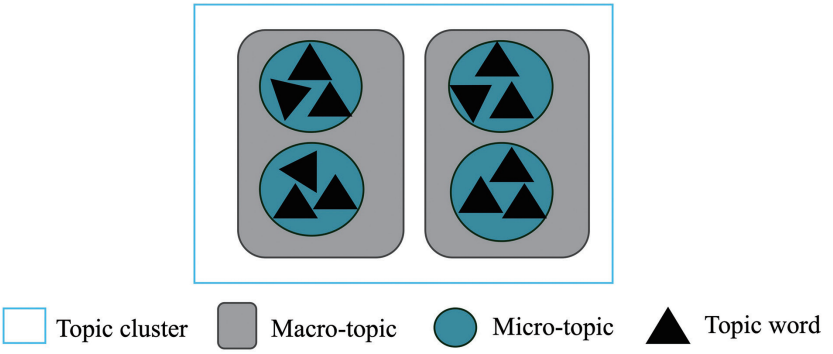

Fig. 4. The classification of topics.

3. Results

3.1. Overview

In this section, we investigate the most studied topics based on fine-grained topic words and the evolutions of topic clusters over time. The emergence phase is the start-up stage of the TIM field. It has 23 years, 790 papers, and only 8 journals are included by WoS. Because the co-occurrence relationship of data is sparse, the Linlog algorithm generates too many clusters. By comparing the results in all four phases and asking for experts' opinions, these clusters are divided into four topic clusters. These topic clusters are defined as *technology research, product research, firm research, and future research*. The oscillating-development phase is the high-speed developing phase, the TIM field develops and gains more and more journals and papers: it has 14 journals and 6082 papers in these 15 years. The stable-development phase is a super-speed developing stage, which has 11 years and 10,170 papers. All 22 journals in the FMS list are included by WoS in this phase. The take-off phase has 6 years and 9,252 papers. We use total topic word frequency as the topic size, the proportion of these four clusters in four phases is shown in Fig. 5. *Technology research* is represented in blue, *future research* in purple, *product research* in orange, and *firm research* in pink.

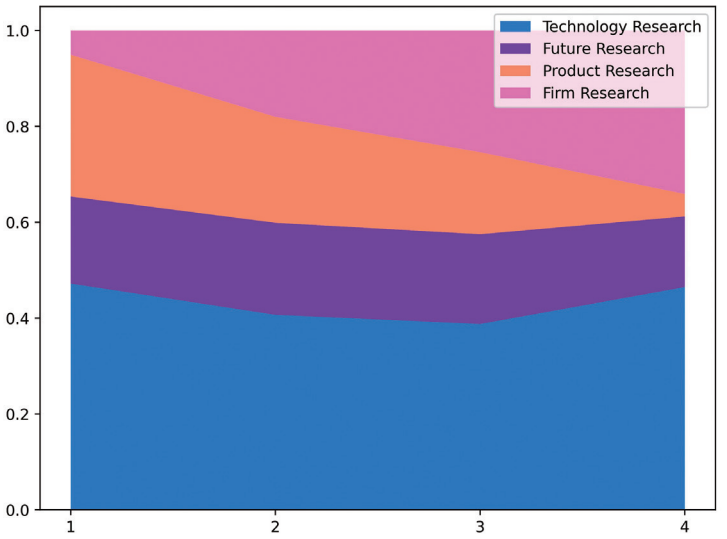

Fig. 5. Topic size proportion of four topic clusters in four phases.

To explore the evolutions of these topics, we use the co-word results of the emergence phase as the core part, from the oscillating-development phase to the take-off phase, the word co-occurrence map corresponding to each phase is placed on the annual ring line to represent the evolution of the topics, thus forming the topic evolution map of this paper. The shade of color represents the scale of the topic. The evolution paths of topics are shown in Fig. 6, https://github.com/hantaiyan/TIM-evolution/blob/main/evolution09261.jpg has a clearer figure. The topic evolution outline can be found in Fig. 7.

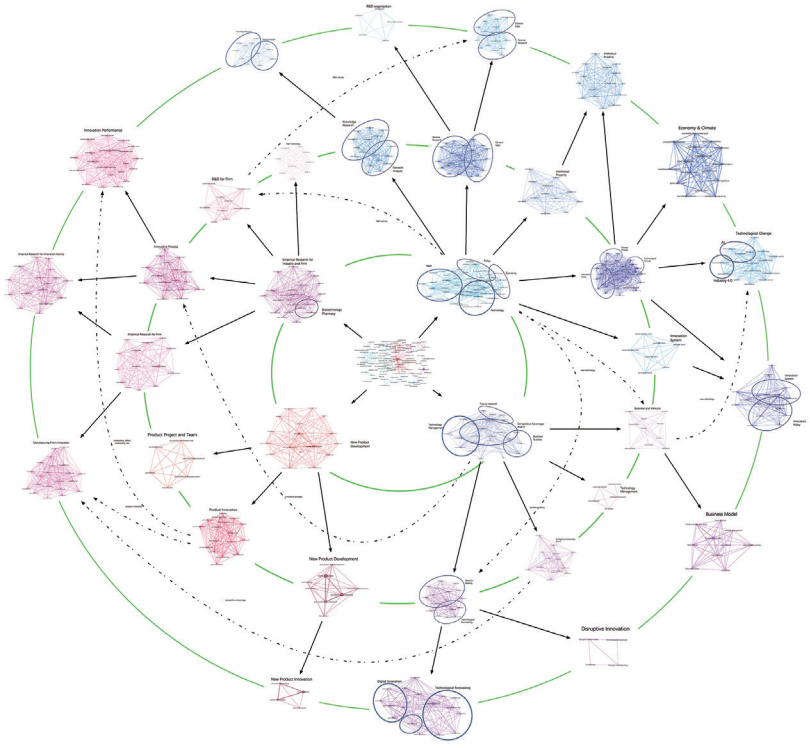

Fig. 6. Topic evolution path of the TIM field.

