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Causal relationship between the global foreign exchange market based on complex networks and entropy theory

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ABSTRACT

The foreign exchange (FX) market is a typical complex dynamic system under the background of exchange rate marketization reform and is an important part of the financial market. This study aims to generate an international FX network based on complex network theory. This study employs the mutual information method to judge the nonlinear characteristics of 54 major currencies in international FX markets. Through this method, we find that the FX network possesses a small average path length and a large clustering coefficient under different thresholds and that it exhibits small-world characteristics as a whole. Results show that the relationship between FX rates is close. Volatility can quickly transfer in the whole market, and the FX volatility of influential individual states transfers at a fast pace and a large scale. The period from July 21, 2005 to March 31, 2015 is subdivided into three sub-periods (i.e., before, during, and after the US sub-prime crisis) to analyze the topology evolution of FX markets using the maximum spanning tree approach. Results show that the USD gradually lost its core position, EUR remained a stable center, and the center of the Asian cluster became unstable. Liang's entropy theory is used to analyze the causal relationship between the four large clusters of the world.

1. Introduction

With global economic liberalization, international trade and international capital flows rapidly grow. As a result, violent changes occur in the foreign exchange (FX) market supply and demand, the risk of the FX market increases, and microeconomic and macroeconomic subject behaviors are significantly influenced. The trades and scales of the FX market exhibit sustainable growth, thus ranking FX investment as the second most important investment area while the stock investment is the first investment field. Consequently, the currency market risk management increases. Volatility in the FX is influenced by numerous factors, and it increasingly appears in a dynamic, complex, and unpredictable nature. The occurrence, formation, and evolution of exchange rate fluctuations involve complex system characteristics and form a nonlinear mechanism. Therefore, complex network theory was introduced into FX market research as a powerful tool for complex systems.

Complex network theory, which originated from random graph theory by Erdős and Rényi [1], has been applied in statistical physics, computer science, sociology, and economics in recent years. Many systems comprise a large number of interactive discrete individuals and can be abstracted as a complex network for research. Watts and Strogatz [2] and Barabási and Albert [3] proposed small-world networks on Nature and scale-free networks on Science, respectively; complex network theory has since attracted worldwide attention and has been applied in various fields, such as in the topology of the Internet [4], predatory relations between species [5], virtual market structure building [6], gene network of pre-senile dementia, and climate network of El Niño or southern oscillation [7]. Complex network theory is widely used to study financial markets, such as global stock markets [8,9], European stock markets [10], the Asia Pacific stock market [11], the South African stock market [12], the Euro Stoxx market [13], the Greek Stock Market [14], the Korean financial market [15], goods markets, stock markets, and credit markets [16]. FX markets act as an important part of financial markets with nonlinear characteristics. Different approaches are used to analyze FX markets, and they include the Lyapunov exponent [17], R/S method [18], detrended fluctuation analysis (DFA) [19], detrended moving average analysis (DMA) [20], detrended cross-correlation analysis (DCCA) [21], multifractal de-

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trended fluctuation analysis (MFDFA) [22,23], and multifractal detrended cross-correlation analysis (MFDCCA) [24,25]. Complex network theory opens a new approach to the study of the nonlinear dynamic characteristics of FX markets. Rate fluctuation is influenced by many factors, and it has evolved into a complex system of micro and macro factors that interact with one another.

The remainder of the paper is structured as follows. In Section 2, we present a literature review on the application of complex network theory, the approaches of financial markets and the research of FX markets. Section 3 presents the data sources and processing methods. Section 4 generates an international FX network and Section 5 analyzes its topology structure. In Section 6, it shows the topological evolution of FX markets by extracting MSTs. Section 7 presents the four big clusters' causal relationship based on Liang's entropy theory [26]. Finally, Section 8 provides the final considerations.

2. Related literature

Complex network theory has become an efficient method for analyzing complex systems. Jiménez [27], who utilized the Virginia California earthquake activity data from January 1, 1932 to December 31, 2010 to establish a complex network, analyzed the transmission mode of seismic information in seismically active areas by calculating the mutual information between various parts of the Earth's crust and introducing the average path length (APL), clustering coefficient, and degree distribution characteristics. Yang et al. [28] adopted the mutual information method to determine the sliding window and further used the transfer entropy method to review the risk transmission between US departments; the results show that the financial industry sector is the chief culprit that seriously and gradually affects the energy, raw materials, and industrial industries across all industries. Silva and Zhao [29] proposed a hybrid classification technique that not only can realize classification according to the pattern formation, but also is able to improve the performance of traditional classification techniques. What's more, as the class configuration's complexity increases, the high level term is required to get correct classification.

