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NETWORK RESILIENCE IN THE FINANCIAL SECTORS: ADVANCES, KEY ELEMENTS, APPLICATIONS, AND CHALLENGES FOR FINANCIAL STABILITY REGULATION

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Abstract. Security against systemic financial risks is the main theme for financial stability regulation. As modern financial markets are highly interconnected and complex networks, their network resilience is an important indicator of the ability of the financial system to prevent risks. To provide a comprehensive perspective on the network resilience of financial networks, we review the main advances in the literature on network resilience and financial networks. Further, we review the key elements and applications of financial network resilience processing in financial regulation, including financial network information, network resilience measures, financial regulatory technologies, and regulatory applications. Finally, we discuss ongoing challenges and future research directions from the perspective of resilience-based financial systemic risk regulation.

Keywords: financial network, network resilience, financial stability regulation, systemic risk.

JEL Classification: G2, C8.

Introduction

Containing the financial risks of financial sectors is the main target of financial stability regulation and also an important part of national financial security safeguarding. After the 2008 financial crisis, the prevention of financial systemic risks has become a consensus achievement for global financial governance. To this end, many countries worldwide have strengthened the macro- and micro-prudential regulation of their financial systems. Macro prudence mainly aims to counter-cyclical management and the important financial institutions management to prevent systemic financial risks. Micro-prudential supervision is more concerned

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with the compliance and risk exposure of specific financial institutions, that is, individual risk control and behavioral norms (Ilollari & Gjino, 2013; Lui, 2010; Zhou, 2010; Persaud, 2009). Additionally, multiple financial regulatory standards have been applied to financial system risk regulation. In 2010, the Basel III resilient banking system emphasized that financial systems need to expand the risk coverage of the capital framework, introduce leverage ratio regulation, adopt countercyclical capital buffer measures, and propose liquidity coverage ratios, and create a net stable financing ratio and other liquidity regulatory standards.

Modern financial markets are highly interconnected and form complex networks (Haldane & May, 2011; Helbing, 2013; Battiston et al., 2016). With the rapid development of Internet and digital finance, a wide range of financial institutions are becoming interrelated through financial transactions, such as asset guarantees, equity investments, and financial derivative product holdings. Further, with the advancement of regional financial integration process, unions of financial institutions have been formed, such as the European Banking Union and the British Credit Union. These union through financial transactions can jointly prevent financial risks and improve the ability of the financial system to respond to risks, but also hide financial systemic risk exposure, thus threatening local financial security. Consequently, the stability of a financial network formed by such financial institutions through financial transactions is the main objective of financial regulation (Chabot et al., 2019; Khabazian & Peng, 2019).

Network resilience (Gao et al., 2016; Almoghathawi & Barker, 2019; Ghorbani-Renani et al., 2020) refers to the ability of entity-associated networks to quickly detect, respond, and resume normal business operations after network security incidents. The network resilience of a regional financial system represents the ability of the financial entity network to respond to financial security shocks, which is manifested by financial systemic risk identification and processing capabilities, loss absorption and functional protection capabilities, and learning and recovery development capabilities. The resilience of a financial network is also an inherent requirement for deepening financial reforms. Improving the network resilience of regional alliances of small and medium financial institutions is the main relationship and key for the defense against risks and maintaining regional financial stability and security. Although the resilience of the global financial market has increased, regional financial networks show complex evolutionary processes, structural heterogeneity, and risk contagion dynamics. Therefore, the resilience measurement, evaluation, and risk regulation of regional financial networks face many challenges as follows. First, network resilience is being affected by a variety of external interference factors. The current financial market is facing the impact of the COVID-19 pandemic and the ensuing economic downward pressure, uncertainty and instability, credit risk, liquidity risk, as well as other factors that are either mixed or superimposed to the ones mentioned above. Second, the influence mechanism of financial network structure on network resilience is unclear. The structure of a financial network is typically irregular and random and the influence mechanism of network complexity on resilience is still unclear. Third, the resilience monitoring technology of financial networks is still insufficient. Financial network resilience is time-varying, and the strength and capabilities of network resilience in different evolution stages require timely monitoring. Currently, the monitoring of resilience relies mainly on macro- and micro-prudential policies. From a technical perspective, that is, from the viewpoint of network structure characteristics, network power systems, machine learning technology early warning, and other regulatory technologies are less used, and smart monitoring technologies need to be further developed.

Through a new resilience perspective, the measurement and evaluation of financial system stability has become a research hotspot in financial regulation in recent years (Amini et al., 2016; Floyd et al., 2015; Khabazian & Peng, 2019). The stability evaluation of the financial system can be obtained from the network structure, resilience characterization, and resilience measurement of financial institutions (Chabot et al., 2019). The main research perspectives include the structural characteristics of financial networks, network resilience measurement, financial resilience characterization, regulatory techniques based on resilience, among others. Compared with macro-prudential and micro-prudential financial regulation methods, direct intervention in the financial market can be reduced through research on financial system resilience. Therefore, cultivating and strengthening the resilience of financial networks is an important mean to improve financial regulation efficiency.

For a comprehensive perspective on the network resilience of financial networks, this paper reviews in detail the origin of resilience research, the concept and connotation of financial resilience, the research methods of financial networks, and the application of networks in financial supervision. Then, we analyze the main methods and trends of using the resilience of the financial network as a tool to realize financial supervision by reviewing the rudiments of some existing studies. We also propose future research directions and identify the major challenges. To carry out our proposal, we index related articles included in Web of Science. Our search terms include three groups: "Internet resilience + finance", "finance + resilience", "complex network analysis + resilience", and then we select articles related to financial regulation and financial risk to review in the literatures. This approach aims to provide a new research perspective for the development of financial regulatory policies and financial regulatory technology, as well as create a research direction on future financial network stability.

The remainder of this paper is organized as follows. Section 1 briefly describes the main concepts related to financial networks and the development process of financial resilience. The relationship between the structural characteristics of financial networks and financial stability are introduced in detail in Section 2. Section 3 illustrates the main technical process of network resilience and its applications to financial stability regulation. Section 4 introduces governance resilience in financial networks. Section 5 focuses on the financial stability regulatory based on network resilience and proposes future research challenges and directions. Finally, the last Section concludes the paper.

1. Resilience and financial resilience

Resilience originates from the research on the stability and restoration capacity of ecosystems (Holling, 1973), and was introduced into social systems research to characterize the risk resistance of societies or organizations under external shocks (Pimm, 1984; William, 2000; Dehghanian et al., 2018), for example, disasters response, emergency management, social governance. It is generally believed that a resilient system should be able to reduce the probability of failure, reduce the losses caused by failure, reduce recovery time (Bruneau et al., 2003), as well as possess robustness, redundancy, intelligence (resourcefulness), and rapidity. In sum, resilience means that a network remains stable and recovers quickly under external shocks and realizes the rapid allocation and optimization of system resources.

