Summer 5-27-2016

The Review of Network Theory Applied to the Financial System

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Abstract: As the globalization is developing, financial interdependence has been increasing sharply among financial organizations, such as central banks, commercial banks, investment banks, etc.. And the relationships in this system can be perfectly explained as network structure. Many researchers have studied a lot in this intersection. In this paper, we select 158 literatures (2004-2016) from SSCI journals, and summarize the relative researches about network theory applied to the financial system in the western world. This research shows the development of financial network theory and four aspects of latest research results. In the future, IT will be the major driving force and the most popular solving method to analyze the financial network related problems.

Keywords: network theory, financial network, contagion, cascade effect

1. INTRODUCTION

Nowadays, network structure is applied to many areas in our life, such as social relationships, enterprises' organization structures, and interbank markets. Network, which is widely understood as a collection of nodes and edges, can be a useful method to depict the interrelationships among organizations, and explain the idiographic effect that one organization has on another. For example, in interbank markets, banks are the nodes in this network structure, and edges represent the lending relationships between banks. In this setting, if the collateral's value of one bank decreases, it may trigger an adverse effect on other banks' value through the lending relationships. Therefore, it can be predicted that a small fluctuation can result in a significant drop in lending and borrowing activities across the network.

The network theory can explain the reason of many financial problem. Take the big turmoil in financial markets in August 2007 for an example. For the high degree of intertwined nature of financial systems, when the shock in the U.S. subprime mortgage market occurred, it rapidly spilled over to debt markets all over the world. The contagions spread through the claims on each financial organization, and these claims, such as debts, loans, cross-holdings, were also referred as edges in the networks. So, relative literatures have been increasing sharply since the 2007's financial crisis.

This paper selected 158 latest research literatures about network theory applied in financial system form SSCI journals, which induced and summarized the current research progress and trend around world in following sections. In the second section, we introduce the concept and the origin of network theory. The third section analyzes this review process in four dimensions, such as literature sources, research subjects, research in static-dynamic view, and research in modeling and application of financial network theory. Then, the fourth section summarizes the limitations and presents the future research directions. Finally, the last section makes some conclusions.

2. DEFINITION OF CONCEPT

Network theory, originated from the study of graphs, is regarded as a representation of either symmetric relations or, more generally, of asymmetric relations between discrete objects. The network theory was first brought up by G.R. Kirchhoff in 1845. He applied the graph theory and matrix theory to prove two important

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laws of the bi-network theory, which built the foundation of the network theory.

Network theory has been applied in many disciplines and areas, including computer science, electrical engineering, biology, economics, operations research, and sociology. Recent years, its application to social networks and financial networks seems to be more and more popular. Because its specific network structure can well describe the particular relationship among these different individuals.

When it comes to the financial area, there is no doubt that modern financial system has exhibited a high degree of interdependence, with connections between financial institutions stemming from both the asset and the liability sides of their balance sheets. Such interdependence in the financial networks, like holding other's shares, debts, and obligations, can lead to cascading defaults and failures. When the first failure occurs, it will cause other financial organizations in this network fail. Finally, it may form a big financial crisis in a wider range.

3. RESEARCH AND ANALYSIS

To analyze the current situation of financial networks better, we choose 'financial networks', 'contagion' and 'interbank networks' as keywords to search relative literatures in WEB of SCIENCE. Finally we selected 158 literatures from over 220 pieces. The principles of selection are as follows.

- Literatures must be published by SSCI (Social Sciences Citation Index).
- We excluded proceedings papers, book chapters and book reviews, and retained articles at last.
- We excluded articles of physics multidisciplinary (categorized by web of science), and retained categories of economics, business finance, multidisciplinary sciences and mathematics interdisciplinary applications.
- Literatures which are obvious irrelevant with financial networks are excluded.

We made a classification and review to summarize and analyze the process of financial networks theory in different perspectives. After that we could further existing research contents and future research of financial networks, in order to find the unknown area of this theme.

3.1 Journal sources analysis

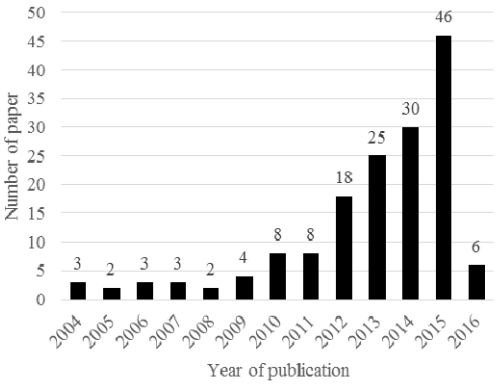
Among the 158 literatures selected, all of these belong to the SSCI journals, such as Journal of Economic Dynamics Control, Journal of Banking Finance, Journal of Financial Stability, Plos One, Quantitative Finance, Journal of Economic Behavior Organization and so on. The distribution by journals as shown in Table 1.