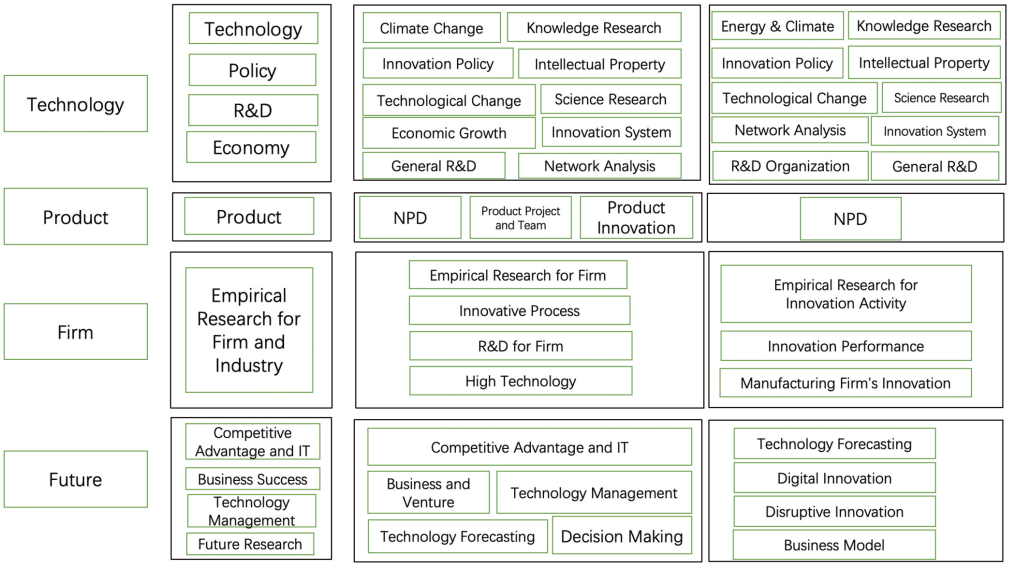

Fig. 7. Topic evolution outline of the TIM field.

3.2. Topic evolution of technology research

As can be seen in Fig. 6, this topic cluster has a total of 14 macro-topics: one macro-topic in the emergence phase, one macro-topic in the oscillating-development phase, five macro-topics in the stable-development phase, and seven macro-topics in the take-off phase. Over time, the topics become more diverse. In Fig. 8, we can see that micro-topics split and integrate with the advance of time, which brings more complex topics. The technology splits into policy, economy, technology, and R&D. Policy is more focused on innovation policy in the stable-development phase and take-off phase. Technology splits into seven micro-topics: climate change, innovation system, technological change, knowledge research, network analysis, and intellectual property. These topics remain their popularity except for climate change. Climate change combines with economic growth becomes a new topic. The topic R&D has two topics in the oscillating-development phase: scientific research and general R&D. Scientific research remains in the take-off phase. General R&D splits into two topics, one is still general R&D, and the other is R&D organization. Although some topic words related to policy, R&D, and innovation systems have appeared in the emergence phase, they have not formed clusters, so these topic words are not treated as micro-topics for analysis.

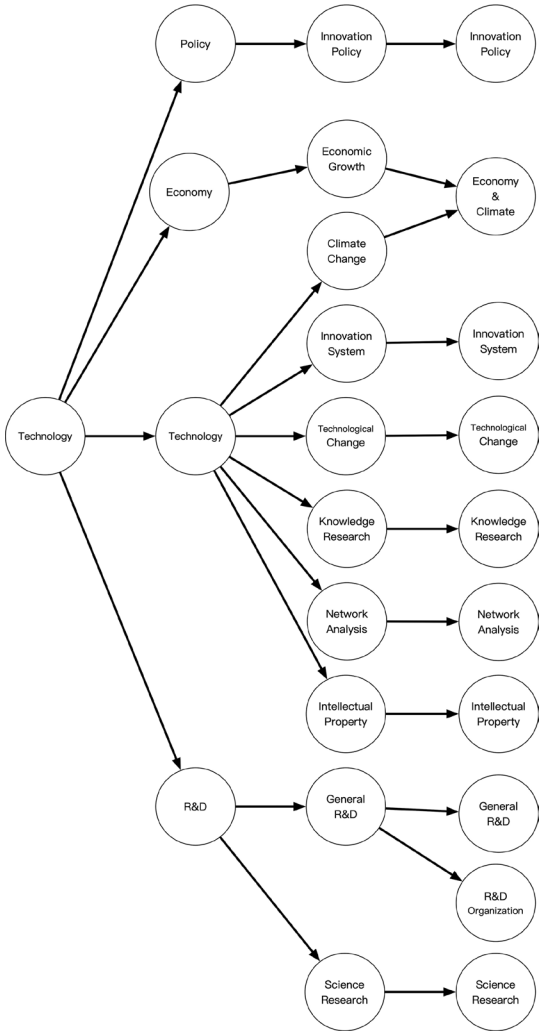

Fig. 8. Topic evolution of technology research.

