A Review of Financial Risk Contagion Modeling Based on Complex Systems Approach

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Abstract. At present, the number of domestic and foreign literature on modeling and analyzing financial risk contagion based on complex network theory is large and rich. These models can be mainly divided into four aspects: continuous, credit, behavioral, and discrete. In this paper, we have made a more comprehensive compilation and review of the relevant studies from these four aspects, and we have also made an outlook on the future development trend of, with the purpose of providing scholars engaged in academic research in this field and regulatory authorities with reference and ideas.

Keywords: Financial crisis; contagion risk; complex systems

1 Introduction

The purpose of the financial market at its inception was to provide funds for the real economy and to ensure the smooth operation of the economy. As financial markets have grown and financial products have been introduced, they have gradually become detached from the real economy and investors have become speculators. The collapse of financial markets has spread around the world through various channels, affecting the stability of the overall financial system and jeopardizing the normal operation of the global real economy[1]. Financial risk contagion has become an inevitable issue in the history of economic development. With regard to the definition and existence of financial risk contagion, the broad definition is that contagion is the general process by which shocks are transmitted across countries. Shocks occur in both non-crisis and crisis periods, and crises are associated not only with negative shocks but also with positive spillovers. Narrower definition: A shock is a situation in which shocks are transmitted between a group of countries in excess of what would be expected based on fundamentals[2], and in which there is a linkage caused by a common shock;

Financial markets, like many other systems, have a similar complex organization and dynamic behavior. Edgar (1999) pointed out that the actual financial market is a typical complex system, and its self-organization, nonlinearity, and self-adaptation, diversity, evolution, and emergence all show great similarity with complex systems. The studies of Bekenski, Iwane and others have proved the complex network charac-

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teristics of financial systems[3]. Schweitzer et al. (2009) clearly indicated that with the deepening of our understanding of the dynamic evolution of the financial system and the further enhancement of the complex network model[4], the network research of financial system will play an effective role in promoting the policymaking of decision makers in the future.

Based on this, this paper provides an overview of the financial risk contagion models are comprehensively and meticulously summarized and dissected to gain an in-depth understanding of the mechanisms and transmission paths of financial crises[5], to analyze the interconnections and interactions within the financial system at the micro- and macro-levels[6], and to provide theoretical support for the understanding of the instability of the financial market.

2 Financial Risk Contagion Models

Financial markets have different types of sub-markets, including not only the interbank market, futures market, stock, but also various kinds of complex financial derivatives market. Therefore, in this paper, based on the viewpoints of He Jianmin et al. (2012), we four types of contagion risk and their main models and methods according to the different nature of contagion risk generated by different financial markets[7]. Of course, due to the wide variety of financial products and the rapid development of financial markets[8], the above categorization and modeling still cannot be called perfect.

2.1 Continuous Financial Risk Contagion Model

2.1.1 GARCH Models.

The GARCH model belongs to the generalized ARCH (Engle, 1982) model, which was developed by Boleslef[9].

The GARCH model reduces the complexity of parameter estimation, and the simple low-order GARCH model can replace the high-order ARCH model to analyze and predict the samples with volatility[10] characteristics (Gao, M.F., Zhou, D.W., 2021). The formula is $\sigma 2t= \omega+ \alpha \sigma 2t-1+\beta \sigma 2t-1$[11].

Where ω is a constant, α and β are parameter coefficients, $\sigma 2t-1$ is the residual variance for each period, and $\sigma 2t$ is the heteroskedasticity for each period The values of α and β range from zero to unity to indicate the invariant variance of the error term. This model plays a very important role in finance by using past volatility and past error terms to predict future volatility[12] (Yi-Xuan Zhang, 2020).

The most widely used GARCH improvement model is DCC-GARCH, a model used by Engle Sheppard (2002) to estimate the dynamic conditional correlation between multivariate time series variables. The DCC-GARCH model can help us to understand the volatility of different kinds of assets, and to a certain extent, it can help us to reduce the propagation of risk [13](Li, Boyang, Zhang, Jiabang, Shen, Yue, 2023).

2.1.2 ACD Model.

With the development of technology, it has become possible to obtain every piece of data in the financial markets. As a result, the of sampling has increased, and this data is generally referred to as high frequency data. High-frequency data has become a hot research topic in the market.

However, the persistent irregularity of high-frequency data itself makes traditional econometric models potentially lose some data[7]

(Fu Keang Wu Mengxue Huang Wei, 2020). Engle and Russel (Engle and Russel, 1998)

The ACD model, also known as the autoregressive conditional duration model, was proposed. The standard ACD (p, q) model can be expressed as ACD is mostly used to analyze market liquidity in terms of duration or waiting time in financial events. After the ACD model was proposed, there are many scholars based on the ACD model to promote it, and nowadays, most of the parametric ACD models that are widely used are the QMLE model[14].