Unlike ecological and engineering resilience, social resilience not only implies resistance to risks, but also pays attention to inter-organizational disruptive effects and the ability to learn and develop (William, 2000; Simmie & Martin, 2010). In a highly interconnected modern society, network information and resilience have become a hot research topics. In 2013, the U.S. President's decision report included the concept of "resilience" in national security documents (The White House, 2013). In modern financial network ecology, monitoring the resilience of financial networks is an effective way to realize financial regulation.

Financial resilience focuses on the analysis of the influence mechanisms of external impact factors (Chabot et al., 2019; Khabazian et al., 2019). However, there is currently no unified definition of financial resilience. The characterization of financial resilience is mainly understood and shaped under three aspects: financial stability, function, and development. Financial network resilience is different from the resilience of a pure physical network, with significant differences between different groups and countries. Regarding the micro factors of the financial market, some studies focus on the relationship between personal financial resilience and financial availability. For instance, Chabot et al. (2019) investigate the resilience of the UK financial system using a network of relationships for the credit default swap market. Salignac et al. (2019) define an individual's financial resilience as the ability to recover from adverse financial events and propose a multi-dimensional financial resilience evaluation index, finding there are serious financial vulnerabilities in the adult group. Klapper and Lusardi (2020) and Lusardi et al. (2021) consider that financial resilience is related to the financial literacy of individuals or families. In terms of macro research, Barbera et al. (2017) conduct a multi-case analysis of the financial resilience capabilities of 12 European governments, including Austria, Italy, and the United Kingdom. They find that financial resilience is related to self-regulation, restraint, or responsive adaptation.

In sum, resilience is the result of the mutual influence and development of internal and external dimensions. Financial resilience is a function, with which the independent variables are the ex-ante risk prevention and control, ex-post response and recovery, and ex-post learning and reflection, and the dependent variables are the financial stability, service, and reform. Its connotation is inherently consistent with the requirements of serving the real economy, preventing and controlling for financial risks, and deepening financial reforms. Therefore, financial resilience can be measured under four aspects: safety, resume ability, adaptability, and transformation ability.

2. Financial networks and their representations

The financial market is one of the strictest and safest systems for metadata preservation. The large amounts of intelligence information contained in financial networks need to be identified and transformed into the government knowledge on financial regulation, thus forming user profiles and knowledge management models.

2.1. Entity network and financial risk-related information mining

Through financial transactions, the various financial entities in the financial market form extensive financial networks. The relationships between financial entities are based on asset-related networks such as joint asset holdings, debt holdings, equity investments, credit guarantees, or mutual guarantees, and trading networks such as capital transactions such as credit derivatives, securities, and derivatives investments. At the same time, the practice and professional experience among the senior managers of regional financial entities overlap to form a social network. From the financial reports, financial news, punishment cases, among others, of the financial market entities, a network of information connections emerges. Hautsch et al. (2015) propose that the source of systemic risk in financial networks comes from systemically important institutions. Wetzel and Hofmann (2019) use network analysis methods to study the functional form of the relationships between capital assets and company performance beyond a traditional single company perspective. In fact, this is also an application of the financial network perspective to supply chain finance.

Similar to the natural ecosystem, financial networks are also complex power systems with different conditions for steady state transfers. Namely, financial network risks are easily spread through the highly connected entities, causing the collapse of the monetary system (Haldane & May, 2011). Further, the systemic risks of the financial system are related to the structure of the financial network (Giudici et al., 2020). The correlation between bank risks can transform and influence each other, which significantly affects the accuracy of bank risk measurements. The stability of the internal structures of highly interdependent financial systems makes the entire financial system a risk threat. Therefore, financial system stability requires the discovery of tipping points, thresholds, and breakpoints in the system (May et al., 2008). However, financial system stability can be achieved through systematic financial regulation and risk defense capability cultivation (Battiston et al., 2016).

A financial network carries financial functions and services and, at the same time, is the main channel for spreading regional financial risks. In the context of digitalization and networking, the credit choices and behaviors of entities are susceptible to mutual infection and influence, resulting in a complex dynamic mechanism for the formation and evolution of financial network resilience. A comprehensive description of financial network resilience requires insights into the interactions between different influencing factors and the evolutionary nature of financial network resilience.

2.2. Financial network construction

Big data need to be integrated and developed to form an interconnected structure and realize new information organization. As the financial market has a wide range of network structures, the financial networks used to evaluate financial risks are constructed through the relationships between financial entities. Network analysis is used to deconstruct the overall relevance of financial networks and the characteristics of intra- and inter-departmental relevance. In this context, Kou et al. (2021a) use the flows of transaction funds between small and micro enterprises to build a financial network and apply it to the credit risk evaluation of small and micro enterprises. Poledna et al. (2015) build a financial network through the relationships between credit, derivatives, foreign exchange, and securities transactions in the financial market. Lee and Nobi (2018) construct financial networks based on a cross-correlation matrix, such as the threshold network and the minimal spanning tree, in the threshold network, which assigns a threshold value by using the mean and standard deviation of cross-correlation coefficients. Further, McCallig et al. (2019) use blockchain to strike a balance between public access and privacy, which can enhance the representational faithfulness of financial reporting systems.

2.3. Financial network structure

A financial network contains significant information resources and obtaining effective information is a prerequisite for financial risk control. There are multiple layers of network structure (multilayers) in the financial system. This structure reduces the ability to withstand financial risks due to the risk exposure of common or borrowed assets between financial institutions (Battiston et al., 2016; Korniyenko et al., 2018). Poledna et al. (2015) believe that the multi-layer structure of financial networks comes from the investment relationship between financial entities, such as credit and derivatives. The financial multi-layer network often presents non-linear events, which is why its risk may be underestimated. Bargigli et al. (2014) find that the layers of a multi-layer financial network have different topological properties, which need to be considered globally rather than as specific layers. Fabio and Mario (2018) constructs the interbank deposit network as a flow network and analyze the efficiency of three network structures: star-shaped, complete, and incomplete in transferring liquidity among banks. The star network induces banks to hold interbank deposits that are closest to the effective level.