3.2.1. Technological change

Technological change is the basis of *technology research*. This topic combines deeply with society. From the emergence phase, this macro-topic has many high-frequency topic words such as technological change, information technology, technological forecasting, and new technology. Topic words and their relations in the current phase are scattered. They aren't integrated together until the oscillating-development phase. In the take-off phase, this topic can be explained as technological change brought about by Industry 4.0.

Technological change is a core topic word, appearing 22, 266, 222, and 198 times respectively. Technological change shows a slow decreasing trend after a fast increase. This phenomenon can be found in many topic words, it doesn't mean that the topic word is unpopular, it just shows that the topic words become typical. In the emergence phase, technological change is in a central location, it only connects with six topic words: computer industry, service industry, industrial distinct, sectoral pattern, technological paradigm, and technological trajectory. From the oscillating-development phase, technological change connects with more topic words. Among them, technological change, technological capability, and technological development are the most contributing topic words. New technology is also an important topic word, it belongs to technological change in the emergence, oscillating-development, and take-off phases, but just moves to *future research* in the stable-development phase and contributes more to the business and venture when it is in the *future research*. We take three papers to illustrate the changes. *Developing and assessing radical technological changes: lessons from the PBX industry* is a paper in the oscillating-development phase, in which new technology is related to technological change that belongs to *technology research*. *Success factors in new ventures: A meta-analysis* is a paper in the stable-development phase, where new technology is used with new ventures that is an important topic in *future research*. Then in the take-off phase, new technology connects with technological change more. *Technology opportunity discovery using deep learning-based text mining and a knowledge graph* is another example paper. In this paper, new technology opportunity is discovered using intelligent methods. New technology is the most discussed topic word as it is in the emergence stage. In the take-off phase, artificial intelligence, machine learning, and text mining are used as new technologies shown in this topic. Technological forecasting is a part of technological change in the emergence and oscillating-development phases. Later it becomes a main micro-topic in *future research*. Technological advance and technology adoption are two first-shown topic words. Technological advance refers to the process and improvement in technology, this often results in new product, new service, and new system. Technology advance is an important concept that explains the acceptance, adoption, integration, and embracement of new technology to make full use of it (Granić, 2023). These two topic words have a deep connection with technological change because the popularity of technological advances and technology adoption is based on the fact that technology emerges and develops fast. The service industry is commonly used in the TIM field. It used to be researched with technological change in the emergence phase. Then in the stable-development phase, some topic words related to the service industry are shown in the *firm research*. The most recent trend in *technology research* is the technological change brought about by Industry 4.0. This macro-topic is combined with technological change, Industry 4.0, and artificial intelligence (AI). Technological change is a traditional topic and others are new topics. Industry 4.0 is short for the fourth industry revolution, it changes the industry with informatization. Therefore, it is deeply connected with AI and technological change. Artificial intelligence is now the most popular topic word in almost all fields. Artificial intelligence in this field is reflected in machine learning and text mining. With the impact of AI and Industry 4.0, smart cities and electric vehicles appear and become popular.

3.2.2. Knowledge network

Knowledge Network contains two micro-topics: knowledge research and network analysis. Knowledge research is an old topic, and this macro-topic develops from three knowledge-related topic words: technological knowledge, knowledge base, and knowledge transfer. In the stable-development phase, knowledge research is going to realize knowledge management through acquiring, creating, and transforming explicit knowledge and implicit knowledge. In this phase, network analysis begins to appear. The topic words within both networks are closely interconnected. In the take-off phase, the knowledge network has a structure similar to that in the previous phase. This topic has fewer topic words but two new ones: patent application and pharmaceutical industry. The pharmaceutical industry is the most popular case industry in the research about knowledge network. Technological knowledge disappears in the stable-development phase but shows again in this phase.

3.2.3. Economic growth & climate change

Although economic growth and climate change are two different topics, they have deep connections between each other. So we analyze them together in this part. Economic growth is a traditional topic, it emerges in the oscillating-development phase and grows fast in the stable-development phase. And in the take-off phase, economic growth combines with climate change as one topic. Economic growth brings so many dilemmas. For example, blind development of the economy could lead to environment pollution and the climate change. Climate change is one of the most important issues caused by economic growth in the TIM field. And climate change appears in the stable-development phase and also has a connection with energy. Environmental problems have constituted great challenges for sustainable economic development (Zhang *et al.*, 2016), so economic growth & climate change is a hotspot.

In the emergence phase, economic growth & climate change includes economic growth, economic development, economic activity, sustainable development, and developed country. Among them, economic growth is the most frequent core topic word that appears 111 times. In the oscillating-development phase, there appears also a small part of papers dealing with the topic economic growth, with developed countries especially those with the European Union as the most frequently studied subjects. There is a strong relationship between economic growth, technological development, and government policy. The development of technology drives the growth of the economy. In the stable-development phase, economic growth & climate change has two new central topic words: economic benefit and economic performance. In the take-off phase, economic growth and climate change combine into one macro-topic, which means their link gets closer. This topic has many important topic words: energy consumption, carbon emission, sustainable development, and green innovation. These topic words serve for green innovation. Green innovation is growing fast and getting more important in the TIM field (Schiederig *et al.*, 2012). Due to rigorous environmental, climate, and energy issues, this topic will continue to be popular.

3.2.4. R&D

R&D is a traditional and important topic in the TIM field. R&D represents research and development. Its main part is general R&D; aside from traditional R&D activity, science research also becomes active in the stable-development phase. In the take-off phase, another new topic: R&D organization is separated from general R&D.

