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Research Article

Dynamic Development Analysis of Complex Network Research: A Bibliometric Analysis

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In recent years, the method of the complex network has been applied to various fields. Dynamics research in complex networks is also an important branch. There are many types of research into dynamic complex network, but few scholars use bibliometrics to study it. Therefore, this paper adopts the method of bibliometrics to analyze the development history and status quo of dynamic complex network, providing a summary description of this research field. We used CiteSpace and Pajek to analyze 2936 relevant papers on the website of Web of Science and further interpreted and summarized the analysis results. To fully show the bibliometric results, we further derive the productive countries, institutions, sources, and authors and some main research directions in the dynamic complex network research. The research results show that the dynamic complex network research method was applied to various fields after the dynamic research method had been integrated into the complex network. According to the subject analysis of the cited papers, we find that the dynamic complex network method has been widely used in various subjects. Through emergent analysis, we found that the latest hot research trends are the study of infectious diseases and applications in neural networks. At the same time, through the main path analysis, we find the essential literature to elaborate on the development context of a dynamic complex network at different time points. This paper gives a comprehensive analysis of dynamic complex network research and provides some enlightenment for the future research direction.

1. Introduction

Since Euler, a mathematician in the 17th century, put forward the "Konigsberg Seven Bridges," related theories about complex networks have begun to take shape. The Seven Bridges problem abstracts land and bridge into points and sides, and the connection between points and sides constitutes a simple network structure. In the last ten years, from the analysis of small network graphs to the study of the large-scale complex network, the study of networks attracted more and more people's interest. Nowadays, the complex network has been widely used in various disciplines. It is a general method of representation of the complex system, which is mainly used to simulate a complex topological system composed of many nodes.

The first essential discovery of a complex network was the ER stochastic network model proposed by Erdos and Rényi in the mid-twentieth century [1]. This model makes it possible to use graph theory and probability statistics theory to analyze large-scale networks, which opens the door to a new research field, stochastic network theory.

As a significant branch of complexity science, the research on complex network theory steadily deepens, and its application field is gradually expanded. Nowadays, complex networks generally refer to networks with nontrivial topological characteristics. Unlike traditional networks, complex networks are characterized by lattices or random graphs. Typical examples are nervous systems, metabolic networks, ecological networks, power grids, and wireless communications [2–6]. A lot of scholars focus on the formation mechanism, evolution

law, and dynamics of complex networks, which have formed the intersection school of complexity research, system dynamics school, chaos theory school, adaptive systems school, and structure school. The application of social network analysis is also a hot research direction at present [7]. In the social media [8], the social networks [9, 10], and the information dissemination [11], scholars explained a series of issues such as the logical relationship between complex networks and reality. At the same time, scholars also carried out in-depth research on the mechanism and practice of complex networks. The co-integration of information transmission and behavior in social ecology has become a hot research direction [12]. Lu and Chen [13] briefly analyzed the work on complex networks prior to 2009. In recent studies on complex networks, Zhou et al. [14] reviewed the main advances in the analysis, control, and application of complex networks in the past decade. They summarized the basic analysis methods of complex networks and their applications in different fields. Holme [15] believed that the network approach can simplify the complex system so that people can better understand its overall function.

However, the complex network is not static, just as cells in our brain's nervous system are constantly changing. The complex network also shows the same small-world effect and scale-free distribution with high aggregation [6]. At the same time, it has different characteristics in the dynamic evolution process [16]. In this case, how a complex network shows the dynamic balance of these characteristics is often affected by the age of nodes and the cost and capacity of adding connections. Broomandi et al. [17] used a dynamic complex network to analyze PM2.5 concentration in the UK and used layered digraph analysis. In a one-year study, this paper found that the relative change of PM2.5 concentration in the urban background from sparse network data was determined by meteorological conditions and emissions from regional sources. Some scholars have also studied the application of complex systems; for example, Borgnat et al. [18] learned the community bike-sharing system by establishing a complex network system and Aplin et al. [19] explored the generation conditions and mechanism of civilization norms. In these studies, cultural integration is regarded as the critical factor of the human complex system.

Since it can represent the relationship between the complex systems in a relatively complete way, the complex network has attracted more and more attention in various fields. Bibliometric analysis is a scientific literature analysis technique, which can be used to analyze the literature in the selected area through the metrology to get the development information of a particular field. Zhu and Guan [20] used the small-world theory of network to analyze the service innovation and found the study status and hot spots in service innovation. Based on the analysis of 437 papers retrieved from the Web of Science database from 1992 to 2011, the authors explored the knowledge structure of this field and found the most popular keywords, which also showed the dynamic change in research hot spots. Then, complex networks have been applied to many areas, especially ecology. Borrett et al. [21] systematically reviewed the studies published in ecological network analysis from 2010 to 2016, using a combination of bibliometrics, networks, and feature analysis to establish 8 subject clusters from the bibliographic records, and the analysis identified 387 authors in a collaborative network consisting of eight more significant components. Finally, it is concluded that ecological network analysis is a diversified collective scientific field, and further development of ENA is proposed to better solve the problems of theoretical ecology and environmental impact assessment and management.

In the following years, complex networks, especially social networks, became an important method to study social problems. Wang et al. [22] aimed to discuss international talent flow and its negative and positive factors through bibliometric methods. Wang modeled the complex network of international talent flow using Scopus bibliometric data, established corresponding network indicators, and introduced improved multiple linear regression gravity models. The reasons explaining global talent flow are identified. The research results can provide a theoretical basis and policy suggestions for further research on cultivating, attracting, and retaining global scientific and technological talents.

Some scholars use the method of bibliometrics to study the complex network and its related application fields. Zhang and Zhou [23] analyzed the literature on complex networks retrieved from WoS data source. They analyzed the research status and development trend of this field using methods such as bibliometric analysis and visual analysis and presented the research status and development trend of this field in detail. The results show that the research of complex networks has entered the stage of vigorous development and some research directions have become mature. Future research directions may focus on the algorithm analysis and design of complex networks, dynamics research, and structure recognition. The popularity of social network analysis has improved our ability to test hypotheses about complex animal social structures. Webber and Vander [24] systematically surveyed the literature and used social network analysis to extract information about publishing trends from the literature. At the same time, the authors also gave some guidance on future research directions. We find that studies using bibliometrics methods mainly focus on traditional complex network methods. For some emerging complex network research, such as dynamic complex networks, scholars have not used the method of bibliometrics to systematically elaborate.

Meanwhile, some scholars analyze dynamic complex network research from different perspectives and fields, but few try to explore the mapping knowledge field of dynamic complex network research. Most of the research field changes over time, the application of a dynamic complex network of research methods and fields has been widened, and the intersection of different disciplines related to research also gradually came to the attention of the scholars. Therefore, it is necessary to analyze the present situation and the emerging trend in these areas in a productive way. From the perspective of bibliometrics, the results obtained using CiteSpace software are more comprehensive and intuitive, so CiteSpace is one of the most popular bibliometrics tools [25, 26]. CiteSpace can mine the information we need for a specific topic with

relatively simple operation steps from the massive literature data, including the knowledge base of the research topic, the corresponding discipline structure, and the latest research frontier. Using this analysis software, we can capture the information we want from the vast literature, and make a deep analysis of our research field based on this information.