Table 1. Distribution of literatures from SSCI journals.

No	Journal	Quantity	Proportion
1	Journal of Economic Dynamics Control	19	12.025%
2	Journal of Banking Finance	14	8.861%
3	Journal of Financial Stability	11	6.692%
4	Plos One	9	5.696%
5	Quantitative Finance	8	5.063%
6	Journal of Economic Behavior Organization	7	4.430%
7	Computational Economics	6	3.797%
8	Scientific Reports	5	3.165%
9	Journal of Financial Intermediation	4	2.532%
10	Others	75	47.739%
	Total	158	100%

The period of all these literatures covers between 2004 and 2016 (In Figure 1). Since 2009, the number of literatures on financial networks has been surging along with the great financial crisis spreading all around the world. These literatures come from different countries, mainly focused in U.S and other western European countries. The financial networks theory were widely applied to those financial systems in those developed countries, for the higher degree of connection between different systems.

Figure1. Amount of literatures from SSCI journals.



As for the methods used in those literatures, it's revealed in this review research that mathematics with mathematics interdisciplinary applications is the main way to solve these problems.

3.2 Research subjects analysis

Having been studying carefully, the 158 literatures selected could be classified into following different categories (in Table 2 †).

Table 2. Classifications of literatures from SSCI journals by research subjects.

Category	Research subjects	Amount
Type of financial market	Banking market	14
	Interbank market	35
	CDS market	3
	Loan market	2
	Sovereign debt market	4
Type of risk	Credit risk	10
	Systemic risk	28
	Liquidity risk	8
	Rollover risk	1
Mechanical	Networks contagion	31
	Networks structures	19
	Networks characteristics	19

- When talking about the categories of different financial markets that forms the financial networks (58 pieces), there are banking markets (14 pieces), interbank markets (35 pieces), Credit Default Swap (CDS) markets (3 pieces), loan markets (2 pieces) and sovereign debt markets (4 pieces) discussed in these literatures.
- When selected in different types of risks spread in financial networks, these literatures discussed credit risk (10 pieces), systemic risk (28 pieces), liquidity risk (8 pieces) and rollover risk (1 pieces).
- There are 31 literatures researched on networks' contagion problems. The other research problems in financial networks theory are network structures (19 pieces), and network characteristics (19 pieces).

† For the reasons that each category may not completely cover all the 158 literatures, and each literature may include two or up to two themes in the following subjects, so the number of literatures ("pieces") does not add up to 158 in one category, and the total amount in the following table is not 158.

3.3 Research in static-dynamic classification

3.3.1 Static View: the structure of financial networks

Structural type. Nowadays, the literatures about financial networks focus much of their investigation on the structural characteristics which describe the networks from static view. Many scholars take the structural type of networks as a tool to research more features of the financial networks. Such as the core-periphery model (Elliott et al., 2014[1]), ring network model (Allen and Gale, 2000[2]), power-law distribution (Gabrielli, 2011[3]), networks with externalities (Acemoglu D, 2013[4]), heavy-tail distribution (Bech and Atalay, 2010[5]) and a model with segregation among sectors (Elliott et al., 2014[1]).

Structural property. Besides, some properties of networks are used as the breakthrough point to analyze financial networks, such as robustness and fragility[6]. In a special condition, for example, a financial network where linkages not only spread contagion but also induce private-sector bailouts in which liquid banks bail out illiquid banks because of the threat of contagion, if liquidity is concentrated among a small group of banks, the whole network may collapse[7]. We know that the network is fragile since banks have an incentive to gamble with depositors' money when not sufficiently capitalized. It turns out that both the efficient financial network and the decentralized one are characterized by a core-periphery structure. Under the assumption that bank capital transfers are not possible, it can be shown that the two structures coincide if the counterparty risk is sufficiently low[8].

Structural complexity. Complex network includes all or part of those properties, which are self-organized, self-similar, self-attracted, small-world and scale-free properties. In recent years, the academic research on complex networks is just unfolding. In particular, the two pioneering work raised a study upsurge of small complex network. One is that Watts and Strogatz [23] published in the Journal *Nature* in 1998, the paper introduced the Small-World model to describe the transition from completely regular network to completely random network. The small-world network not only has the clustering characteristics which is similar to those of regular networks, but also the average path length which is smaller the random network. Moreover, in 1998, Barabasi and Albert [24] published an article claimed that the connection degree distribution of many real complex networks has power law form.