It has been shown that the limiting distribution of QMLE in the ACD model is sensitive to the finiteness of the tail behavior of the duration or the unconditional moments in the ACD model (Yan Haibo Peng Fengjiao, 2023).

2.1.3 SCD Model.

Financial ultra-high-frequency data (SCD) refers to the data collected in real time during the trading process[15], which not only includes real-time price and volume information, but also includes the time interval between transactions and the real-time status of the market order book at the time of the transaction. Currently, two types of models are mainly studied. One of them is the SCD model proposed by BAUWENS et al. SCD has advantages in fitting, but the model invokes double model variables[16], which brings difficulties in model parameter estimation, thus restricting the development of SCD model. (Wang Yannan, Dong Yaqin, Wu Qizong, 2014) The SCD model is a duration series model, which assumes that there exists a latent random variable that generates duration. This stochastic variable can be obtained from the stochastic information flow that exists in financial markets, which is generally difficult to observe. Wang et al. concluded that the biggest difference between SCD model and the ACD mode is that the ACD model has only one stochastic variable but the SCD model is a double stochastic process. (Wang Yannan, Wu Qizong, Liu Feng, 2011) Through the study of, it can be seen that the SCD model has a better fitting effect[17], and the model is more simple and clear, but the ACD model has a better convergence effect than the SCD model, and the convergence speed is faster.

2.1.4 Applications.

Continuous contagion risk models are important for financial market valuation, portfolio management and pricing of derivative products. Continuous contagion risk models are in capturing and forecasting the volatility of financial time series, and GARCH models are effective in predicting future volatility. In addition to this, continuum contagion models can also be used to calculate VaR[18], which is a widely used

indicator in risk management. VaR can be calculated by modeling the return on financial assets. VaR is a widely used indicator in risk management. It can be calculated by modeling the return on financial assets[19].

2.2 Credit-Based Financial Risk Contagion Models

2.2.1 KMV Models.

Theory of the KMV Model, also known as the Expected Default Rate Model (EDF model), is a risk-measurement model created by KMV based on the Black-Scholes option pricing theory for assessing the probability of a company defaulting on its obligations[20]. The central idea of the KMV model is to consider the ownership interest of the target company as a measure of the price of the company's assets.

The KMV model is a European call option based on the theory that if the market value of the company's assets is higher than the value of the company's debt at the time of debt maturity, the equity value of the company is greater than zero, and its equity value is the difference between the market value of the company's assets and the company's debt[21], and if the market value of the company's assets is lower than the value of the company's debt, then the equity value of the company has no value, and the company's shareholders, i.e., the debtor, may give up the company and default on their obligations (Shao-Rong Li, Xing-Yang Liu, 2023). The advantage of the KMV model is that it utilizes the modern option theory and makes full use of capital market information rather than historical book information to make, which makes it better reflect the current credit status of listed companies[22]. In addition, since the model is based on stock market data, it has a faster data updating speed and foresight. However, the model also has some limitations, such as its harsh assumptions, in particular, the distribution of asset returns may not satisfy the assumption of normal distribution, and it mainly focuses on default prediction rather than changes in firms' credit quality[23] (Valaskova, Katarina, 2014).

2.2.2 Applications.

Credit contagion models such as the KMV model have been empirically studied in China, such as the credit risk measure of Chinese insurance companies, the credit risk contagion effect measure of the tertiary industry, the credit risk measure of the real estate industry[24], the credit risk measure of municipal bonds, etc. The credit risk of the financial market has continued to ferment under the dual effects of changes in the internal correlation structure and the turbulence of the external economic environment[25]. Credit risk in the financial market continues to ferment under the dual effects of internal structural changes and external economic environment turbulence. Take real estate as an example, as an important industry in China's economy, it is a typical capital-intensive industry with high gearing ratio and great dependence on financing. At the same time, the development cycle of the real estate industry is closely aligned with the macroeconomic cycle, with a strong driving force for economic growth, and with a large degree of correlation with related industries, and the related enterprises inside and outside the industry have a risk-linked dependence relation-

ship[26]. Therefore, in the period of industrial transformation and upgrading and macroeconomic pressure, measuring the credit risk of the real estate industry and exploring its contagion effects are crucial for stabilizing the order of the financial market and promoting the healthy and rapid development of the economy[27] (Long, Jinyou, Ling, Yuxiu, Xie, Chie, 2022). Against the background of the unprecedented changes in a hundred years, based on the frequent occurrence of bond defaults in China's financial market, it is of great significance to explore the of the credit risk of bond defaults on the pricing of bond issuance of companies in the same industry to improve the quality of financial services[28], service to the real economy, and the prevention and resolution of major financial risks (Su Jie Wang Yong, 2023).