2.4. Evolution in financial networks

From an evolutionary viewpoint, the ability of financial networks to withstand risks is initially the same as wetland storage, which can absorb and buffer risks, but beyond a certain critical point, risks will be exposed (Acemoglu et al., 2015). Financial systemic risk contagion will lead to the expansion of financial network risk exposure (Hu et al., 2012; Bluhm & Krahnen, 2014). Giudici and Spelta (2016) establish a method to identify the core sources of infection in the network through a graphical model of financial network associations between different countries. Further, Huang et al. (2016) construct the minimum spanning tree and show the system risk contribution and dynamic evolution of financial network structure. Chowdhury et al. (2019) reveal that the relationship between the Asian market and the rest of the world has generally deepened over the past 20 years by investigating the constantly changing financial market network in the six periods between 1995 and 2016.

Through the effective mining and extraction of financial market sentiment and customer opinion evolution, the risk factors in the financial network can be identified. The main channels for extracting emotional factors include financial news, annual reports of listed companies, social media, among others (Cerchiello & Giudici, 2016; García, 2013; Tsai & Wang, 2017; Choi, 2014). Choi et al. (2017) use the textual information from the financial reports of financial institutions to predict financial risks, results showing that market sentiment is closely related to financial risks. Correa et al. (2021) analyze the relationship between the sentiment they convey and the financial cycle using the text of the Financial Stability Report issued by the Central Bank. They construct financial stability sentiment indexes which can be used to predict banking crises.

Based on the above literature review (Table 1), the research on financial networks has matured and the importance of financial networks in the financial system has gradually

Table 1. Financial network and their representations

Category	Literatures	Main methods	Data	Main results
The correlations of financial network and financial risk	Hautsch et al. (2015), Wetzel and Hofmannln (2019), Haldane and May (2011), May et al. (2008), Battiston et al. (2016), Giudici et al. (2020), Li et al. (2021).	Statistical inference; correlation network models; complexity theory, etc.	US financial system; BANK of settlement.	Financial network spillover effects systemic risk; The stability of the financial network is impacted by certain nodes, causing rapid risk contagion; The idea of complexity theory helps predict and manage financial system risks, because it can be used to explain the risk paths in related financial networks.
Construct financial network	Kou et al. (2021a), Poledna et al. (2015), Lee and Nobi (2018), McCallig et al. (2019).	Fund transaction relationship; relationships between credit, derivatives, foreign exchange, and securities transactions; cross-correlation matrix; blockchain.	China Local Financial Institutions Alliance; daily closing stock prices of global indices located worldwide; Listed company financial report, etc.	The establishment of a network between financial entities is aimed at different research objects and data availability, through financial transactions such as credit relationships, capital transactions, guarantee relationships, equity relationships, etc.
Financial network structures	Battiston et al. (2016), Korniyenko et al. (2018), Poledna et al. (2015), Bargigli et al. (2014), Fabio and Mario (2018).	Maximum entropy models; Threshold network; star-shaped; completed network; flow network.	EU interbank deposit data; supervisory reports transmitted to Banca d'Italia by all institutions operating in Italy, etc.	The financial network presents a multi-layer and multiplex structure and is non-linear, and the topological properties of different structural layers are different.
Evolution in financial networks	Cerchiello and Giudici (2016), García (2013), Tsai and Wang (2017), Choi (2014), Choi et al. (2017), Correa et al. (2021), Acemoglu et al. (2015), Giudici and Spelta (2016), Huang et al. (2016).	Graphical model; minimum spanning tree; textual mining; sentiment analysis.	Asian market; Financial Stability Report issued by the Central Bank; Securities market news, reports, annual reports, etc.	The evolution of the financial network presents different risk tolerance and stability states with the changes of external information.

reached consensus. Currently, various results regarding the factors affecting the stability of the financial system and risk propagation modes in financial networks are presented in the literature. However, based on the network perspective, there are no studies on the network resilience and resilience structure of the financial system. The representation of financial network resilience is unclear. Further, there is no mature research on network recovery and the evolution process under risk impact. Therefore, further research is needed.

3. Network resilience under regulatory technology

From the perspective of network resilience, studying issues such as the cultivation of financial network resilience is a new way to study financial system stability.

3.1. Network resilience analysis

Network resilience refers to the ability to quickly discover and recover after a network security incident occurs. The resilience of a network system includes three main factors (Gao et al., 2015; Kaiser-Bunbury et al., 2017): network structure, network dynamics, and malfunction mechanism. The Financial Stability Board [FSB] (2019) defines "cyber resilience" as an organization adapting to the changes in the network environment, as well as the tolerance, containment, and rapid recovery of cyber incidents. Anand et al. (2018) use granular data for a wide range of financial networks to define resilience in terms of the ability to reconstruct the structures of links and exposure in networks.

Aiming at a multi-layer integrated financial network, by combining the evolution characteristics of network resilience and multi-dimensional measurement indicators, the following measurement models of financial network resilience are studied:

$$\frac{dx_i}{dt} = F\left(x_i\right) + \sum_{1}^{N} A_{ij} G\left(x_i, x_j\right),$$

where x is the network node, $F(x_i)$ is the resilience dynamic function of the node itself, A_{ij} is the node incidence matrix, and $G(x_i, x_j)$ is the node correlation dynamic function.

Through the composite system of a node's own dynamics and the associated dynamics of the other nodes, the properties of the fractional-order node dynamics of a financial network are studied and, then, the stability measurement model of the financial network is proposed to obtain the node dynamics of the financial network. Gao et al. (2016) propose a dynamic parameter control method in a multi-dimensional large-scale network. This method separates system dynamics from network topology to obtains the general cognitive process of resilience behavior. Barzel et al. (2015) consider that the micro-mechanisms in the network system can be obtained through a paired dynamic mechanism. Yazıcıoğlu et al. (2016) find that, if network resilience maintains the minimum capacity between node flows, its resilience will weaken under external shocks and cause failures. Therefore, the relationship between the disturbance structure of a network system and its resilience is very important, and its resilience has a general dynamic mechanism (Barzel & Barabási, 2013). Tu et al. (2017) identify that the resilience collapse of a network depends on the internal interactions and dynamic characteristics of the network. The risk prevention ability of a physical network in different fields can be evaluated and researched through system resilience. Dev (2018) believe that the formation of sub-association groups in the network comes from the cost sharing game. Chabot et al. (2019) conduct a detailed descriptive analysis of network topology and describe the nature of the relationship between financial institutions, revealing the connection dynamics of the network. They use a panel analysis to detect the centrality and influence variables of a bank in its network, which can help determine the priority areas of action for regulators and risk managers.