Like the complex networks in other areas, the real financial network also shows the complex characteristics of small world network and scale-free network. Gabrieli [11] studies the overnight lending market network in European countries and finds that the network is very scattering, with characteristics of a small world network, and the distribution of its nodes are subjected to power-law distribution. That is, the majority of banks only build relationships with a fewer banks, and there are only a small number of banks, which are usually large banks, have a larger network connections. Similar to that of European bank overnight market network, American federal funds market network also has the characteristics of small-world network, but distribution of network node degree is a heavy-tailed distribution rather than a power-law distribution [5].

3.3.2 Dynamic View: the contagion of financial networks

In recent years, most scholars are interested in the contagion in the financial networks as well as the formation of this contagion. That is, we can also analyze the financial networks from dynamic view, which is more popular in recent literatures. Financial contagion is usually modeled as an equilibrium phenomenon. The possibility of contagion depends strongly on the completeness of the structure of interregional claims, and it is shown that complete structures tend to be more robust than incomplete structures [2].

Cause of contagion in financial networks. How did it happen that the edges in financial networks is formed in reality? Generally, there are two factors as follows. First one is cross-holding, which occurs when corporation holds securities issued by other listed corporations [9]. Notable examples include the stock markets in Japan, Germany, and several other European countries. Such cross-holding is found, albeit to a lesser extent,

in US securities markets as well. Second one is interbank lending, also known as 'debt' between banks. It plays a key role in the financial system, which is vital to banks' liquidity management [10].

Factors of contagion in financial networks. Because of the previous introduction and analysis of this paper, the real financial system presents increasingly complex network characteristics. Moreover, the complex network mainly manifested in the following aspects，which constitute the factors of the real contagion. First, the complex network can constantly evolve, which shows on the production and disappearing of nodes or edges in the financial networks. Second, the complex network has diversity of connection, which influence the weights of edges between nodes, and the direction of edges. Third, the complex network has dynamic complexity, which means the nodes may belong to nonlinear dynamic system, in other words, the state of nodes vary as the time goes. To conclude, the complexity of the financial network affects the stability of nodes and edges, which turns to the result that the contagion will be stochastic and unpredictable.

For example, we know that the banking institutions are the nodes of the network, and the relationships of the assets and liabilities between banking institutions constitute the edges of the financial network. But it's hard to figure out how much each bank owns other banks' debts or crossholdings or how they operate between each two banks. Things are always changing in a dynamic view. Thus, this banking market can be regarded as a kind of complex financial network which is conducive to the distribution of liquidity, however, the risk may occur that a single bank's failure can spread to other banks, because no one can predict the changes happening in this network, no one can do any bailout measures, and then there will be a Domino effect, resulting in the collapse of the entire financial system. Acemoglu et al. [4] called this cascading reaction as the contagion (also called "Externality") of financial network.

The externality of network can explain the overall vibration related to social economy which cannot be cleared by the internal variables, such as the stock market crash, group events and so on. For the reason that social and economic activities are embedded in social networks, the individual's activity is influenced by the result of the other individuals in this group [11]. Thus, if we regard the financial system as a financial network, when faced with financial risk, we need to pay attention to "Too-Big-to-Fail" risk, as well as the "Too-Connect-to-Fail" risk [12].

Results of contagion in financial network. When talking about the credit risk in a network economy, Henri Schellhorn [13] studied a structural model of credit risk based on queueing theory. This model is used to analyze an economy composed of I firms engaged in a network of possibly looping lending relationships, that is, we can price the debt of 3 firms A, B, and C, where A lends to B, B lends to C, and C lends to A, so that loop effects are complex and indirect. When there are no fixed or linear refinancing costs, so that debt is completely volatile. And if we deal with linear refinancing costs, with results in quasi-constant debt. Besides, Allen and Babus [14] addressed the issue of systemic risk by studying two questions: how resilient financial networks are to contagion, and how financial institutions form connections when exposed to the risk of contagion. While more links between banks might be expected to increase the risk of contagion, their research shows that banking systems with a more complete set of connections may be less susceptible to contagion than those with an incomplete structure. Prasanna Gai and Sujit Kapadia [15] developed an analytical model of contagion in financial networks with arbitrary structure. They model two key channels of contagion in financial systems by which default may spread from one institution to another.