From the above analysis, we can see that the theoretical analysis and the specific application of dynamic complex network have been gradually improved. However, regarding these studies, scholars have not carried out a comprehensive summary to elaborate on the development context of dynamic complex network research. In addition, we have learned some useful information about dynamic complex network research to help beginners understand the field. Therefore, the purpose of this study is to fill the gap between scientometric analysis and dynamic complex network research. We hope that, through the research of this paper, we can discover the past and present of dynamic complex network research.

Therefore, this paper uses CiteSpace and Pajek to analyze all relevant articles downloaded from the WoS website. Based on the statistics of keywords, authors, countries, cited literature, and main development paths, the corresponding charts are given, the general situation of dynamic complex network research is introduced, and some enlightenment is provided for the following research direction of scholars.

To achieve the above objectives, this paper is organized as follows: Section 1 mainly introduces the basic quantitative analysis methods; Section 2 analyzes from the levels of publication, country, institution, and author and obtains the basic information of this research field. In Section 3, the special econometric analysis method is used to introduce the research status, research emphases, and premature and hot issues expounded on the application of sudden detection in dynamic complex network research. We point out the potential research direction in Section 4. In Section 5, the main path analysis is used to review the development path of related research in the dynamic complex networks, and the important node literature is reviewed and analyzed. Finally, Section 6 is the conclusion summarized based on the above analysis results.

2. Basic Bibliometrics Analysis in Complex Network Research

Before applying CiteSpace for analysis, we need to build the database for analysis. In addition, we will analyze production countries and regions, institutions, hot issues, and research trends. Furthermore, we will also dig into the keywords and breakout point fields in the papers related to dynamic complex networks. Finally, the visualization is performed based on the above data.

2.1. Building the CiteSpace Database. There are two steps to build the data analyzed using CiteSpace. The first step is to select the database, which should contain all relevant literature and include the use of a co-cited network represented by references to selected articles. Among them, valuable information about the knowledge connection between each theory and concept is generally reflected in its references [27], which fully displays the knowledge map of a dynamic complex network and visualizes its evolution and development process. More specifically, this section introduces influential institutions and papers. On this basis, the authors analyze the research status of the dynamic complex network by using a co-citation network.

After selecting the database, we used CiteSpace to introduce the meaning of each map of the complex network. Firstly, we analyze the publications and citations in the complex network methods through the Atlas to observe the trend of publications and sources changing over time. Secondly, we use CiteSpace to study the evolution of dynamic complex networks. Evolution process analysis mainly includes the classification of knowledge clusters in the dynamic complex networks; identification of the main clusters in the complex network and dynamic analysis knowledge graph; and time dimension analysis of the source, development, and status of important keywords. Finally, burst detection refers to the value of variable significant changes in a relatively short period. By studying burst words, we can highlight the research hot spots in the field we want to study and the corresponding change trend. Below, we will introduce the detailed citation analysis process in dynamic complex network research.

2.2. Citation Analysis of the Dynamic Complex Network. We retrieved 2936 papers on dynamic complex networks from WoS according to the field we wanted to study. The literature has been filtered and irrelevant papers were excluded. In terms of time, we selected the period from 2011 to 2021. In recent years, complex network theory develops rapidly and is widely used in various fields. At the same time, we can grasp the future development trend of this field by analyzing relevant literature in recent years. Next, we will elaborate on our data sources.

Social Sciences Citation Index (SSCI) and Science Citation Index Expanded (SCIE) were downloaded from the Web of Science on December 31, 2021. Based on 2936 papers published from 2011 to 2021, the number of papers on dynamic complex network research published each year is shown in Figure 1.

In the late 1950s, mathematicians constructed a new network method to analyze some coplanar mathematical problems. Using this method, whether there is an edge between two nodes is not a certainty but a probability. The constructed networks are called random networks. By a probability to decide, mathematicians called this the generated network random network. In the next 40 years, it was considered by many scientists to be one of the best ways to characterize natural systems. Until the late 1990s, with the rapid development of computers' data processing and calculating capabilities, researchers found that many real networks are neither regular nor random networks, but the ones which own special statistical characteristics. These networks are named complex networks. The statistical characteristics are average path length, clustering coefficient, and degree distribution distinguish complex networks from

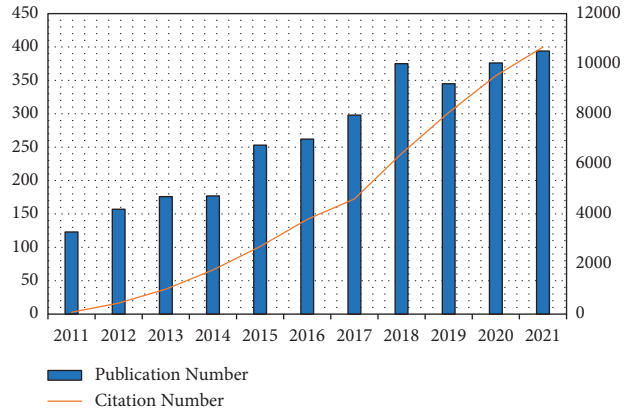

Figure 1: The number of publications about dynamic complex network research from 2011 to 2021.

the formers. They also enable complex networks in accordance with systems in the reality. They are a kind of networks with special statistical characteristics. Such networks are called complex networks. In recent years, the methods of the complex network have been developed and applied to various fields.

We selected references from the past decade to analyze the dynamic complex network method. The reason is that the dynamic analysis method of the relevant complex network was improved and gradually applied to various fields in the past decade. From 2000 to 2011, the dynamic complex network analysis method has not been widely used. Since 2011, the research method of the dynamic complex network has been gradually improved, and various variants have been derived and applied to multiple fields.

Figure 1 shows the number of published and cited papers on dynamic complex network research from 2011 to 2021. According to the number of publications in this research area, the quantitative chart of this paper can be divided into three sections. From 2011 to 2014 is a period of slow development of the dynamic complex network, and the number of published references increased slowly, maintained at about 170. Then comes the second stage, the stage of rapid development. During the four years from 2015 to 2018, the number of citations in this field increased rapidly. In 2015, the number of related citations increased rapidly from 177 in 2014 to 253, and in the following three years, it still maintained the momentum of growth, rising to 375 in 2018. The third stage, from 2019 to 2021, is a relatively stable period. The number of research papers in this field was stable at about 350 and reached 394 in 2021.

Several influential references were selected from the first stage, 2011–2014, to analyze the development of dynamic complex network research through specific literature.

Isella et al. [28] have opened new avenues for investigating the interaction of social networks, human mobility, and dynamic processes such as epidemic transmission. They analyzed the time-resolved data of personal face-to-face proximity in large-scale real-world scenarios. The authors tracked the behavioral networks of face-to-face proximity and extracted their representations from static and dynamic perspectives to reveal their similarities and differences. The authors also used pertinent data to study the dynamic field of the infection model of susceptibility to the spread of infectious diseases. Through the analysis of the transmission path, it is concluded that the static aggregation network will lead to the error of the dynamic network transmission path.

In recent years, Pastor-Satorras et al. [29] pointed out that the complex characteristics of the real-world networks have a profound impact on balanced and unbalanced systems. The study of epidemic transmission is the core of understanding the dynamic processes of the complex networks. The interaction of different units in physical, sociological, biological, and technological systems naturally generates complex network structures. Networks were the focus of research in the past decade, and considerable progress was made in the description of their structure and dynamic properties. However, few efforts have been made to study their dynamic controllability. This paper introduces and evaluates a dynamic process defined at the edge of a network and shows that the controllability of this process is quite different from simple node dynamics.