The causal relationship between the network structures of financial entities and the existence of systemic risks can improve the pertinence and effectiveness of financial risk prevention through the identification of network structure. Huang et al. (2016) measure system risk contribution through the dynamic conditional correlation multivariate GARCH model and find a quantitative relationship contribution and system risk financial network structure. Magner et al. (2020) establish a roadmap for the deeper understanding of how financial networks can improve the quality of forecasts for financial variables, and find that the network effect is a key factor for the sharp increase in uncertainty and volatility during financial shocks. Nie and Song (2018) introduce a planar maximally filtered graph and threshold method to construct a correlation-based network that is more stable during financial crises. Capponi et al. (2020) illustrate that the "doom loop" can exacerbate the "too interconnected to fail" problem in financial networks when the public debt holds. Esmalifalak (2021) construct financial networks using the Euclidean (dis)similarity metric, which enables the incorporation of risk and returns instead of the traditional correlation between underlying assets. The importance and influence of central countries (e.g., hubs in the United States and Japan) in the spreading of high volatility is mostly reported by correlation networks. The vulnerability of a financial network based on the linear optimization model is also analyzed and sensitivity analysis conducted by Khabazian and Peng (2019) and Eisenberg and Noe (2001). Brancaccio et al. (2018) use complex network analysis on the Thomson Reuters Eikon database from 2001 to 2016, pointing out that global network control is highly centralized.

Network resilience depends on the resilience of the nodes in a financial network. Controlling key risk nodes in the financial network through network analysis is an important technology for financial regulation. For instance, Bhattacharya et al. (2020) use syndicated loans to establish financial connectivity based on network statistics. As a result, the borrowing banks that are more active in the network also help increase credit risk and the concentration of close relationships shows that the credit risk of lending banks has been greatly reduced. Liu et al. (2021) use a state-space model to estimate the dynamic network of North American financial institutions from January 2005 to May 2020. They also measure the strength of the network, find that the spillover effect increased significantly during the 2008 financial crisis and the COVID-19 pandemic, and monitor the communities in the network. Isogai (2017) analyzes the dynamic correlation network of the returns of highly volatile financial assets under a network clustering algorithm. He converts the correlation network of individual stock returns to the correlation network of group-based portfolio returns and, by studying the differences between the three sub-period networks, makes inter-period comparisons of dynamic correlation networks. Korniyenko et al. (2018) propose a novel multi-layer network framework that can be used to connect the debt and equity risk exposures between countries because the network is highly vulnerable to central countries and those with larger financial systems (e.g., the United States and the United Kingdom). Inekwe et al. (2018) study the impact of global financial integration on liquidity risk. Using online methods and bank-level data from 95 countries/regions, they find that the banks in the financial network with close relationships with important lenders bear higher risks than those with independent financing channels. Li et al. (2019) construct an inter-provincial regional financial risk spatial correlation network from 2009 to 2016, and use social network analysis to test the overall connectivity of the regional financial risk spatial correlation network. Their results show that the China Regional Financial Risk Space Association Network is a typical "scale-free network" and the associations in each province are unevenly distributed and have "world characteristics". Fabio and Mario (2018) imply that the star-shaped network is most resilient to systemic risk.

Currently, the most studied network is the (dynamic) correlation network constructed by the debt and capital networks and other financial transactions (Table 2). The main method is complex network analysis. However, most studies focus on the multi-layer structure and topological network properties of financial networks.

Table 2. Representative research methods for network resilience

Category	Literatures	Main methods	Data	Main results
correlation network; dynamic correlation network	Li et al. (2019), Khabazian and Peng (2019), Eisenberg and Noe (2001), Nie and Song (2018), Liu et al. (2021), Huang et al. (2016), Barzel and Barabási (2013), Lee and Nobi (2018).	social network analysis; network clustering; optimization model; sensitivity analysis; a planar maximally filtered graph and threshold method; a state-space model; dynamic conditional correlation multivariate GARCH model; dynamic parameter control method.	China Regional Financial Risk Space Association; Thomson Reuters Eikon database; North American financial institutions.	Small word characteristics; "too interconnected to fail" problem in financial network; resilience will weaken under external shocks; resilience has a general dynamic mechanism.
multi-layer network	Korniyenko et al. (2018), Huang and Wang (2020), Esmalifalak (2021), Chowdhury et al. (2019), Poledna et al. (2015), Battiston et al. (2016), Jing and Chao (2022).	Complex network analysis; dynamic system.	95 countries/ regions; Asian market and the rest of the world.	central countries are more influence; This structure reduces the ability to withstand financial risks; multi-layer structure of the financial network comes from the investment relationship.
Toplogical network	Au (2021), Bargigli et al. (2014), Tang et al. (2018).	textual mining; sentiment analysis.	Chinese and American financial markets.	financial network has different topological properties.

General cyber-physical resilience is researched in more detail (Wang et al., 2011; Shi et al., 2014; Dehghanian et al., 2018; Ghorbani-Renani et al., 2020; Almoghathawi & Barker, 2019; Chen et al., 2019; Chiou, 2018). However, the multiple networks of networks formed by different financial networks have complex structural dynamic mechanisms. There is no mature work on the financial system. Further, there are few studies on the causal decoupling and intervention relationships of resilience characteristics in a network. Currently, the resilience information representation and motivation mechanism of the internal and external characteristics of financial networks is less analyzed.

3.2. Risk contagion in financial networks

The systemic risk caused by financial networks is the main problem in relation to modern financial market risk prevention (Kou et al., 2019). The widespread use of the law of financial risk in a network is different from that in traditional financial markets. Due to the differences in structure and the different roles of key nodes in the financial network, the spread of risks in the network presents different characteristics. For example, Choi (2014) considers that large financial institutions will have a positive impact on financial networks. Therefore, supporting the development of large institutions can effectively help maintain banking system stability. Further, Amini et al. (2016) use a non-uniform directed graph to study the cascading process and gradual contagion of a financial network, and propose that minimum capital ratios of institutions in the financial network need to be set for the degree of contagious exposure. Network topology has a significant impact on system robustness and also influences the effects of different rescue sequences. Different types of events have different degrees of influence on the connectivity and robustness of a stock market network. Gao (2021) indicate that systemically important companies can actively suppress the spread of shocks in production networks, given that companies in the US economy are closely connected in the production network and are affected by the impact of the internal transmission of the network.