In the emergence phase, R&D organization, industry R&D, scientific publication, and R&D project appear, and most of these topic words remain popular in the subsequent phases. In the oscillating-

development phase, R&D-related activities in research are more and more diverse. The most common topic words are R&D project, R&D organization, and R&D activity. Among them, industrial sector, public sector, and private sector are three important sectors. In the stable-development phase, science research splits from R&D and becomes active. The public sector and private sector remain to be well studied, research councils and public research organizations are two new organizations. Science research is given great attention, scholars get to know the role of science in promoting technology. Research gets to explore social science, life science, and science policy. Basic research, which is different from applied research, is gradually recognized for its crucial effect on the TIM field (Henard & McFadyen, 2005). In science research, peer review is the common method. In the take-off phase, R&D project is the most popular word in the general R&D. And R&D activity, academic R&D, and R&D collaboration are also important. This topic cares about industry-university collaboration, scientific research therefore appears frequently in this topic. In scientific research, social science remains popular. Although intersectoral collaboration grows fast, universities are still at the center of knowledge production through scientific research (Hessels & Van Lente, 2008). In the take-off phase, R&D organization is independent of general R&D and becomes a macro-topic. In the R&D organization network comprising five nodes labeled as R&D organization, public research organization, public R&D, private sector, and public sector, there exists a dense interconnectivity among all pairs of nodes except for the absence of a direct edge between nodes public research organization and public sector.

3.2.5. Innovation policy & innovation system

Innovation policy and innovation system are two topics, but they have often been examined together since the oscillating-development phase. The research about innovation policy and innovation system can be traced back to the emergence phase. These two topics are classic topics in the field of TIM and have maintained a certain degree of popularity throughout the four phases. At the same time, the topic innovation policy is discussed more frequently than the one innovation system.

In the emergence phase, technology policy is the most important topic word. Technology policy related topic words are innovation policy, research policy, public policy, government policy, policy maker, and policy implication. In the oscillating-development phase, innovation policy and innovation system remain important. In this phase and the next phase, the topic words connect more with each other. Innovation system splits into regional innovation system and national innovation system. Innovation system and innovation policy got closer in the take-off phase. In this topic, European countries and the European Union are the most studied subjects. Data envelopment analysis (DEA) and comparative analysis are the most used methods in this macro-topic. Data envelopment analysis is a linear programming-based technique for measuring the relative performance of organizational units where the presence of multiple inputs and outputs makes comparison difficult (Boussofiane *et al.*, 1991). The comparative analysis method is a very common method in many fields. In the TIM field, this method makes it easier to explore why other countries or firms win innovation success (Trajtenberg, 2001).

3.2.6. Intellectual property

Intellectual property is a topic that mainly contains intellectual property, technology transfer, and knowledge transfer. It becomes an independent macro-topic in the stable-development phase. In the take-off phase, technology transfer and policy maker become the biggest topic words. They surpassed intellectual property. At the same time, entrepreneurial ecosystem has become a new trend.

Intellectual property becomes an independent macro-topic in the oscillating-development phase,

repeatedly appearing 119 times. It is well connected with technology transfer and knowledge transfer. At the same time, public policy and other social changes affect the environment for technology transfer (Bozeman, 2000). So policy implication has become important in this topic. When this topic becomes dependent in the stable phase, its words connect to each other more closely. In the take-off phase, higher education and technology transfer are two important issues. The United Kingdom is just as popular as usual in intellectual property activities. But different from the UK, South Africa has become a research hotspot for its catch-up (Morrison & Rabellotti, 2017). And its related academic entrepreneurship begins to give great importance to higher education (Mars & Rios-Aguilar, 2010).

3.3. Topic evolution of product research

Product research is the most typical topic cluster in the TIM field. It has a long and deep impact on the TIM field. The most important three topic words are new product, product development, and new product development, which always appear at the center. In fact, in the TIM field, compared with other topic clusters, *product research* takes the lead in the process of maturity. In the emergence phase, *product research* is located in the center of the cluster. It connects to *technology research, firm research*, and *future research.* Then *product research* becomes bigger and connects with other topic words closely in the oscillating-development phase. Internal topic words connect with each other, forming a more complex network. This means that this macro-topic gradually becomes mature. New product, product development, and new product development are three core words in this phase. Then *product research* splits into three macro-topics, the first is basic new product development, the second is product innovation, and the third is product project and team. *Product research* has clearer partition results. Product innovation has more topic words, its nodes are highly related to market. New product development has a smaller network, but the above three core words still appear in high frequencies. Product project and team form a small network but every node has a connection with each other. Product innovation moves to *firm research* in the take-off phase, it is often used with manufacturing firm, just as seen in the paper *Absorptive capacity, coopetition and generation of product innovation: Contrasting Italian and Portuguese manufacturing firms.* In the take-off phase, product research suddenly decreased in frequency and only four topic words are above the threshold of 50 counts. Although the topic word new product appears 355 times, product development appears 211 times, and new product development appears 155 times, all smaller than the corresponding frequencies in the previous phases, they are still researched frequently. The topic evolution can be seen in Fig. 9.

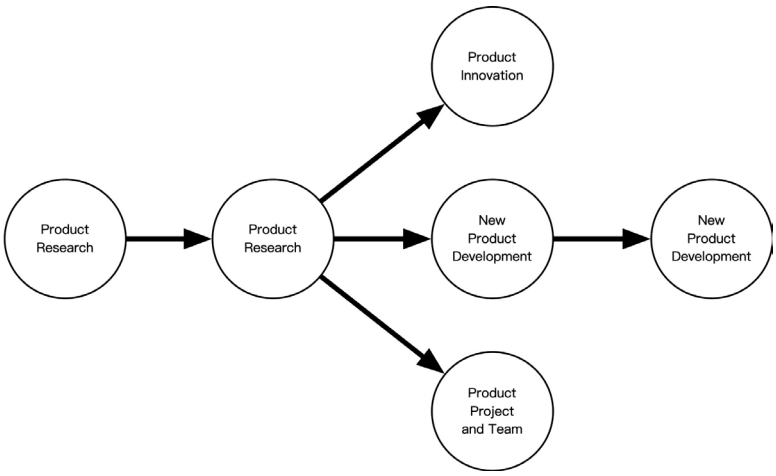

Fig. 9. Topic evolution of product research.