From epidemic prevention and control, innovation diffusion, viral marketing, and social movement to concept dissemination, it is a problem of great significance for finding influential communicators in the complex network [30]. These findings can not only guide the design of new power grid systems but also provide a deeper understanding of the dynamic behavior of social networks. Based on the above research, scholars have carried out further research and exploration. Pecora et al. [31] proposed that synchronicity is of central importance to power distribution, communication, neural network, and biological network. Many networks have been observed to have patterns of producing synchronous clusters. Through the combination of complex networks and neural networks, this paper proposes a new framework and development technology to analyze network dynamics.

In the second period, 2015–2018, the number of citations tended to explode. In the process of its rapid development, we extract influential and frequently cited kinds of literature and analyze how the dynamic complex network method is applied to various fields at this stage.

Leskovec and Sosic [32] described the Stanford Network Analysis Platform (SNAP) as a general-purpose, high-performance system that provides easy-to-use, advanced operations for the analysis and operation of an extensive network.

With the in-depth study of the Internet of Things, some scholars witnessed the intensive interaction and heterogeneous communication between different devices. The potential of the big data information generated on devices has been described as a specialized branch of the field known as "human dynamics." One of the papers proposes a new concept of Smart Buddy, focusing on the smart cities, ecosystems provided by wearable devices, deterministic human behavior, and big data of human dynamics [33]. Fosdick et al. [34] examined subtle but important decisions under configuration model specifications and examined the role these choices play in the graph sampling process and a set of applications. In particular, they emphasized the importance

of specifying appropriate graph labels (stub or vertex labels) to consider empty models; the choice closely links the study of random graphs to that of random contingency tables.

The third stage, 2018–2021, is a relatively mature stage of development in this field. Broido and Clauset [35] applied state-of-the-art statistical tools to databases made up of social, biological, technological, and information sources. The database is made up of nearly 1000 network databases. They tested the universality of scale-free structures, applied the power-law model to each degree distribution, and tested its statistical validity. They found that a scale-free network is sporadic, with only about 4% of the network showing a scale-free structure. Zhang and Wang [36] incorporated the influence of priority imitation rules into a social network infectious disease model based on the vaccine game. Their results showed that priority imitation of middle nodes could considerably improve vaccination coverage and thus significantly reduce the epidemic scale. This paper suggests that human behavioral responses are an important factor in communication dynamics. Huang et al. [37] established a two-layer network model to imitate the interaction between epidemic transmission and information competitive transmission. The results showed that knowledge diffusion can eliminate both rumors and epidemics, and knowledge plays a crucial role in the penetration intensity of rumors. Even when self-protection measures are not very effective, the penetration intensity of knowledge significantly increases the threshold of rumors and outbreaks. The results also show that when people have more connections in a communication-layer network, knowledge is more likely to spread widely and rumors and epidemics can be eradicated more effectively.

In this part, we divided the research on the dynamic complex network from 2011 to 2021 into three time stages according to the annual publications and citations of a dynamic complex network. In the three stages, we selected, reviewed, and analyzed the highly cited papers. We found that with time, papers on dynamic complex network research rarely appear with high citation frequency, but the number of highly cited papers is increasing. This shows that the method of dynamic complex networks is being gradually applied to different fields. The specific network structure and application methods are also changing with the change of different fields. Therefore, it is difficult to find them in some highly cited comprehensive papers, in spite of many highly cited papers with specific application scope in different fields.

2.3. Most Cited Countries and Regions in Dynamic Complex Network Research. In the analysis of the contribution to the research field, the more research results published by a country, region, or institution, the more outstanding its contribution to the research field. We can see that developed countries and regions tend to be more productive because the methods of dynamic complex networks involve mathematics, sociology, finance, and medicine, and the developed countries tend to do more in-depth research.

To analyze the characteristics of a dynamic complex network, we use CiteSpace to analyze the scientific cooperation network between countries and regions. According to the results of WoS and CiteSpace analysis, further discussion can be seen below. In recent years, scientific partnership has become more frequent, with many articles written by authors from different continents. Such collaboration can solve the problems of complex scientific and promote a variety of agendas [27]. Therefore, there should be more international cooperation to let researchers diversify their problem analysis.

The development of dynamic complex network methodology varies from country to country, and Figure 2 shows the 26 most productive countries and regions in this field. The United States is the most productive country in this field, followed by China, the United Kingdom, Spain, Italy, Germany, Japan, France, Australia, Canada, etc. The United States, China, and the United Kingdom have muscular strength in fundamental disciplines, being able to conduct in-depth research independently or form a complete cooperation system in this field.

2.4. Most Cited Institutions in the Dynamic Complex Network Research. On the institutional level, some organizations use the dynamic complex network approach to study real problems. Table 1 lists the ten most productive organizations. There are four in the US, three in China, two in the UK, and one in Germany. In the dynamic complex network research, China has three institutions in the top 10, ranking second among all countries. Generally speaking, the amount of research output is related to the number of research institutions, the amount of research funding, and the number of researchers in countries concerned with the application of dynamic complex network methods. In addition to China, we can also see that some other countries also pay high attention to the theory and application of dynamic complex network methods, such as the United States, Britain, and Germany.

The institutions represented in Table 1 contribute greatly to the overall development of research. As you can see from Table 1, four of the top ten productive universities are American, Arizona State University, Northeastern University, Boston University, and the University of Michigan. Arizona State University in the United States ranked first with 48 papers, while the Chinese University of Science and Technology of China ranked second with 42, six short of the first place. In terms of overall numbers, the United States is undoubtedly the most productive country in dynamic complex network research. The cooperation between various institutions often improves the development of academic research disciplines to a large extent.

2.5. Most Cited Sources and Authors in the Dynamic Complex Network Research. As shown in Table 2, the top 10 journal studies of the dynamic complex network were identified based on statistics from the WoS core corpus database. As can be seen from the results, Physica A: Statistical Mechanics and Its Applications published the largest number of papers in the field of dynamic complex network research, with 153 papers published, accounting for 5.229% of the total number of papers. Secondly, we find that Scientific Reports and PLoS

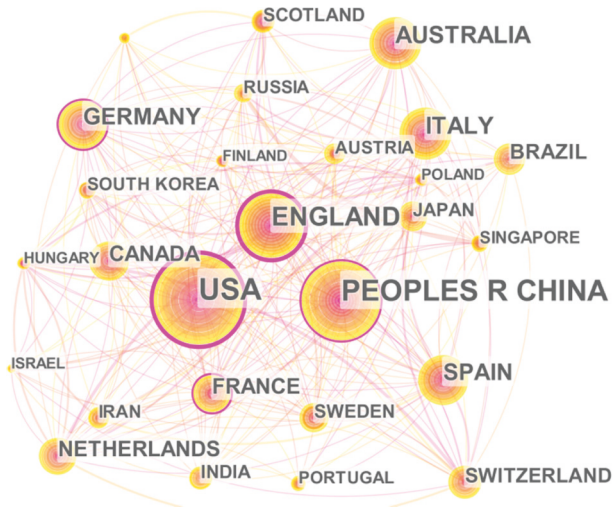

Figure 2: Top 26 production countries in dynamic complex network analysis.