Finally, some scholars cared about the rescue in an interbank network. Traditional solutions such as the issuance of new equity or bonds cannot be achieved in the timescales available. More recent study paid attention to this field. For example, L.C.G Rogers and L.A.M Veraart [16] modeled this market as a directed graph and provide a rigorous analysis in which banks have incentives to bailout distressed banks. They discussed possible measures of soundness of a financial system, together with possible policy implications for resolution of

distress.

3.4 Research in modeling and application of financial networks

The literatures use financial network modeling to evaluate the risk of the system in the process of setting up the risk. The literature usually assumes that a bank or banks go bankrupt at the same time, which will lead to the bank creditor bank interbank assets loss. If the loss is more than the capital of the bank creditor's rights, creditor banks bankruptcy, which occurred in the domino effect [20]. In reality, the risk contagion process is very complex, not only the bank's default will make the bank bankruptcy, the crisis period creditor bank in advance to recover the debt of bank loans will also lead to the bank's liquidity crisis. Some banks even have to sell off assets. In addition, the common impact of the banking system will also reduce the stability of the whole banking system through the use of a single bank's capital, such as macroeconomic fluctuations, real estate prices led to the increase in real estate loan defaults, etc.. Therefore, a small amount of researches have attempted to combine the liquidity shock, the common impulse and the risk exposure of banks, and the financial network model is used to evaluate the risk of the system.

Another important application in the research of financial network is to evaluate the risk of the system by using real data. If you can get balance sheet data between banks, accordingly, it can be used directly to construct the network. The effects caused by one or more bank bankruptcy risk contagion can be studied, such as Müller [17], Degryse and Nguyen [18], Sokolov [19], etc.. However, in reality, balance sheet data between banks is difficult to obtain, but we can use maximum entropy method [20] to make estimation of bank assets and liabilities positions.

According to the data of total liabilities between the bank’s total assets from German banks' balance sheet, Upper and Worms [21] used the Maximum Entropy Method to estimate between banks and asset liability positions, and then do research on risk contagion problem by setting up bank network. They found that probability of infection in German banking system is very small, but once it happens, only through the bank's assets and liabilities exposure it can lead to large-scale risk transmission. This method has been widely used due to solve the data problem, for example Mistrulli [22] of the Italian banking system research, Degryse and Nguyen [18] of the Belgian banking system research.

4. RESEARCH LIMITATION AND FUTURE RESEARCH

This paper is just based on foreign research literatures rather than domestic literatures, which is the main limitation of our research. In the future, we are going to make an intensive study of the difference between China and the Western world.

Besides, because the data is not available, the characterization of the real network structure is not comprehensive, and the evaluation of the risk in the system can only be a reference. In the future, there is a trend to apply the financial network theory to evaluate different types of risk, such as the setting of the default loss rate, the liquidity shock and the parameter setting of the common shock, spread in the different types of financial system.

By the description of the maximum entropy method, it seems that the Maximum Entropy Method has assumed that the financial network is fully connected to the network, that is, every bank is in a transaction with other banks, which is clearly not in conformity with the real network structure. Mistrulli [27] compared the real data and the network based on the Maximum Entropy Method to estimate the data the network set up, found that using Maximum Entropy Method to establish the network will overestimate the degree of risk contagion. Therefore, the financial network model based on the maximum entropy method cannot accurately assess the risk of the system, and it can only be a reference.

As the Internet technology and information communication technology develop so fast. More and more

innovative forms of financial individuals have played an important role in nowadays financial networks. For example, the number of peer-to-peer financing platforms surges in a large scale. These electronic financing platforms also have connections and interactions with each other. Because of its instability and scattered distribution. This area is going to be the future research target.

Moreover，the Internet finance which is integrated with traditional financial is bound to become a rapid rising field in recent years. The advantages of Internet technology in information collection, product delivery and risk prevention is expected to be the engine for traditional financial institutions to reform. The advanced technology and organization mode of the Internet would help the tradition financial corporations expand their service areas and improve the working efficiency, through with the traditional financial institutions would accomplish the adjustment and transformation. Faced with the developing big data technology and cloud computing, the financial network would inevitably turn to a more complex and efficient system in the future.

5. CONCLUSIONS

Our financial systems are networks, and today these networks have grown increasingly complex and interlinked. In this paper, we analyze the financial network from both static view and dynamic view. We first study the structural types and properties of network such as robustness, fragility and complexity. More recent work has focused on the contagion of financial networks especially in interbank markets as well as investment and corporate governance. There are also some literatures that have referred to the rescue in an interbank network. Moreover, we summarize the modeling methods and application of financial network theory in this area. These research results are very helpful for us to know more about the trend of financial networks and predict its future research directions.

ACKNOWLEDGEMENT

This research was supported by the National Natural Science Foundation of China under Grant 71471038.

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