3.4. Topic evolution of firm research

Firm research is mainly about empirical research for industry, firm, and innovation. Its evolution path is shown in Fig. 10. Empirical research is important for the TIM field. Through analyzing some firms' success or failure, useful advice can be given to other firms' decision-making processes. In the oscillating-development phase, research is conducted mainly in the empirical research for industry and firm. And then in the stable-development phase, research splits into four parts. The first is empirical research for firm, the second is innovative process, the third is R&D for firm, and the fourth is high technology. In the take-off phase, these four topics intersect with each other to form three new topics: empirical research for innovation activity, innovation performance, and manufacturing firm's innovation.

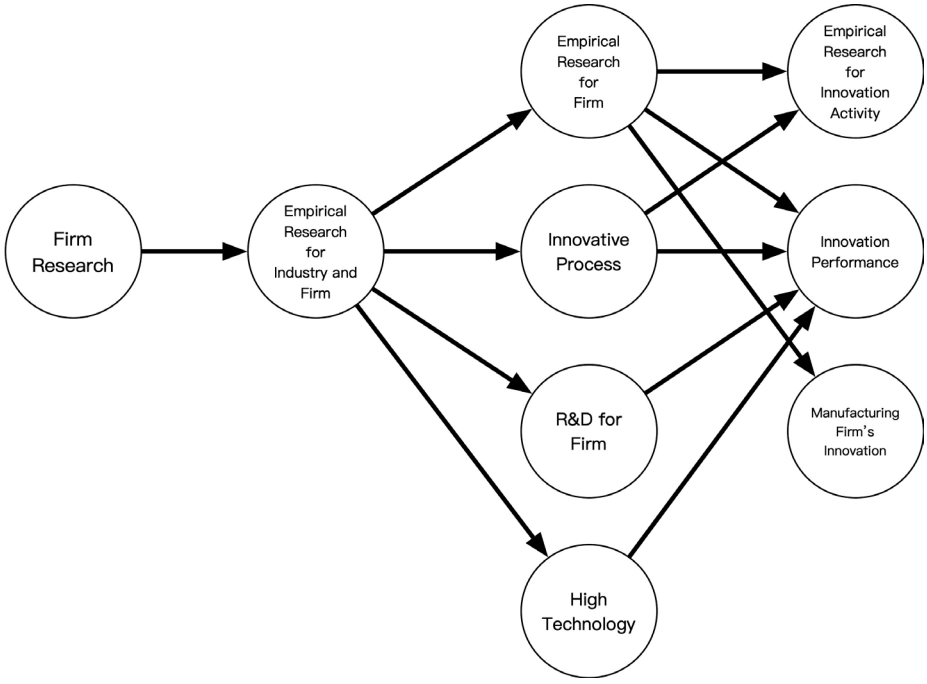

Fig. 10. Topic evolution of firm research.

In the emergence phase, *firm research* is a little bit small, it only has two clusters and nine topic words. The bigger micro-topic is technology firms and high technology firms, it is connected with *product research*, and even has the related topic words: product quality and software product. The smaller micro-topic is mixed with market, trade, industry, and firm. The most researched firm is the Japanese firms, and the industry researched is the machine tool industry. The machine tool industry helps the development of *firm research*. Market and trade are two important parts of firm activity.

In the oscillating-development phase, the manufacturing industry and firms are paid great attention. The electronic industry has also been studied many times. Firm size is a common topic word. The research varies from small firms to medium enterprises, and then to large firms. In particular, the biotechnology and pharmacy industry and firms have received much attention from scholars. R&D investment, R&D expenditure, and R&D intensity are the most used R&D-related words in this topic. Empirical research for industry and firm can help to find the reason why a firm can succeed or fail in a specific industry. Japanese firms got attention in this phase because before the 1990s, Japan started its path to innovation

and it succeeded (Oshima, 1984). So in this phase, scholars started to find the secret for Japanese unique success. Therefore, many scholars took Japanese enterprises as empirical objects and attempted to analyze the internal and external reasons for the rise of Japanese enterprises in certain fields.

In the stable-development phase, *firm research* has gradually received more and more attention from scholars. It has four macro-topics: empirical research for firms, innovative process, R&D for firm, and high-technology. Empirical research for firms still pays attention to the firm's size. Firm level is a commonly used topic word, it even appears more often than firm size. In the oscillating-development phase, the manufacturing firm holds its popularity, the electronic industry doesn't appear in this topic, and service firm begins to be concerned. Innovation process, innovation performance, and innovation activity are the three most significant topic words in this macro-topic. These three topic words are well connected with each other. Open innovation began to be popular in this phase. It appears 290 times. The topic Chinese firm has been one of the hottest topics in the TIM field. The topic words in this macro-topic are deeply connected with innovation, most of them have "innovation" in their terms. In the oscillating-development phase, the topic R&D for firms only has three topic words. In this phase, R&D intensity, R&D investment, and R&D expenditure kept their popularity. R&D activity, firm R&D, and internal R&D also appear in this phase. The topic word manufacturing sector manifests in this macro-topic, indicating that manufacturing firm has a great impact in this topic cluster. High-technology research is a traditional macro-topic. In the emergence phase, the topic word high-technology firm has appeared. Because of the development of technology and society, the world needs high technology to solve difficult problems. So this topic are needed for a long time. Biotechnology and pharmacy are two typical industries that need to be well and carefully treated. Since the oscillating-development phase, they have been researched as high-technology objects.