Table 1: Top 10 productive organizations in dynamic complex network research.

Institutions	Publication number	The percentage of total (%)
Arizona State University (USA)	550	34.48
University of Electronic Science and Technology (China)	372	23.32
University of Oxford (England)	133	8.34
Chinese Academy of Sciences (China)	114	7.15
University College London (England)	104	6.52
Beihang University (China)	81	5.08
Northeastern University (USA)	70	4.39
Humboldt University (Germany)	55	3.45
Boston University (USA)	48	3.01
University of Michigan (USA)	46	2.88

Table 2: Top 10 productive sources in the dynamic complex network research.

Sources	Publication number	The percentage of total (%)
Physica A: Statistical Mechanics and Its Applications (Netherlands)	153	5.229
Scientific Reports (England)	94	3.212
PLoS One (USA)	93	3.178
Physical Review E (USA)	72	2.461
IEEE Access (USA)	56	1.914
Complexity (USA)	34	1.162
Proceedings of the National Academy of Sciences of the United States of America (USA)	30	1.025
New Journal of Physics (England)	27	0.923
Sustainability (Switzerland)	24	0.820
Expert Systems with Applications (USA)	22	0.752

One mainly focus on basic science, from which we can conclude that the research on the dynamic complex network has great prospects and potential for application in other fields. It can also be seen from Table 2 that among the 10 journals, more than half are published in the United States, and the rest are mainly in European countries led by the United Kingdom. Therefore, this also explains why the United States and the United Kingdom are the main contributors in this field.

It can be seen from Table 3 that Wang is ranked at the first one among the most productive authors in this field. He is also an experienced scholar with many research outputs that contribute to this field from theoretical and practical perspectives. In addition, we can also find that Wang L. and Wang W. have written many influential research papers in this field.

3. Special Bibliometric Analysis

3.1. Research Status Analysis of the Dynamic Complex Network. To clarify the research status of dynamic complex networks, this section summarizes the research focus and

Table 3: Top 10 productive authors in the dynamic complex network research.

Authors	Publication number	The percentage of total (%)
Wang Z	23	0.786
Wang L	21	0.718
Wang W	21	0.718
Moreno Y	18	0.581
Perc M	17	0.581
Wang Y	16	0.547
Xiao YP	16	0.547
Li Q	15	0.513
Lai YC	13	0.444
Li X	13	0.444

hot spots of dynamic complex network method. It analyzes the crucial courses, production sources, authors, countries, and institutions of dynamic analysis method of complex network and gives detailed explanations.

Co-citation methods are more reliable in providing important insights into knowledge domains than using citation analysis alone because citation-only analysis can rule out promising articles. The half-life of an article is defined as the years in which the article has been cited more than 50% of the time since its publication so that cutting-edge developments in research can be measured. As shown in Figure 3, we use the method of logarithmic likelihood ratio to conduct clustering and generate clusters in dynamic complex network research, where T is selected as the marker source. We generate the labels of the clusters based on the cited literature. Therefore, according to the cited references in the cluster and LLR algorithm, we distinguished 14 meaningful co-cited clusters. Hence, there are only 14 clusters in the cluster network, which is analyzed through threshold adjustment. Thus, we can see the main fields in the study of a dynamic complex network.

As Figure 3 shows, the label of each cluster represents distinct segments of the domain. Based on the literature we retrieved, we visualized the first 14 cluster labels. We find that each cluster has its different meaning and represents an area of study in dynamic complex networks. The evolving network is one of the hot areas of dynamic complex network research and has become a mainstream method to study social evolution. Cluster #2, complex network connectivity structure, represents the part of the literature mainly studying the connection structure of the complex network. There are several other cluster tags, from which we can find some characteristics of dynamic complex networks and the main genres of past and future research. Therefore, we can better systematically summarize the research in this field through this co-citation network. In addition, through this way of visualization, readers can better understand.

The number of publications is shown in the second column of Table 4. For example, cluster #2 has 71 members and is one of the largest clusters in dynamic complex network research, cluster #0 has 81 members, and cluster #1 has 72 members. In Table 1, we can see that the LLR value in the last column is the reliability indicator of cluster classification. If the score of this indicator is higher than 0.5, the corresponding clustering result is reliable. The LLR score values of the first 14 clusters range from 0.669 to 0.998, indicating that the members of each cluster are consistent enough and the cluster analysis results of these categories are reliable.

LLR value refers to a method to determine the maximum likelihood value according to the probability density function and find the most likely words. The index of mean (year) in Table 1 represents the average reference year for each cluster, which represents whether it is composed of the most recent documents or using older documents. Therefore, we can see from Table 1 that cluster #1 is made up of older documents than the other clusters. Similarly, cluster #10 "complex dynamical network" is a newly cited cluster with an average cited in 2013. Therefore, it can be assumed that the latest research topics on dynamic complex networks are "complex latency network," "evolving network," and "social trust." We can see that cluster 7 is the eighth cluster with 24 members. Cluster 1 is the "evolving network," with 72 members, which indicates that the research topic of the evolutionary network is more popular and valued. Global diffusion properties is the sixth-largest cluster, with 29 members, according to the LLR value. The above cluster classification further indicates the high quality of clustering analysis of dynamic complex network knowledge graphs.

In general, based on the Silhouette values in Table 4 and the color classification in Figure 3, we can conclude that the clustering results are reliable. The meaning of the color can be analyzed here. From the results of the cluster size and average year, the research topic "social trust" has more potential for further research.

3.2. Double-Figure Overlay Analysis in Dynamic Complex Network Research. The double-figure overlay analysis in a dynamic complex network is shown in Figure 4, which represents a wide range of subjects that this research method is applied to, including mathematics, computer, economy, politics, chemistry, and biology. In addition, over time, research on dynamic complex network approaches has become more interdisciplinary. The ellipse on the right of the chart represents the subject of the cited paper. Through the path analysis, we can see that there are four paths from the left circle (as the origin of the path) to the right circle (the end). In the figure, the left is the cited discipline, the right is the cited discipline, and the curve is the cited line. As can be seen from Figure 4, the most cited papers in physics,