2.3 Behavioral Financial Risk Contagion Models

2.3.1 Theoretical and Methodological Foundations.

The main theories of behavioral financial contagion risk include complex dynamical networks. These are categorized into complex network synchronization methods and complex dynamical network coordination and counter-coordination game methods. At the intersection with epidemiology, multiple epidemic transmission models are also important research methods[29]. This network propagation behavior obeying certain laws can be extended to modeling the risk of contagion in financial markets. However, most of the existing studies are based on the fundamental, technical and market aspects of stock market volatility, focusing on retrospecting the existence and macro-static characteristics of stock market herding behavior, while there are relatively few studies on the dynamic evolution of the process[30].

2.3.2 Flock Effect Modeling.

Its name comes from the behavior of investors in the stock market, i.e., investors tend to follow the actions of the majority when market sentiment changes, just like sheep. The basic assumption of the model is that investors are influenced by market sentiment and peer behavior in addition to fundamental information when making investment decisions (Sornette, 2001). When market sentiment is high, investors are more likely to be influenced by the behavior of their peers, increasing their buying behavior; on the contrary[31], when market sentiment is low, investors are more likely to be influenced by the behavior of their peers, thus increasing their selling behavior.

2.3.3 Applications.

In practice, based on the attribute characteristics of the subject nodes in the stock market and following the ownership relationship between stock market investors and underlying stocks, we theoretically constructed the stock market investment generalized network and derivative network models, and simulated and analyzed the network and robustness characteristics. Both types of networks are characterized by small world and scale-free. The average path length increases linearly with the logarithmic growth of the network size[32]. In addition, the robustness of stock market investment

derivative networks is higher under the random attack strategy and lower under the deliberate attack strategy (Yuan, 2011).

Therefore, in order to effectively promote the healthy and stable development of the stock market, from the perspective of complex networks, government regulators weaken the degree of heterogeneity of the stock market network and increase the cultivation of the degree of rationality of market players (Yang Shanlin, 2009).

2.4 Discrete Financial Risk Contagion Models

2.4.1 SIR Model.

Because of the similarities between financial systems and ecosystems, the transmission of financial risks is very similar to the transmission of epidemics.

Similarly (May R M Levin S A Sugihara G, 2008), so more and more scholars apply the infectious disease model to the field of economy and finance. The classical SIR model, first proposed by Reed and Frost, categorizes into three states: susceptible (S), infected (I) and recovered (R). A node in the susceptible state is infected by a node in the infected state with probability[33], while a node in the infected state recovers to the always-immune state or dies with probability. In the SIR model, a evolves from susceptible to infected to recovered (S→I→R) or remains susceptible. When a steady state is reached, the number of susceptible nodes does not change, meaning that no new infected nodes are added to the network and all infected nodes have been transformed into recovered nodes (Lin Yin 2021).

2.4.2 Applications.

Individuals in the contagion satisfy homogeneity, which is consistent with the structure of China's insurance system. There are a large number of small and medium-sized insurance institutions in China's insurance market, which have homogeneous insurance products, risk exposure and governance issues[34] (Xu Hua, 2020). The growing homogeneity of product distribution among China's life insurance companies has also further increased the linkage between investment risk and insolvency risk[35] (Wang, Xiangnan, 2018). These similar characteristics make insurers homogeneous in risk contagion.

3 Conclusion

Against the backdrop of economic and financial globalization, the interconnectedness of financial markets is increasing, and various types of capital with different risk characteristics are being reallocated and combined in them, which greatly promotes financial deepening, enlarges the financial scale, and improves the efficiency of the financial market, but at the same time threatens the stability of the financial market. Localized sources of risk can easily generate spillover effects through contagion channels, resulting in contagion risk. In the main part of this paper, the main models of financial contagion risk based on the complex system approach are sorted out and analyzed, so as to excavate the formation law and evolution charac-

teristics of various types of contagion risk. Although there are obstacles to the development of the current research such as the difficulty of theoretical breakthroughs and the difficulty of obtaining data, the complex network model provides a lot of theoretical concepts and a brand-new perspective for solving problems, which enables us to more accurately and clearly describe the structure of the financial system in the real world. We believe that through the deepening of theoretical research and the continuous development of network science and computer simulation technology, we can build bridge through the network model to cross insurmountable gap between the qualitative conceptual view of crisis amplification mechanism and the quantitative model of financial vulnerability.

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