Other studies show that the geographical distribution of financial institutions is also a reason for systemic risks. For instance, Chu et al. (2020) find that the geographical diversification of various banks increases the possibility of holding similar asset portfolios among banks, which exposes banks to the same risks and increases the systemic risks in the banking system. Yang et al. (2019) use a modified spillover index approach to explore China's financial institution network after the global financial crisis, finding that non-bank financial institutions also have considerable influence. Large market-oriented commercial banks typically outperform the four large state-owned banks in transmitting financial shocks. The variance decomposition network method, tail risk contagion of multi-tier financial networks and co-high-order moments (e.g., co-skewness, co-volatility, co-kurtosis), risk contagion determination method, opinion dynamics (Zha et al., 2020), fuzzy rough set theory (Hu et al., 2021), financial aware spatiotemporal social network analysis (Ruan et al., 2019), and data envelopment analysis (Kaffash & Marra, 2017) are empirically used methods in financial network risk detection. Additionally, multi-objective decision-making methods are common risk decision-making methods (e.g., Lin et al., 2020; Zhang et al., 2021; Kou et al., 2014, 2016, 2021a, 2021b; Chao et al., 2018, 2021a, 2021b, 2021c; Jing & Chao, 2021).

In short, there are few studies on the measurement model of financial resilience from the perspective of network structure (i.e., the composite system of a node's own dynamics and its associated dynamics), calculation method of node resilience, and intervention and modification relationship between sub-network collusion structure and network resilience.

4. Resilience governance in financial networks

Financial regulation and financial stability maintenance are facing an increasingly complex economic and financial environment, which makes them more challenging to achieve. The modern financial network is linked and the degree of coupling between market entities and transactions is increasingly higher. Further, the spread of financial risks is more concealed and faster, which is why regulation becomes more difficult.

4.1. Bankruptcy reimbursement mechanism in financial networks

The asset repayment mechanism and risk management of financial networks are more complex. Bankruptcy disposal often needs to consider issues such as pairwise netting and ownership association of a network. The disposition of bankruptcy payments for the companies in the financial network has been a hot issue in recent years, providing a theoretical basis for financial regulation. Csóka and Herings (2020) study the axiomatization of the bankruptcy repayment ratio in financial networks in terms of management science. They point out that debt relationships in financial networks need to consider the debt of the affiliated agents, as well as the net settlement of joint claims. Moulin and Sethuraman (2013) consider the fair distribution of claims when resources are lacking under two-way rationing. Csóka and Herings (2017) find that decentralized asset liquidation under the default state has the same results as the centralized liquidation under a sufficiently small unit of account. Further, there are differentiated uncertainty spillover network structure characteristics in transnational economies, and different economies have different contagion patterns. Regarding the systemic risks in a financial network, macro-prudential policies should be divided into a more refined way, and monetary policy and macro-prudential policies should be combined to establish and improve a macro-prudential policy framework. Christopher and Tesar (2019) find that lifting of the systemic important financial institution designation can bring about an increase in corporate wealth.

4.2. Regulatory technology for financial network resilience

The current financial risk governance needs to start from the complex relationships between the virtual and the real economies by facing financial risks, security, and innovation and regulation in the complex financial system and building a risk management model different from the traditional one to meet current challenges. The development of regulatory technology (Reg-Tech) is a powerful means to achieve effective financial regulation, that is, financial compliance and stability through information technology. This concept was first proposed in 2014 by Andy Haldane, the chief economist at the Bank of England. In a narrow sense, regulatory technology refers to the technology developed by the financial industry to meet compliance requirements and assess risk management. Broadly, regulatory technology includes the use of information technology by regulatory agencies to improve the efficiency of their supervisory industry responsibilities and financial technology has established a new regulatory technology mechanism (Arner et al., 2017; Buckley et al., 2020). The application of artificial intelligence, machine learning, and other technical means to the supervision and disposal of financial risks is a new research hotspot (Currie et al., 2018; Wall, 2018). In this respect, Chao et al. (2019) propose a monitoring and early warning intelligent decision support system for trade money laundering. They also establish a standardized fusion method for multi-dimensional heterogeneous data, construct data feature engineering, and propose information management and classification methods for regulation cases. Singh et al. (2021) study the intelligent monitoring of money laundering in charity activities. There are also some views that there are negative effects of regulatory technology. For instance, Packin et al. (2018) consider there may be an anti-RegTech phenomenon. Specifically, many of RegTech's automation and efficiency improvements have been offset by the expanded regulatory costs. Anagnostopoulos (2018) puts forward an explanation of banking and regulatory issues from the behavioral perspective, indicating that a more liberal and principled approach to financial regulation should be adopted. Therefore, choosing appropriate technical regulation is beneficial to the financial industry. Based on the network resilience perspective, Liu et al. (2019) propose a genetic algorithm approach for parameter selection under gradient boosting decision tree and integrated network-based variables for financial distress prediction, which can enhance predictive performance in terms of accuracy. Avdjiev and Takáts (2019) point out that the monetary networks in cross-border bank loans have a significant impact on monetary policy spillovers. This has had a serious negative impact on cross-border funds flowing into emerging markets. Hautsch et al. (2015) proposed a method to measure the

Table 3. Representative resilience governance methods

Category	Literatures	Main methods	Data	Main results
Bankruptcy reimbursement mechanism	Csóka and Herings (2020), Moulin and Sethuraman (2013), Csóka and Herings (2017), Christopher and Tesar (2019), Kwon (2021), Jun and Yeo (2021).	Axiomatic method; regression analysis; firm's Value-at-risk; time-varying marginal effect analysis.	Simulation data; Financial Stability Oversight Council; USA Metlife data, etc.	Asset disposal needs to combine the relationship between financial network and capital network; Resource matching considering network spillover effects.
Regulatory technology	Arner et al. (2017), Buckley et al. (2020), Currie et al. (2018), Wall (2018), Chao et al. (2019), Singh et al. (2021), Packin et al. (2018), Anagnostopoulos (2018), Liu et al. (2019), Avdjiev and Takáts (2019), Xiao and Ke (2021).	Regression analysis, statistical inference, supervised learning and unsupervised learning, etc.	International Banking Statistics; BIS consolidated banking statistics; loan supply between 17 developed source and 94 emerging market destination countries.	The currency network in cross-border bank loans has a significant impact on the scale, distribution and direction of international monetary policy spillovers.

contribution of financial companies to systemic risk in view of the network interdependence between corporate tail risk exposures. It can be used to monitor the systemic importance financial institutions, thereby achieving transparent macro-prudential supervision.

Based on the above-mentioned studies, the current risk regulation of financial networks focuses mainly on the identification of "large institutions that cannot fail", the coordinated use of macro-prudential policies, and the systemic-inducing mechanism of financial network risks (Table 3). However, the risk resistance and recovery of financial networks depend on a network's resilience. Currently, the research is based on the resilience nodes in a network composed of small and medium financial institutions, especially the risk resistance and resilience evaluation of the regional financial system from the perspective of network resilience, while the applications of resilience regulation are still insufficient. Regulatory technologies based on network resilience thus need to be developed into a means of quantitative regulatory policy analysis.