In the take-off phase, *firm research* is a topic cluster that has been showing a good development momentum. The latest phase has three macro-topics: empirical research for innovation activity, innovation performance, and manufacturing firm's innovation. In this phase, scholars target their empirical research directly towards innovation. They care about innovation activity, innovation process, and open innovation. Through empirical research, many useful suggestions about innovation are proposed to help other firms learn successful experiences. Different from innovation activity and innovation process, open innovation is a latecomer hotspot. Open innovation is affected by many important technological, organizational, and societal changes, then it has matured (Dahlander *et al.*, 2021). This macro-topic gets two new topic words: incremental innovation and radical innovation. Incremental innovation and radical innovation are two different innovation types, they are different in the complexity and newness of the embodied knowledge against the context of open innovation (Kobarg *et al.*, 2019). It is worth noting that the development of service firms and service innovation reflects that with the improvement of people's living standards, people have higher requirements for the quality of service received. In the topic of innovation performance, firm size and firm level are also two important issues. Firm size pays close attention to the two topic words large firm and small firm, yet the topic word medium firm doesn't appear in this macro-topic, which is close to firm performance. At the same time, the topic word medium enterprise is more common than medium firm in the TIM field. In this phase, the topic word Chinese firm appears, signaling the development of Chinese firms. Another reason is that Chinese scholars have started to publish more papers in these top journals, and they tend to use familiar national firms for research. There are two important terms in the TIM field: inverted u-shaped relationship and moderating effect in the current phase. Manufacturing firms' innovation becomes a dependent topic. The topic word

family of the manufacturing firm includes manufacturing sector and manufacturing firm. The second important topic word is product innovation, which is moved to *firm research* from *product research*. The closer distance to *firm research* means that product innovation is not only independent of the product but integrated with firm performance.

3.5. Topic evolution of future research

Future research is a stable topic cluster in the TIM field. It nearly shows no increase and decrease trend, and this means it has always been popular. The topic evolution can be found in Fig. 11. In the emergence phase, the biggest one is future research, and three topic words are related to it: public goods, alternative future, and social science. Future research appears 58 times, which is the second biggest topic word in the first phase. Future research is popular because the journal *Futures* to some extent develops early. *Future research* splits into four topics: competitive advantage and information technology (IT), future research, technology management, and business success. In the stable-development phase, competitive advantage and IT have given birth to another topic: decision-making. The other three topics remain its main body. The topic word decision making belonged to *technology research* before, it was often used with policy and knowledge. For example, *Ex post evaluation: A more effective role for scientific assessments in environmental policy is from technology research* and *Cognitive benefits of scenario planning: Its impact on biases and decision quality is from future research.* Technological forecasting is a core topic word in *future research*. Business success gradually expands to include business and venture because more topic words related to venture emerge. In the take-off phase, technological forecasting splits into three topics: digital innovation, technological forecasting, and disruptive innovation. The other topics all disappear in this phase, except for business and venture. The topic business and venture further turns into business model, and competitive advantage moves to *firm research*.

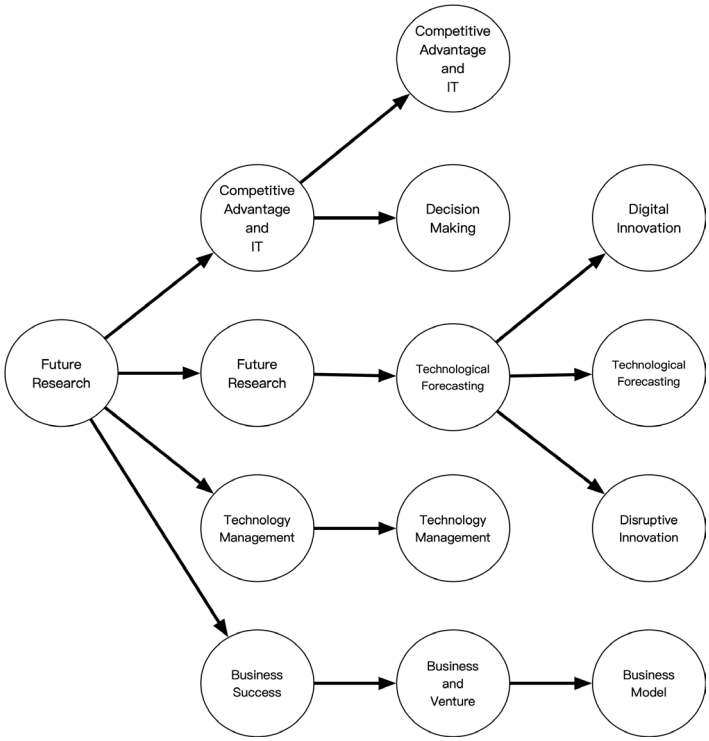

Fig. 11. Topic evolution of future research.