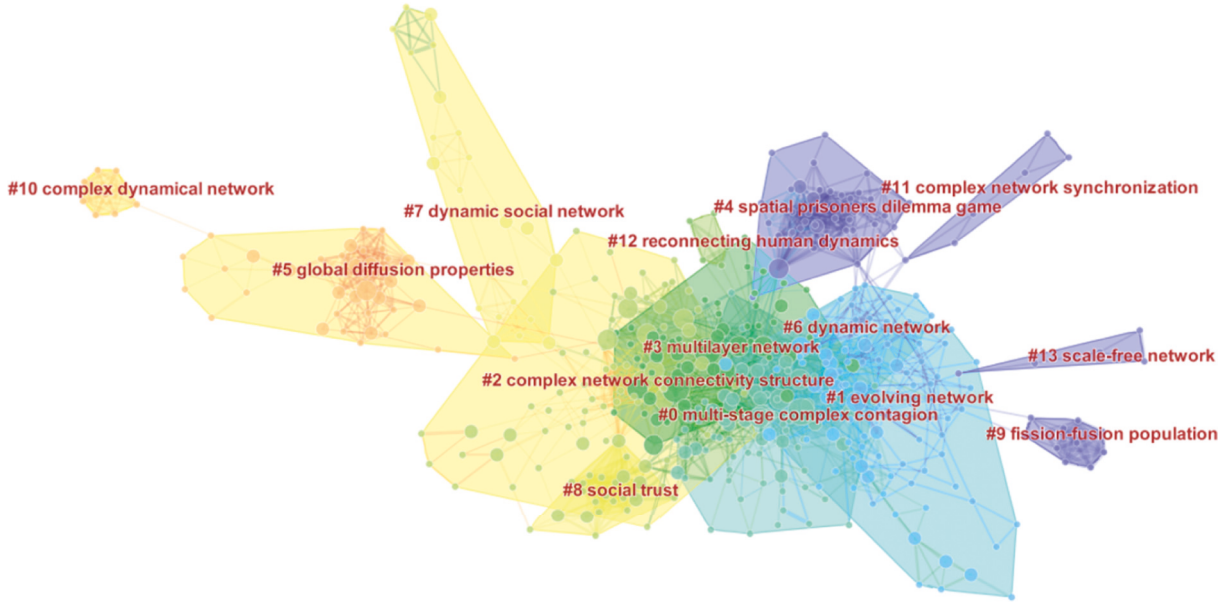

Figure 3: Cluster network in the dynamic complex network research field.

Table 4: Summary of the largest 14 clusters in the dynamic complex network research field.

Cluster ID	Size	Silhouette	Label (LLR)	Mean (year)
0	81	0.669	Multistage complex contagion	2007
1	72	0.178	Evolving network	2014
2	71	0.762	Complex network connectivity structure	2007
3	58	0.795	Multilayer network	2017
4	42	0.938	Spatial prisoners dilemma game	2007
5	39	0.948	Global diffusion properties	2016
6	29	0.862	Dynamic network	2016
7	24	0.97	Dynamic social network	2009
8	23	0.965	Social trust	2018
9	10	0.996	Fission-fusion population	2007
10	9	0.998	Complex dynamical network	2013
11	6	0.976	Complex network synchronization	2015
12	5	0.996	Reconnecting human dynamics	2008
13	5	0.986	Scale-free network	2011

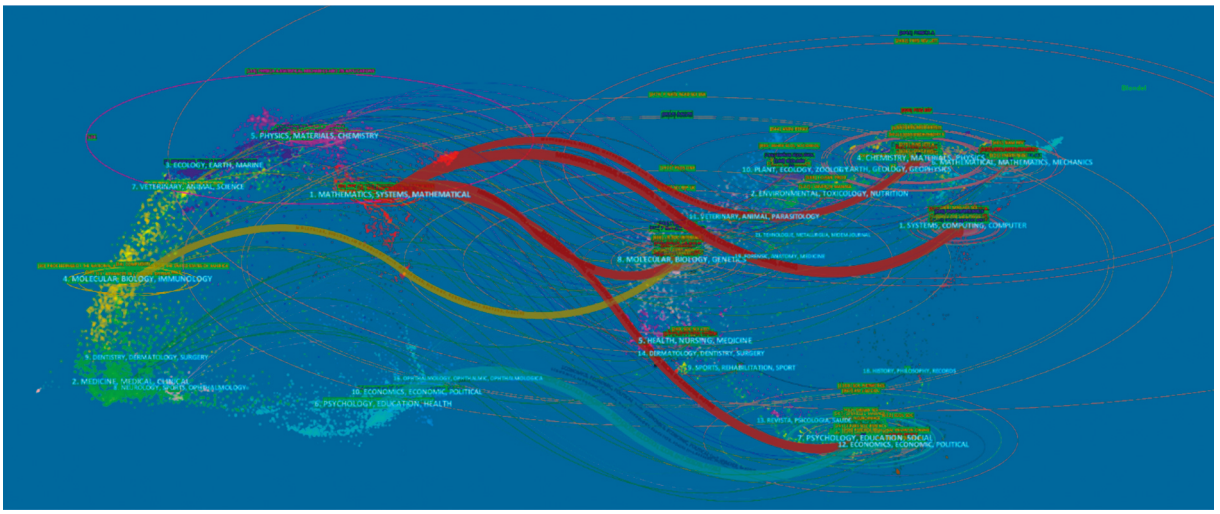

Figure 4: Double-figure overlay for the dynamic complex network research.

chemistry, computer, biology, economics, and politics come from mathematics and systems science.

Therefore, it can be found that the method of dynamic complex networks is also relevant to a variety of disciplines. With the increasingly close connection between various disciplines, the research on the dynamic complex network is also widely applicable to diversified fields. From a temporal dimension, the time analysis of keywords is capable to reflect the emerging trends and research hotspots of complex network research in this study. Due to the reason that the timeline of keywords provides an effective way to briefly and accurately reflect the development and evolution of a research area, it has also been utilized by researchers to learn the development trends of multiple disciplines. We use CiteSpace software to analyze the time axis of keywords, to obtain the keyword time matrix of the keyword time axis analyzed in this paper. Figure 5 shows the time axis of keywords in dynamic complex network research, and the corresponding publication time or peak time of keywords is visualized in the figure.

Here, we can analyze the scope and evolution process of different keywords on the time axis through the time axis analysis and the cited literature. First, we need to find the related articles that are related to a research area. The similarities and differences of the research topics could be further investigated. After that, we can learn the research development trend based on the change in research topics. In this study, the main keywords are "complex network and dynamic," "social network analysis," and "time series" [38], indicating that many research outputs related to them are of great influence. As time goes by, it can be found that the above methods have gradually been applied in various research areas.

Different from the clustering result of co-citation analysis, the time axis analysis of keywords also has a separate clustering result. For nearly three years, most researchers focused on the cluster "complex dynamical network" and cluster "dynamic social network."

In addition, we can see from Figure 5 that since 2011, relevant studies on the complex network have been on a certain scale. The influence of the keyword "complex network" in 2011 runs through the time axis of our study. For example, Wang et al. [39] introduced complex network theory into public cooperation and constructed a utility function that clearly expresses the evolution of two interdependent public cooperation. The authors conclude that the strength of the level of public cooperation is proportional to the bias of the utility function. Wang et al. [40] constructed a multilayered complex network to analyze the evolution of the Game by coupling the network through the utility of the participants, the flow of information, and the popularity of strategies at different network layers. The authors also emphasized the importance of pattern formation and collective behavior under adversity and the promotion of cooperation, as well as the evolutionary game theory between network science and synergy. Zhang et al. [41] studied the seasonal influenza disease model by integrating the interaction between subsidy policies and human behavioral responses. By establishing a complex network framework, targeted subsidy policies have advantages only when individuals tend to imitate the strategies of subsidized individuals. Ning et al. [42] pointed out that individual actions play an important role in the prevention and control of these diseases. These studies show that the higher success rate for self-protection may not reduce the outbreak size.

Second, "COVID-19" was one of the most prominent keywords in recent years' research on complex networks. Zhu et al. [43] constructed a complex network of COVID-19 from January 19, 2020, to August 15, 2020; deconstructed the global network connectivity; and analyzed the connectivity of the global coronavirus. "Social network analytics" (online) is also a significant keyword for 2021. Wan et al. [44] proposed a new competitive information coupling diffusion model to describe the complex process of information diffusion in online social networks. They analyzed the effectiveness of intervention strategies for competitive information coupling diffusion under both constrained and unconstrained conditions. This has important practical significance for the commercial marketing of online social networks.