5. Discussions

In response to the urgent issue of maintaining financial stability, network resilience opens up new ways of financial regulation. In view of the current research status and hot issues, we identify below the main challenges and possible future research directions for the current context of resilience-based financial stability regulation (Figure 1).

5.1. Limitations

Financial resilience is closely related to the prevention of financial risks. Currently, there are relatively mature methods used for information resource management and the risk evaluation of financial networks, which also provide a good theoretical basis and methodological guidance for further research on financial network risk regulation from the resilience perspective. Additionally, many limitations can be drawn from current research, as follows:

(1) The current research on financial networks focuses on topological properties, such as network structure, network information, and network partitioning, but there are few studies on the network resilience of financial systems. In-depth research on the topology and information integration of financial networks, characterization of financial network resilience, exploration of financial network resilience measurement, and clarification of the evolutionary law of financial network resilience under external shocks form the theoretical and information foundations of financial network risk regulation.

(2) The current financial resilience research mainly focuses on the mechanism and determinants of financial resilience and other macro policy research but, from the perspective of network resilience, the financial system has a lower ability to withstand risks and recuperate development. As research is aimed at the network of financial sub-network interaction structure, it is necessary to start with the correlation between the structure and resilience of financial sub-networks and study the resilience assessment of regional financial networks and other related issues.

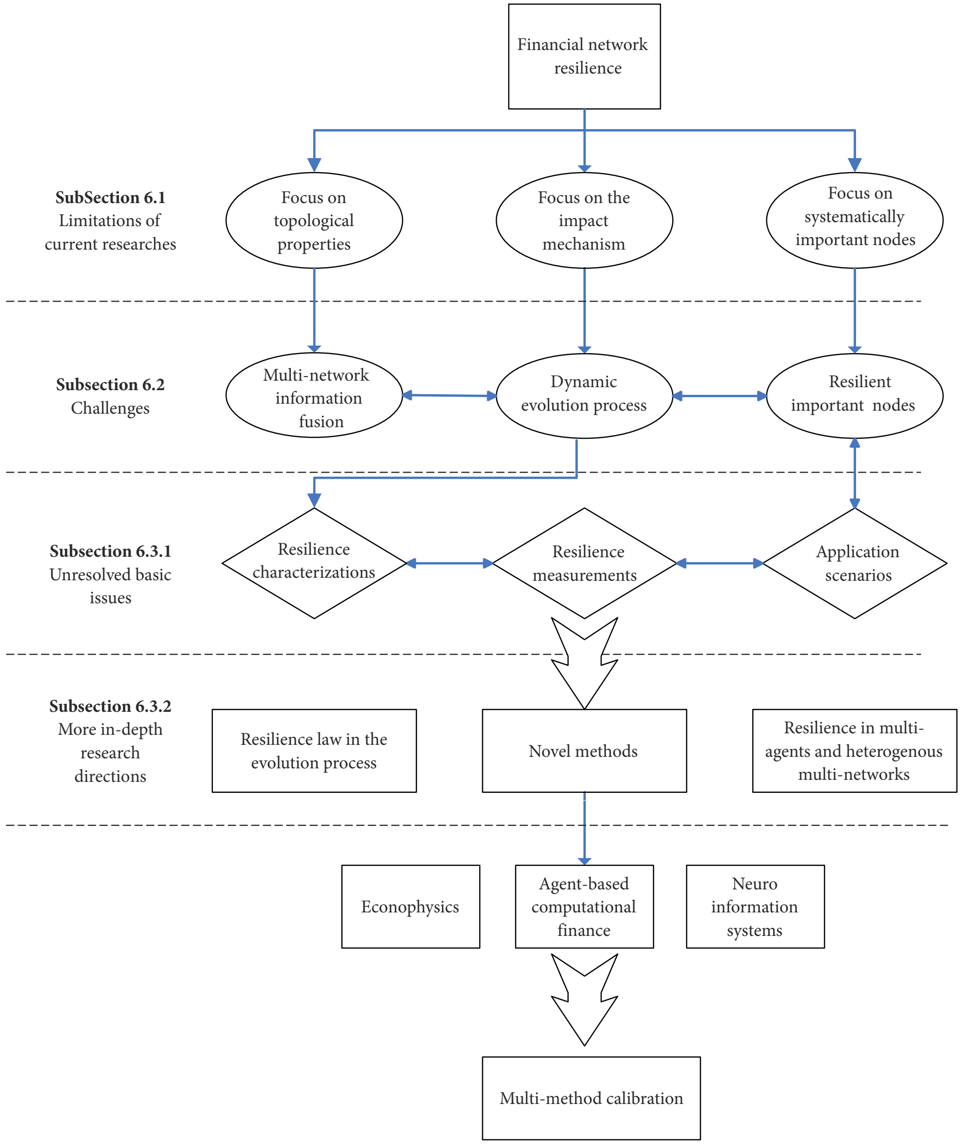

Figure 1. The further research framework

(3) The research on systemic risk evaluation methods is relatively mature and the risk contagion in the financial network pays more attention to "large institutions that cannot fail". However, the identification, monitoring, and early warning of resilience of financial institutions are being paid less attention, and there is also insufficient research on the evaluation of resilience of financial networks. Therefore, from the perspective of network resilience, studying the resilience management of regional financial stability, especially the resilience management of financial networks, is of great significance for advancing financial reforms and maintaining financial security.

5.2. Challenges

Although there are many studies on financial networks, we have also seen that these studies focus on the analysis of risk transmission mechanisms and influencing factors in the network. Research on the resilience of financial networks is still insufficient. The main reason is that there are many challenges hindering the development of in-depth research, as follows.

Coupling the construction of financial networks with information networks. The entities in the financial market form a financial network based on the financial transactions between them, which is common in regional financial markets between non-bank financial institutions such as city commercial banks and rural commercial banks, local asset management companies, financing guarantee institutions, mutual credit assistance, social crowdfunding institutions, and various local trading venues. In fact, there are interactive relationships among the senior managers of financial institutions, especially for the alliances of local financial institutions (Colladon & Remondi, 2017). The financial annual reports, financial news, and scandal disclosures in the financial market have caused many information associations among financial institutions. How to establish the information coupling network of financial entities, obtain the characterization and evolution mechanism of financial network resilience, and describe their characteristics is a challenge in this research field. This requires not only realistic data support, but also theoretical analysis and empirical research on the coupling relationship between multi-source heterogeneous networks. Of course, text mining and complex network analyses are among the many methods to accomplish this kind of work. However, due to the periodicity of financial research, such research needs to undergo multiple economic cycle observations.