3.5.1. Competitive advantage and IT

This topic makes its appearance in the oscillating-development phase and the stable-development phase. The formulation of future technology trend strategy is conducive to maintaining the core competitive advantage of enterprises (Nazemi *et al.*, 2022). Except for business strategy, technology strategy, strategic planning, strategic management, competitive advantage, and core competence are important elements for the future. Information technology belongs to the *future research* in the middle two phases but belongs to the *technology research* and *firm research* in the emergence phase and take-off phase respectively. In the emergence phase, it connects with technology policy and the automotive industry. Organizational learning is a commonly used topic word in this topic and appears 95 times in the oscillating-development phase. Organizational learning is a way to achieve competitive advantages for firms (Hong, 1999). It is considered a process of knowledge creation and is determined by the interaction of stocks and flows variables (Real *et al.*, 2006). In the stable-development phase, information technology in this phase gets a fast speed for development. Powell and Dent-Micallef find that ITs alone have not produced sustainable performance advantages in a specific industry, but that some firms have gained advantages by using ITs to leverage complex human and business resources (Powell & Dent-Micallef, 1997). At the same time, there is a cluster for organizational learning, organizational structure, and organizational capability. ITs that act as the enabler of organizational learning play an important role in technological distinctive competencies (Real *et al.*, 2006).

3.5.2. Technological forecasting

Technology forecasting is obviously an important issue in the TIM field. It becomes a dependent topic in the stable-development phase. Its studies are systematic investigations into the future development and application of technologies (Wissema, 1982). In the oscillating-development phase, the topic word technology forecasting appears in *technology research*. But now in the stable-development phase, it appears in *future research*. Technology forecasting connects with decision and strategy deeply, and it has become an important part of the national innovation system that supports national strategic decision-making. And in the take-off phase, technological forecasting is still the basis of this field. The bibliometric analysis method is a commonly used method in this topic. Digital innovation is a new research hotspot. Big data is one of the digital technologies that contributes to the development of digital innovation. The COVID-19 pandemic has become a special issue in this phase. The COVID-19 pandemic is a public health emergency, it has a broader impact on human beings as to all kinds of work that humans do. The COVID-19 pandemic has changed people's views about the future (Komonen & Seisto, 2022). The impact of the COVID-19 pandemic on the TIM field is explored and it is found that COVID-19 pandemic changes many aspects. The first aspect is organizational design and work practices, the second aspect is collaboration, creativity, and innovation, the third aspect is social contagion, digital transformation, and speed of adoption, the fourth is research infrastructure for innovation, the fifth is industry disruption and emergence of new technologies and business models, and the last is distributional consequences of innovation (George *et al.*, 2020). In our research, the COVID-19 pandemic is written with digital innovation and technological forecasting together, which correspond to the third and fifth aspects. As for disruptive innovation, blockchain technology and 3D printing are regarded as two important disruptive technologies now. Blockchain technology is a decentralized digital ledger that facilitates various types of peer-to-peer value transfer, from digital currencies to physical goods and land ownership, without intermediaries (Frizzo-Barker *et al.*, 2020). 3D printing, a method of stacking materials on top of each other

to create three-dimensional objects, is subversive in that it breaks through the limitation that traditional printers can only print two-dimensional objects (Schubert *et al.*, 2014).

3.5.3. Technology management

Management basics include innovation management, technology management, knowledge management, quality management, and strategic management. The management of relevant things such as technology and knowledge can help firms achieve greater advantages in the future. And it decreases in the stable-development phase. Among these topic words, R&D management and technology roadmap are useful tools for strategy planning and technology management (Featherston *et al.*, 2016; Kerr *et al.*, 2012).

3.5.4. Business model

Business is another important topic in the TIM field. In the oscillating-development phase, business success is an important topic word. In the stable-development phase, the topic can be analyzed that through the creation of value, the integration of new capital, the proposal of new technology, and the expansion of new business, the further improvement of the value chain is promoted. Open source software guides to a new generation of information technology innovative development. And in the take-off phase, business model has a clear but deep connection in its network. The business model is studied most and the next is value creation.

3.6. Research trends in the TIM field

As the evolution analysis above shows, *technology research* is a well-developed topic in the TIM field. In the future, it will also have a certain scale of papers. *Technology research* is closely integrated with the development of society. So when the real world changes, the most sensitive topic is *technology research*. *Technology research* has expanded to many topics. These topics such as climate change and technological change are extremely popular in the academia. Others are traditional topics and will remain popular. The economy and climate will be researched together for a long time because of the results of climate change. And sustainable development and energy issues will also be further studied. The research object in the field of technology is no longer limited to developed countries, developing countries such as China and South Africa are beginning to receive attention.

Product research is a mature but decreasing topic in the TIM field. Although there is a decrease in *product research*, research about new product development will remain to be discussed for a long time. Firms will continue their efforts on new product development. So there will also be much research about *product research*.

Firm research is a fast-increasing topic in the TIM field. This empirical research about firms and innovation will be more popular. This topic has a strong interactivity. Among them, open innovation is obviously an important topic and will be studied more. With the continuous opening of information and the increase of firms, there will be more and more empirical studies on firms, and the research methods and perspectives will become more and more diverse. Managers will care more about innovation performance and firm performance.

Future research is a small but important topic in the TIM field. Although it occupied a small part, it has kept its size for all 55 years. *Future research* itself is an important topic. Technology forecasting and future planning are two main studies in the work of firms and government. So technological forecasting as the main body of *future research* will still be the most important topic in *future research*. It is worth noticing that digital innovation will develop fast and become more and more important.