4. Application of Burst Detection in Dynamic Complex Network Research

The phenomenon of "citation explosion" refers to the number of citations for some articles in a short period, which partly reflects the dynamics of a field. Recently, burst detection is an effective method in literature analysis, which can find articles that have received special attention from the relevant scientific community. We use CiteSpace to carry out burst detection and analyze the detection results to have cognition of the development of dynamic complex networks from a different perspective. This section takes the burst detection of references and keywords cited in dynamic complex network research as an example, shows the articles with the rapid increase in citation frequency, and further discusses our research direction.

According to the literature we selected in this research field, we used CiteSpace to conduct sudden detection of references and keywords in all the literature to analyze the trend of research changes and hot topics being studied. We obtained the results of Tables 5 and 6 through CiteSpace. The first column in the table represents references or keywords, the second column represents the year in which the outbreak started, and the third column represents the intensity of the outbreak. The fourth and fifth columns represent the years the outbreak started and ended, respectively. The last column is a visualization of citation burst detection. The bold squares indicate that the corresponding research was highly cited. It can be also interpreted as the Duration when the topic received a burst of research attention. Through such analysis, we can find the hot spots in this field in the past, present, and future from different perspectives.

4.1. References Burst Detection in Complex Network Research. Emerging trends in specific research areas can be found by analyzing articles with rapidly increasing citations. Firstly, we use the burst detection method to explore the emerging development trend of a dynamic complex network with

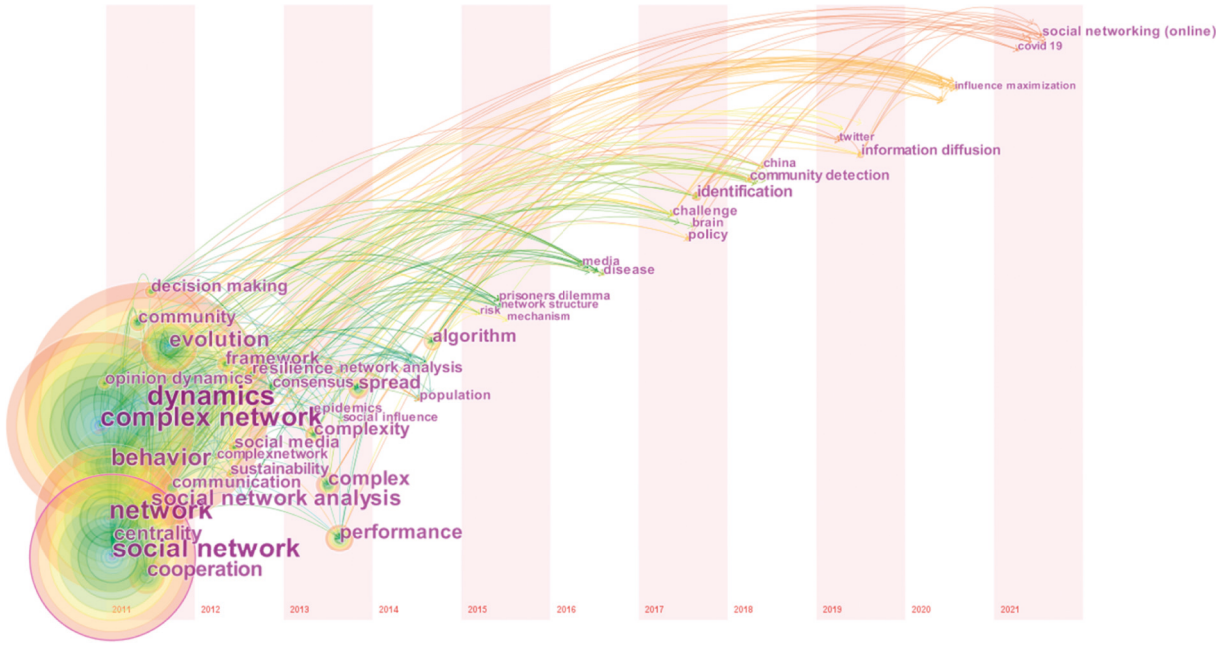

Figure 5: Time axis diagram of dynamic complex network research keywords.

Table 5: Top 15 references with strongest citation bursts.

Reference	Year	Strength	Start	End	Duration (2015–2021)
Roca et al. [13]	2009	3.4822	2015	2017	
Centola et al. [26]	2010	6.1728	2015	2018	
Newman et al. [45]	2010	4.1282	2015	2018	
Leskovec et al. [32]	2009	2.1382	2015	2017	
Castellano et al. [7]	2009	13.056	2015	2017	
Borge et al. [18]	2012	2.9439	2015	2017	
Ahy et al. [26]	2010	3.7373	2016	2018	
Lu et al. [9]	2011	3.8389	2016	2018	
Fu et al. [34]	2011	2.3744	2017	2019	
Chen et al. [46]	2012	3.8917	2018	2021	
Perc et al. [47]	2017	3.8844	2018	2021	
Zhang et al. [48]	2016	3.4491	2018	2021	
Wang et al. [40]	2014	2.8261	2018	2021	
Banerjee et al. [18]	2013	5.3908	2018	2021	
Wang et al. [39]	2012	3.1101	2018	2021	

Table 6: Top 10 keywords with strongest citation bursts.

Keyword	Year	Strength	Start	End	Duration (2015–2021)
Diversity	2015	5.1996	2015	2017	
Transmission	2015	2.2284	2015	2016	
Communication	2015	4.5688	2015	2016	
Knowledge	2015	3.3983	2015	2016	
Disease	2015	3.8538	2016	2017	
Technology	2015	3.7799	2016	2018	
Scale-free network	2015	4.9241	2017	2018	
Prisoners dilemma	2015	3.2803	2017	2018	
Epidemics	2015	3.1427	2018	2021	
Neural network	2015	4.7233	2019	2021	

CiteSpace. To better extract emerging trends in this field in recent years from the references, we further shorten the time range to 2015–2021. As shown in Table 5, the top 15 references with strong citation frequency are displayed during this period. As can be seen from Table 6, the emerging trend of outbreaks changes with time. In the past

four years, centrality measurement and application of complex networks [46], related models of information diffusion [48], and studies on the dynamics of social networks [47] have become important references for emerging trends.

4.2. Keyword Burst Detection. First, we also set the time frame from 2015 to 2021, and we extracted the top 10 keywords. Among them, the top four keywords all showed signs of breaking out since 2015. Keywords have changed over time. "Disease," "technology," "prisoners dilemma," and "scale-free network" were the keywords of the 2016 to 2018 outbreaks, which ranged in duration from two to three years. In recent years, especially in the last three years, some emerging keywords have gradually become the new breakout point in this field. "Epidemics" and "neural network" were both emerging breakout keywords that lasted until 2021. Deep neural networks and artificial intelligence emerged due to more deep insights and wide applications of complex networks, as well as a mass of data that are continuously utilized to train and adjust the nodes in the networks. Therefore, in recent years, neural network models are the crucial direction in the area of complex network research.

5. Main Path Analysis in Dynamic Complex Network Research

As an effective tool for citation network analysis, main path analysis is one of the most problems of concern. Compared with the h index and G index, the main path analysis method considers not only the direct influence but also the indirect influence. In addition, the main path analysis can correct the problem of citation bias due to different publication years. The main path analysis method is also used to compare papers published, rather than comparing the latest paper with the historical paper. The specific operation process of the main path analysis can be divided into two steps. First, check whether the network is a citation network to ensure that it is loop-free, and assign a weight to each edge in the network. Second, select a specific search algorithm to determine the main path of literature analysis.