Complex network theory presents a new perspective for the study of financial markets and provides a new method for investment decision making. Mantegna [30] first proposed the minimal spanning tree in financial markets as a technical tool for topology network analysis, in which the similarities among stock prices are analyzed, and later found significant implications for portfolio optimization. Chi et al. [31] constructed a complex network to detect two cycles of the U.S. stock market covering the periods of June 2007–May 2009 and July 2005–August 2007 and discovered that the correlation of stock closing prices presents a scale-free property and that the market is greatly affected by the financial sector. Souza et al. [32] proposed a novel methodology to extract banking communities for measuring the systemic risk in networks composed of financial institutions, and they find that these communities have a relevant effect on systemic risk. Domestic scholar Xu et al. [33] studied the interaction mechanism of U.S. stock markets from the perspective of complex networks, built a G-causal relation model according to 68 typical institutional stock returns, and analyzed complex network density and degrees of ranking to evaluate the stability of the U.S. financial system. Many scholars have conducted studies on domestic markets. Zhang et al. [34] dealt with the high frequency data of the Shanghai stock index from March 5, 2007 to March 16, 2007, considered different consolidation parameters k (i.e., the range of the nodes in the network) and the filter parameters of vc based on complex network theory, and found that scale-free networks can identify the dynamic movement of original sequences. Huang et al. [35] built a stock market network with the price correlation and threshold value method, determined the stability of the network with the random failure and attack method, and further used data mining technology to classify financial instruments and understand the internal structure of the stock market. A study explored the Chinese stock market on the basis of co-integration instead of correlation. Tu [36] concluded that the properties of a co-integration-based threshold network are approximate to a complete graph. The existing research results show that real networks often exhibit a highly nonlinear relationship. Hence, methods for analyzing the relationship between nodes must urgently be developed.

There are a lot of works related to FX markets research. Jang et al. [37] employed complex network theory to study the network characteristics and topological structures of FX markets; he analyzed the time sequence characteristics of the currency network under crisis. Wang and Xie [38] then analyzed a sample of the real FX rates of 42 major currencies from 2005 to 2012 and proposed a concept of tail dependence networks, which is aimed at investigating the tail dependence structure of FX markets. Yao et al. [39] constructed a unique currency that defines a four-day fluctuating situation as a mode and multi-currency complex networks that define one-day fluctuating situation as a mode by using the time series data of RMB against USD, EUR, JPY, and GBP from September 16, 2008 to November 12, 2014. The authors revealed that the transmission route for the fluctuation modes of the RMB exchange rate exhibits the characteristics of a partially closed loop, repeatability, and reversibility. Sultornsanee et al. [40] adopted Thailand Baht exchange rates with 82 countries from 2004 to 2012 to generate networks on the basis of the methods of phase synchronization–maximum spanning tree (MST) and cross correlation–MST; such networks are utilized to study the differences in the market dynamics captured by these methods.

The first innovative contribution of the present study is the calculation of correlation coefficients. Correlation coefficients are commonly calculated as Pearson correlation coefficient (PCC), which has at least two drawbacks. (1) The theoretical assumption of PCC is that the joint distributions of time series obey a Gaussian distribution, but evidence indicates that the dependence between different financial asset returns is non-Gaussian [41,42]. (2) PCC is defined to quantify the linear correlation for a whole sample. It ignores the fact that real world data possess a high level of heterogeneity [43]. Correlation coefficients are often calculated by Spearman correlation coefficient (SCC), but the result is not very good by this method, when the threshold value is greater than 0.45, the network is not connected. Therefore, the present study chooses mutual information as the edge weights of nodes instead of PCC and SCC. Such approach overcomes the shortcomings of linear correlation functions. Mutual information can reveal the nonlinear characteristics between two time series statistics, and significant mutual information equates to an intensive nonlinear relationship.

The second innovative contribution of this work is the consideration of Liang's entropy theory [27], which illuminates the cause–effect relation among the world's four big clusters. First employed in the FX markets, entropy theory is regarded as a good guide for the risk management. In this study, we obtain meaningful results that could provide detailed information.

3. Data and methodology

3.1. Data

On July 21, 2005, China began to implement a managed floating rate system based on market supply and demand and a basket of currencies. Thus, this study analyzes the FX rates of 54 major currencies in the FX market for the period of July 21, 2005 to March 31, 2015, which covered 3541 days. The 54 currencies are identified