4. Conclusions

This research explores the technology innovation management (TIM) field. The topic evolutions and research trends are revealed, so a better understanding of this field is obtained, and advice for better development is proposed. Given topic evolutions and research trends in the TIM field, this paper's retrospective look provides a glimpse of where the field is, and it can provide important information about where the field will be. The TIM field has developed fast from 1968 to 2022. It can be divided into four phases: the emergence phase, the oscillating-development phase, the stable-development phase, and the take-off phase. The TIM field has four topic clusters: *technology research, product research, firm research*, and *future research*. These four clusters all have great contributions to the TIM field. They will continue to support the TIM field and play important roles in it.

Technology research connects and changes with society deeply. It has been the most important topic in the TIM field. It mainly has four topics: policy, economy, technology, and R&D. Among them, technology has more micro-topics. It splits into climate change, innovation system, technological change, knowledge research, network analysis, and intellectual property. These topics, except for climate change, remain important and independent in the take-off phase. Climate change combines economic growth and they become a unified topic. In the take-off phase, this topic cluster is influenced by Industry 4.0, thus obtaining intelligent development, climate change and green innovation, higher education, and university-industry cooperation. As for R&D, it has two topics. In addition to general R&D, scientific research is also a popular topic. In the take-off phase, R&D organization is also singled out as a dependent macro-topic. As for policy, it is a traditional topic. It always keeps its size and connects with innovation system deeply. The research on technology related to social and environmental changes should be advocated, and the corresponding research will continue to expand and enrich the TIM field.

Product research is a relatively mature topic cluster in the TIM field. From the beginning of the TIM field development, product innovation has always been the most basic and hottest topic. In the stable-development phase, it has the most diverse topics: product innovation, new product development, and product project and team. But with the development of other topic clusters, the research about product is reduced. In the take-off phase, it only has four topic words: new product, product development, new product development, and innovation capability. However, the size of the topic words is still large. Research about products should continue to keep the *product research* as the basis of the TIM field.

Firm research is a developing topic cluster, it has a trend of increasing. It is conducted mainly about the empirical research for industry, firm, and innovation. The oscillating-development phase has four topics: empirical research for firm, innovative process, R&D for firm, and high technology. These topics are very interactive and are integrated into three topics: empirical research for innovation activity, innovation performance, and manufacturing firm's innovation in the take-off phase. In recent research, open innovation has been given great attention. *Firm research* will expand its research because of more excellent firms and their innovation experience.

Future research is stable for it nearly has neither increased nor decreased in its size. Technological forecasting is the core topic in this topic cluster, it is a fast-developing micro-topic. And in the take-off phase, it splits into three topics: digital innovation, technological forecasting, and disruptive innovation. Among them, digital innovation is the most popular topic in this *future research*. Competitive advantage and information technology occupy a prominent position in the developing phase but lose their popularity in the take-off phase. The same also happens in technology management. Business-related

research is also a basis for *future research*. It develops from business success, business and venture to business model. As a typical research, *future research* will keep its research size and popularity.

Through this study, industry professionals, policymakers, and researchers can shape their strategies, policies, and future directions. For industry professionals, paying attention to the evolutions of topics and trends in technological innovation management is a core task. Only by continuously adapting to changes can organizations ensure long-term competitiveness. First, they need continuous research and observation, only with a good understanding of the development status, can they make the correct environmental assessment and risk assessment. Second, the research can provide clues about future trends. Thus, it is worthwhile for collecting and analyzing topic evolutions to understand potential market needs, competitive advantages, and opportunities. Third, given the rapid changes in technology and management, establishing strong collaborative relationships with partners, suppliers, or customers can be more effective than acting alone. Finally, in addition to tracking current trends, efforts should be made to predict future technological and management trends. This requires deep market understanding, long-term observation of the industry, and extensive industry experience.

For policymakers, paying attention to the evolutions of topics and trends in the TIM field is crucial when formulating policies. By using effective policy tools, technological innovation and management performance can be promoted, fostering industrial development and enhancing national competitiveness. First, through our research, policymakers can track the latest developments and trends in the TIM field. It is essential for them to clarify policy objectives and make suitable policies. Second, the topic evolutions and research trends can help them assess existing policies and understand which policies are effective and which ones need to be adjusted or improved.

For researchers, by deeply studying historical evolution, focusing on current hot topics and frontier issues, exploring interdisciplinary research, as well as continuously self-renewing and learning, they can determine their future research directions. First, it is essential to understand the historical evolution of the field. This decides the basic knowledge base of researchers and helps researchers to catch the frontier issues. Second, the TIM field involves multiple disciplines. By exploring the intersection between different disciplines, researchers can discover new research opportunities and directions. Finally, for researchers, it is necessary to continuously monitor the dynamics and development in the field, and constantly learn and update their knowledge system.

This study has explored the effects of the leadership transfer network structure on the performance of environmental policy diffusion. By regression analysis, we verified the hypothesis that municipal centrality and municipal structural holes in the municipal leadership transfer network have an inverted U-shaped relationship with the environmental pollution index. Furthermore, provincial centrality and provincial structure moderate the double inverted U-shaped relationship in such a way that the curves are steeper in cities with high provincial centrality or provincial structural holes than in cities with low provincial centrality or provincial structural holes.

This study adds to the diffusion literature by expanding the practice of policy diffusion using social network analysis. Most previous research on policy diffusion focuses on the diffusion mechanism and its corresponding empirical tests. The emerging research has begun using the social network analysis method to describe policy diffusion through the overall characteristics of networks. Research on how network structure indicators affect policy diffusion is widely neglected. However, network structure as a perspective is more consistent with contemporary theoretical viewpoints, which see policy diffusion processes as complex systems requiring investigation of their interdependent relationships rather than

their independent components. As a result, the social network analysis method is required to elucidate the effect of relationship network structure on policy diffusion.

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