Resilience dynamic mechanism in financial coupling networks. There is a driving mechanism for the resilience of financial networks, because the nodes in the network have different effects on network resilience. Resilience damage recovery and the responses to external shocks have different mechanisms in different networks. However, the financial-information coupling network relationship is complex, which makes it challenging to verify the correlation and law of the information coupling network relationship and the evolution of resilience. Obviously, such research is at the intersection of information technology, complex networks, and financial risk management. Therefore, the methodologies in different fields need to be effectively applied throughout. This is a difficult problem in itself.

Resilience management of financial network stability. Traditional financial system stability management mainly aims at the regulation of "systematically important financial institutions" (Markose et al., 2012; Hautsch et al., 2015). In fact, the formation of risks in a financial network has hidden trigger points and the response to risks requires the management of financial institutions (Mensi et al., 2021), which are also important to network resilience, to realize the risk prevention of the entire financial network. The relationship between resilience-important financial institutions and systemically important financial institutions under resilience management is still unclear, and it is necessary to carry out challenging research on the substitution and complementary relationships between the two types of institutions.

5.3. Future research directions

Resilience is a prerequisite for regional financial networks to counter risks and resume development. A financial network constituted by financial entities carries financial functions and services and, at the same time, is the main channel for spreading regional financial risks. In the context of digitalization and networking, the credit choices and behaviors between entities are susceptible to mutual infection and influence, resulting in a complex dynamic mechanism for the formation and evolution of financial network resilience. The comprehensive description of financial network resilience requires insights into the interactions between different determinants and the evolutionary nature of financial network resilience.

5.3.1. Unresolved basic issues

5.3.1.1. The characterization of financial networks resilience

Financial network resilience mainly includes the formation, evolution path, and law of resilience in a financial network. Research on the influencing factors and mechanism of network resilience and the interaction relationships between network entities characterizes and describes the evolution characteristics of resilience. These form the theoretical basis for the evaluation of resilience in financial networks and the identification of the importance of financial institution resilience. The specific research areas are:

(1) Information coupling network construction. Construct the control and variable relationships between various related groups and networks at various levels to form alternative and complementary financial networks at these various levels.

(2) The characterization extraction of financial network resilience. Study the default status and network-related loss rates of network groups for different economic cycles and external risk shocks, as well as the dynamic nature of the current and lagging states.

(3) The determinants of resilience shocks based on the key internal and external determinants of the resilience of regional financial networks. For example, the external environment includes macro-influence indicators, such as domestic and foreign policy influence, economic geographic characteristics, regional financial culture, and internal influence mechanisms (e.g., physical investment and financing constraints in the financial network), and analyzes the intervention methods and interactions between the internal and external influencing factors of resilience mechanisms.

(4) The evolution mechanism of financial network resilience. Study the co-evolution, interaction mechanism, and change characteristics of financial network resilience between different entities and for different economic cycles, summarize the formation, evolution and transformation paths of resilience, and establish the evolutionary resilience characteristics description and network resilience driving mechanism. As a result, a comprehensive definition of the resilience of the financial network can be provided.

5.3.1.2. Measurement methods for financial network resilience

Resilience is a multidimensional concept, which is why constructing a measurement model, identifying node resilience, and comprehensively measuring the resilience of the financial network are important components for financial network resilience management. Based on network dynamic system theory and big data processing methods such as data mining and machine learning, the research on the measurement method of regional financial network resilience includes the following main directions:

(1) Constructing a measurement model of financial network resilience. Based on the characterization of financial network resilience, a network stability measurement model can be constructed. This model includes the power function of the network node itself and the network weight correlation function. The functional expression form of resilience loss is also proposed.

(2) Calculation of the resilience of financial network nodes. According to the resilience measurement model, a method for calculating the resilience damage of the nodes between dynamic financial networks under external shocks is established. We can also determine, the connectivity of the financial network after some nodes are damaged, reconstruct the time and intensity model of the repair network, obtain the set of cut points for the traverse network, and realize the resilience stress test in the financial network.

(3) Revision of subnet structure and resilience. The financial network is not an independent network. Aiming at the sub-network structure formed by the associated subgroups in the network, the relationship between the intervention and modification of sub-network structure on resilience is studied. We can also monitor the structural characteristics of the sub-network of resilience destruction, and obtain the law of structure influence of the financial sub-network on resilience.

5.3.1.3. Evaluation of financial network resilience

The loss of resilience means the decline of the financial network's risk defense capability, which causes hidden risks in a regional financial network. To conduct early warning analyses of the risk status of financial networks from the perspective of resilience, it is necessary to develop scientific resilience evaluation methods, thus providing a new way of financial regulation. Based on data mining and multi-objective decision-making methods, there is a need for research on the integrated evaluation methods of financial network resilience, identification of network resilience in different stages of resilience evolution, and identification of key institutions (nodes) in financial networks that affect resilience. In sum, the main research areas include:

(1) Construction of an index system for resilience evaluation. Based on resilience loss measurement and node correlation resilience, comprehensive and scientific credit evaluation features are extracted to form an index system.

(2) Integrated evaluation of financial network resilience. By combining risk identification and resilience status-related monitoring with early warning methods; building a decision support system; and realizing an operable, visible, extensible, and interpretable financial network resilience evaluation system are important for constructing a dynamic monitoring method that integrates resilience and risk.

(3) Dynamic identification of key financial institutions that affect network resilience. Aiming at the response, repair, and adaptation stages of the financial network resilience evolution process, through the analysis of the dynamic loss of the nodes of a regional financial network, the institutions in this network that have the greatest impact on network resilience are identified. We can then identify the group of financial institutions that are important to the resilience of the regional financial network as the main target of the early warning management for financial network resilience.

5.3.1.4. Adapted and balanced management of resilience regulatory resources

It is feasible to use pattern recognition and classification techniques to identify the network resilience management characteristics by linking and embedding financial network resilience management and risk management to form an integrated management model of risk and resilience. There is also the need to establish resilience and risk efficiency boundaries and benchmarks through network data, including analysis and other methods, and establish resilience expectation management methods. Using the multi-detector game method, network node interaction is modeled as the interaction between multiple investigators and management goals are set for different investigators on the same network according to the resilience of nodes and of sub-networks. Through the shortest path multi-interceptor game solution method, the optimal path under different interception strategies is established and transformed into regulatory resource adaptation and balanced management strategy under resilience dimensions such as the asset level.