In the citation network generated by us, one node represents a paper, and the edge between two nodes represents a citation. The main path analysis assumes that knowledge is spread through works between scholars and citation relations between works. The purpose of the master path map is to highlight the development backbone of our field. The main path analyzer first calculates all the paths to the destination, starting from the starting point. The starting point is the earliest published literature, and the ending point is the most recently published literature. Then, the proportion value of each edge in all paths is calculated. This value reflects the importance of each reference forming the whole literature chain, and it can be called the ergodic weight of edges.

The nodes on the main path should be important or key, which can reflect the core of discipline development. The main path carries the most information among all paths in the citation network and reflects the most critical relationship with the highest tightness among nodes. This paper summarizes the primary development path of the dynamic complex network from four aspects and discusses it. The thickness of the lines in the figure is positively correlated with the SPC value in the figure, and the nodes are marked with the name of the first author, the initials of other authors, and the year of publication.

5.1. Local Forward Main Path. As can be seen from Figure 6, seven papers appeared on the local forward main path, and each of these papers was cited more than twenty times in the WoS citation database. The path in the figure adopts the most original master path generation method, which shows the knowledge diffusion in a specific field and helps researchers to capture the knowledge backbone, to comprehensively understand the development process of a dynamic complex network.

The paper of Xiong et al. [49] is the starting point of papers in this research field from 2011 to 2021. In this paper, a diffusion model (SCIR) is proposed, and four states are assigned to the model. The results show that there are more contact agents in the scale-free network than in the regular network. The degree-based density of infected agents increases monotonically with the increase of degree. This paper lays a foundation for the complex network in the field of infectious diseases and social communication by studying the diffusion model of infectious diseases.

2012 is the starting year for the main path analysis. We found that in this year, in addition to the article already analyzed, other articles were using the SCIR model for contagious disease research. This is the beginning of the dynamics research of complex networks.

To study the rumor transmission mechanism, Wang et al. [50] introduced the trust mechanism and proposed a new susceptible infection removal model. The mean-field equations describing the dynamic characteristics of the SIR model are derived on the secondary and inhomogeneous network. Then, the critical threshold and final scale of rumor propagation are studied by steady-state analysis. This paper introduces the trust mechanism into the study of rumor propagation for the first time, simulates how to minimize the influence of rumors through the derivation of different networks, and proves its conclusions numerically through the derivation of the model.

The paper by Zan et al. [51] is also a study on rumor propagation and control. The difference is that it introduced two new models: susceptibility–infection–counterattack–refr actory (SICR) model and adjusted SICR model based on considering the counterattack mechanism of rumor propagation. Based on these two models, the mean-field equation is derived to describe their dynamics in the homogeneous network, and the steady-state analysis is carried out. At the same time, the authors introduce the self-resistance parameter τ into the model to express the influence of this parameter on rumor propagation. The research results show that, through the numerical simulation of different models and comparison, the paper finds the rumor propagation patterns related to counterattack power.

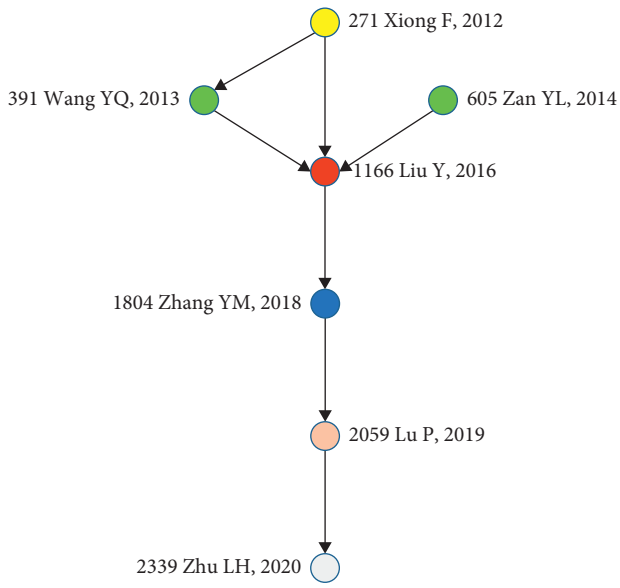

Figure 6: Local forward main path in dynamic complex network research.

After development, there are two important kinds of literature from 2013 to 2014. They improved the model based on the original research, applied it to other social fields, and deduced the mechanism of rumor spreading from the mathematical model. This is the result of development.

Based on the above two types of research on rumor transmission, Liu et al. [52] proposed a new model, SHIR, which is used to study the dynamics of competitive information transmission. At the same time, this paper proposes that a new hesitancy state is considered the neutralization state of information competition. The empirical study of the model shows that the dominant information with a larger stable transition rate controls the overall influence of dual information.

Furthermore, Zhang et al. [53] proposed a rumor and authoritative information transmission model considering the super transmission mechanism. The author deduced the mean-field equation and authoritative information transmission model describing rumor dynamics and estimated the basic copy number and final size of rumor and authoritative information. In the empirical analysis part, the validity of the model is verified by comparing it with the actual data on Sina Weibo, and the dynamic characteristics of the model are analyzed. The results show that the super communication mechanism has more impact on rumors than authoritative information. If the super communication mechanism exists only on rumors, it will eventually lead to the explosive growth of the rumor propagation scale. The research results also show that the stronger the power of authoritative information, the smaller the final rumor spread scale and the final authoritative information scale. This paper continues the previous research ideas on rumor transmission and further examines how the dynamic system functions in rumor transmission. The results are helpful in better understanding the mechanism of rumor transmission and refutation in a complex network.

With the development of technology, many investigations have been conducted regarding the research objects in the path. As a collective behavior, information spread has also been focused in multidisciplinary research areas. In today's Internet age, people interact with each other, exchange and spread information or rumors by using diverse types of social media. Lu et al. [54] found that in addition to the basic and extended susceptible infection removal (SIR) model, direct interaction between agents or individuals often serves as an alternative path for modeling information dissemination. In the model mentioned in this paper, the heterogeneity of social trust and individual judgment is introduced into the model. The authors focus on the conditional heterogeneity effect of the individual judgment under the heterogeneity of social trust. This article is also an important node in the main path. In terms of content, this paper has a broader perspective, taking information transmission as the research object, rather than just the rumor transmission, and finding the transmission path of direct information interaction beyond the previous SIR family model. At the same time, heterogeneity and dynamics are integrated into the research of the model to study the mode of information transmission on a deeper level.

As the final endpoint of the main path, Zhu et al. [55] proposed a new model of delayed SIR type widespread rumor propagation in a homogeneous and heterogeneous network and analyzed the propagation dynamics of the model using mean-field theory. The forward and backward bifurcations and the local and global stability of the equilibrium points of both homogeneous and heterogeneous networks are theoretically analyzed and revealed. The correctness of the theoretical derivation is proved by numerical simulation. This article is the main path of the last node, which is the most recent influence. This article is represented as the last node on the main path, implying its significant influence in recent studies. Focusing on information spread, especially rumor spread, it is quite mature in terms of methodology and

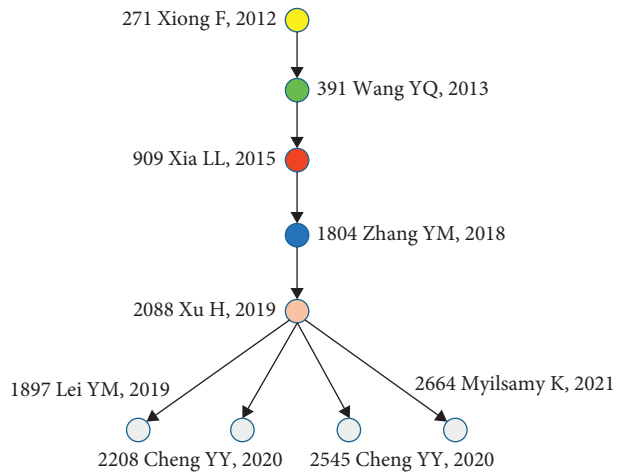

Figure 7: Local backward main path in dynamic complex network research.

numerical simulation. Quite mature, and of the accurate in numerical simulation.

The important nodes in the main path analysis represent the important kinds of literature that have a guiding role in a period. The corresponding time nodes are also important time nodes in the development of this field. In these time nodes, we can see that in the related research fields of dynamic complex networks, the application fields are more and more extensive, with more and more in-depth and specific research objects.

In the study of dynamic complex networks, three observations can be seen from the local forward main path. It can be found from our topic that a dynamic complex network is only a research method, so we should apply this method to the specific research object. In the forward analysis of the main path, we take rumor propagation (information propagation) as the specific research object. We can find that with the deepening of the path, dynamic research and heterogeneity of the network are included in the model. From the starting point, advancing step by step to the original SIR model, the SICR model, and then to the SIHR model, the SIR family model is extended from different angles, making its application more extensive and making the numerical simulation results get further accurate. We can find that the dynamic study of complex networks applied in various fields has a similar development process.

5.2. Local Backward Main Path. Figure 7 shows the partial backward main path, as opposed to the partial forward main path, which tracks the development trajectory from now to the past, while the backward main path focuses on the work of the last decade. We can see that there are more nodes in Figure 7 than those in Figure 6 and the paths are extended in diverse ways. Based on the paths of different algorithms, we can present the development history of citations from different angles.

Similar to the forward main path analysis method, we also perform analysis from the starting point to the endpoint. Different from the forward main path, the backward main path have altogether four endpoints, and four different papers are identified. We will explain why this is the case in the following analysis.

By comparing the backward with the forward main path, we find that the first two nodes of the forward and backward main path are the same; that is to say, in the backward main path, the proposal of the SCIR model is also taken as the starting point [49], followed by the introduction of trust mechanism to study the spread of rumors as the second node [39]. With regard to the third node, different from the forward main path, Xia et al. [56] proposed a modified susceptible exposure infection model (SEIR) with a hesitation mechanism based on existing studies considering the attractiveness and ambiguity of rumor content. In this paper, mean-field equations are derived to express the dynamic characteristics of the SEIR model on the secondary network and heterogeneous network. Then, the threshold of rumor propagation and the final rumor size are studied by steady-state analysis. The results showed that reducing the ambiguity can effectively improve the propagation threshold of the SEIR model. Meanwhile, the simulation results also find that the rumor propagation speed obeys the relationship: "BA network > WS network."

The fourth node is also the same as in the forward main path, while the subsequent node development is different. Xu et al. [57], taking into account people's hesitation, forgetting, and other psychological factors as well as the heterogeneity of online social networks, proposed a new scale-free online rumor propagation model, SHPRS (susceptible–hesitating–propagating–resisted–susceptible). This model uses mean-field theory to analyze the rumor propagation dynamics in detail, studies the global stability and persistence of rumor propagation of rumor-free equilibrium, and verifies the results by numerical simulation.

The following four nodes are developed based on the previous node. Therefore, the four kinds of literature represented by these four nodes are juxtaposed. Lei et al. [58] studied the influence of product discount rate, customers' repurchase intention, and network heterogeneity on the dissemination of group ordering discount information through online shopping. They proposed a scale-free network-based group ordering discount information dissemination model. Cheng and Zhao [59] discussed the dynamic mechanism of rumor propagation, proposed a rumor propagation model, and conducted an empirical numerical analysis. Cheng et al. [60] discussed the important role of individual activities in the rumor spreading process, incorporated randomness analysis into the framework, and verified the theoretical results through numerical simulation. Myilsamy et al. [61] proposed a new model of the rumor propagation process by integrating the group propagation of rumors in social networks and mobile networks and considering people's cognitive factors—hesitation and forgetting. At the same time, this paper also gives an optimal control problem to minimize the hesitancy and infection and proves the existence of the optimal control problem. From the four kinds of literature at the end of the main path, we can see that the dynamics of the complex network have gradually included various analysis elements and have begun to be applied to different fields, such as online shopping and other lifestyles.

6. Conclusions

Based on 2936 papers on WoS, CiteSpace and Pajek software are used to perform bibliometric analysis on the development of the dynamic complex network. Based on the above analysis, some helpful conclusions about the field are drawn: During the eleven years of our study, there were 2936 journal papers on dynamic complex networks. The number of articles published has indicated an increasing trend, from 153 in 2011 to 375 in 2018. This shows that people pay more and more attention to this area of research. From the basic bibliometrics analysis, first from the national perspective, compared with other countries, the United States published the most journal papers in dynamic complex network research. In terms of the top-productive institutions, they share some similarities in the number of publications. The major research institutes are located in the United States, China, and the United Kingdom. In terms of the number of institutions in the top 10, the USA leads the way. Therefore, the most productive institutions for dynamic complex network research are likely to come from countries with strong basic disciplines.

In the special bibliometric analysis, we start from the aspects of co-citation network, double-digit analysis, and emergent detection. We extracted 14 clustering labels from the co-citation clustering results. Meanwhile, we find that the dynamic complex network method is widely used in many fields, including mathematics, computer, economics, politics, chemistry, and biology. Therefore, we can use a variety of methods to investigate the research status of a dynamic complex network. With the continuous development of the discipline, there are more opportunities for scholars in different fields to cooperate, which also provides more useful information for their interdisciplinary research. We conduct emergent detection for reference citations and keywords, from which we find research hot spots and new development trends in our research period.

The early research of complex network methods mainly focuses on the change of network structure. It is mainly used to solve some problems in basic subjects, such as the optimal path problem in mathematics. With time, the method of the complex network has gradually become perfect and integrated into the network and dynamics research, which has been applied in various fields of research accordingly. In recent years, although the number of papers published in this field is increasing, there is still an ample space for the development of dynamic complex network methods. We find the hot spots in dynamic complex network research in recent years through the sudden detection of keywords. For example, neural networks and social networks are the mainstream trends in the field of dynamic complex networks in the future. Through the visual analysis and review of relevant papers, other researchers can better understand the past development and future development trend in this field. At the same time, the unique bibliometric methods inspire scholars from different perspectives to find more effective and novel methods to further study dynamic complex networks.

Data Availability

The data used to support the findings of this study are included within Supplementary Materials.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Supplementary Materials

The data were downloaded from the Web of Science and include 2936 papers in the field of dynamic complex networks. All charts and analyses in this article are derived based on these original data and the CiteSpace software. . (*Supplementary Materials*)

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