5.3.2. More in-depth research directions in the future

The financial system is obviously different from other organizational relationships. On the basis of basic research on the nature of financial networks, it is necessary to deeply explore the main factors affecting the stability of the financial network, the law of the evolution of the financial network itself, the research methods of complex financial systems, and so on. The content mainly includes the following aspects:

5.3.2.1. Resilience in the evolution of the large-scale financial system

The actual financial system is not just a few subjects, but a significant giant system. The entities of the large-scale financial network system have autonomous behaviors. Although the structure of the system is endogenous, these financial network structures may also exhibit different evolutionary processes under the influence of different market transaction mechanisms, legal environments, and risk culture characteristics of market participants. These different evolutionary processes in turn affect pricing laws and trigger different financial risk propagation processes. Then, in this dynamic evolution process, what kind of change trend the network' resilience exhibits is a question worthy of study. At present, with the continuous growth of computer computing power and increasing modeling methods, it is necessary to simulate the changes in the resilience of large-scale financial systems under the evolving environment. Incorporating factors such as the endogenous evolution of the financial system into the resilience analysis framework may be an important trend and hot frontier of future research.

5.3.2.2. Financial network resilience under multi-agents and heterogenous multi-networks

One of the main characteristics of financial networks is different information diffusion mechanisms. In the Internet environment and the modern financial market, the emergence and popularization of new communication methods have made the exchange of information between individuals faster, and the diffusion of information in different external environments shows a differentiated transmission law. As a result of information diffusion, the interaction between different financial networks has become more complicated. In the financial market, the capital network of the bank entity, the production network of the lending entity, and the internet financial information will all have an interactive impact. What kind of influence law is the resilience of these financial markets with multi-agent and multi-network structure is another hot topic of research in the future. For example, in the industrial chain financing network, the resilience of the supply chain network and the resilience of the financial network have an interactive effect. How they affect the stability of the financial market, and what rules of risk absorption and deepening can be produced by the interaction of the dual networks are vital to financial stability. Putting the two aspects into the same analytical framework is a challenging task.

5.3.2.3. New research methods in the study of financial network resilience

Regulatory technology is actually the identification and management of financial risks that are applied to various types of smart technology. Compared with traditional supervision methods (macroprudential policy formulation, ex-post supervision, liquidity and capital adequacy ratio regulations, etc.), supervisory technology can integrate financial data from different sources to dig out effective supervisory information. We have found from existing researches that financial networks and network resilience provide new research ideas for regulatory technology. However, the methods currently used mainly focus on complex network analysis and its derived related methods. New research methods need to be further introduced and we explore the feasibility of several methods in the network resilience study.

(1) Agent-based computational finance (ACF). ACF is an important financial research method besides "experiment", "empirical" and "mathematical analysis". The financial system is composed of a large number of adaptable and interacting individuals, and the system structure is a "complex system" with endogenous evolution. ACF is precisely aimed at describing the characteristics of self-adaptive and interactive individuals, carrying out "bottom-up" micro-modeling of the financial system, and exploring the complex evolutionary dynamics and micro-formation mechanisms of asset pricing in financial networks. For example, the most-used methods in recent researches mainly including individual reinforcement learning, population evolution analysis, and empirical mode decomposition and so on.

(2) Econophysics. Econophysics is an emerging interdisciplinary subject that uses concepts, methods and theories such as statistical physics, theoretical physics, complex system theory, nonlinear science, and applied mathematics to study the macro-rules and their complexity of financial markets emerging through self-organization. The main feature of this method is that it can simulate the adaptability of the subject in a complex system, thereby revealing the overall stability and evolution of the complex

system. The resilience of the financial network is just such an adaptive system. Using financial physics to study the resilience of the financial network is a necessary choice and one of the future trends. The main methods include multifractal characteristics, probabilistic model of microscopic subjects, and game model and so on.

(3) Neuro information systems (NeuroIS). NeuroIS is the application of cognitive neuroscience theories, methods and tools in the field of information system research. It studies and solves a series of related questions in information system research from a new perspective. The research mainly includes the fields of system design and optimization, information service and decision-making, social network and interaction. NeuroIS is the application of cognitive neuroscience theories, methods and tools in the field of information system research. It studies and solves a series of related questions in information system research from a new perspective. The research mainly includes the fields of system design and optimization, information service and decision-making, social network and interaction. In financial networks, system optimization design, information services, and network interactions are directly related to financial network resilience. The verification of the influencing factors and evolution of network resilience through NeuroIS is one of the important research trends. The path to combine with resilience may be stress testing methods such as financial risk shock scenario experiments and financial market multi-task experiments.

5.3.2.4. Multi-methods calibration in financial network resilience

Similar to the research we put forward in 5.3.1.4, financial market resilience and financial stability supervision is actually a kind of balanced management. The research of supervisory technology is a system stability experiment under real data or simulated scenarios. Then the calibration problem of multiple methods is an interesting problem. The calibration method will involve model setting error, model robustness, real data verification, linear system or nonlinear system error, and so on. The main methods include multi-scale geometric analysis. Of course, how to set the parameters and scale analysis of these methods in the resilient evolution of complex financial networks will be challenging tasks in the future.

Conclusions

The modern financial market is a complex network of extensive connections. In this context, the resilience management of financial networks is a new approach to financial stability regulation. Recently, the study of financial networks and network resilience has become a hot issue in the fields of financial regulation and information science. Therefore, the summary and discussion of the network resilience of financial networks play a key role in linking the past and future research in this field. This study summarizes the existing research and the main research categories. We also analyze and expand important issues such as the concept of resilience, financial resilience and network resilience, and resilience management. We consider the main research progress, key issues involved, and limitations. Challenging issues in current research and future research directions have also been put forward.

The financial networks constructed according to the financial transactions in different countries and regions have varying natures. The structures of these networks are either dynamically related or multi-layered. Through diversified research using network analysis, econometric analysis, and stress testing, such as the minimum generation tree, it can be concluded that:

(1) Financial network structure has an important influence on the spread of financial risks, and the degree of resilience of the nodes in different structures. The differences also have different effects on network resilience.
(2) Countries with developed financial markets (e.g., the United States and Japan) have the greatest impact on global financial network resilience, and hold central positions in the financial network.
(3) The stability of the financial system can be comprehensively assessed through financial network resilience. The financial institutions located as central nodes in a financial network can be used to enhance financial stability regulation.
(4) Financial networking is an inevitable trend in financial market integration and the future network structure will be more complex, which poses significant challenges for financial regulation.

We also analyzed the limitations and challenges of current research, and proposed future research directions as follows: (1) the coupling mechanism of financial networks and information networks, (2) the measurement of network resilience in financial networks, and (3) the evaluation and application of resilience in financial networks. We believe scholars continuing to study the network resilience of financial networks will definitely lead to new development prospects in this field.

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