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Visibility graph analysis on quarterly macroeconomic series of China based on complex network theory

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ABSTRACT

The visibility graph approach and complex network theory provide a new insight into time series analysis. The inheritance of the visibility graph from the original time series was further explored in the paper. We found that degree distributions of visibility graphs extracted from Pseudo Brownian Motion series obtained by the Frequency Domain algorithm exhibit exponential behaviors, in which the exponential exponent is a binomial function of the Hurst index inherited in the time series. Our simulations presented that the quantitative relations between the Hurst indexes and the exponents of degree distribution function are different for different series and the visibility graph inherits some important features of the original time series. Further, we convert some quarterly macroeconomic series including the growth rates of value-added of three industry series and the growth rates of Gross Domestic Product series of China to graphs by the visibility algorithm and explore the topological properties of graphs associated from the four macroeconomic series, namely, the degree distribution and correlations, the clustering coefficient, the average path length, and community structure. Based on complex network analysis we find degree distributions of associated networks from the growth rates of value-added of three industry series are almost exponential and the degree distributions of associated networks from the growth rates of GDP series are scale free. We also discussed the assortativity and disassortativity of the four associated networks as they are related to the evolutionary process of the original macroeconomic series. All the constructed networks have "small-world" features. The community structures of associated networks suggest dynamic changes of the original macroeconomic series. We also detected the relationship among government policy changes, community structures of associated networks and macroeconomic dynamics. We find great influences of government policies in China on the changes of dynamics of GDP and the three industries adjustment. The work in our paper provides a new way to understand the dynamics of economic development.

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1. Introduction

In recent years, complex network theory has flourished in many fields. A complex network is helpful to understand the impacts of topological structures on dynamics and functions of a system. It is interesting that some research results have made a bridge between time series and networks or graphs [1–6]. Networks from corresponding time series can be generated with different methods. The studies of the first type deal with many time series to form a complex network with each node standing for a time series and the weight of a link between two nodes characterized by the correlation coefficient

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of the two time series [7] or by the distance between the two time series [8]. Lacasa et al. [5,6,9] proposed a new tool for time series which is called the visibility algorithm and attracted wide attention. Lacasa et al. have shown that time series structure is inherited in the associated graph, such that periodic, random, and fractal series map into a random exponential and scale-free network.

The visibility graph allows us to apply methods of complex network theory for characterizing time series simply. However, most discussions at present mainly focus on stationary time series generated with theoretical models. The applications to analyze real world data are limited. So far the visibility algorithm to analyze real time series is mainly presented in fields of stock market indices, occurrence of hurricanes in the United States, foreign exchange rates and energy dissipation rates in three-dimensional fully developed turbulence [10–14].

In this work, we will investigate some important actual macroeconomic time series by the visibility graph approach which include the quarterly growth rate of value-added of the primary industry series, quarterly growth rate of value-added of the secondary industry series, quarterly growth rate of value-added of the tertiary industry series and growth rate of the Gross Domestic Product series of China from the first quarter of 1992 to the third quarter of 2010. The methods and research thinking in our paper are also suitable for macroeconomic data of other countries. After transferring these time series to networks, we will investigate the statistic characteristics of constructed networks and the dynamic process of macroeconomic series using complex network theory. Finally, we obtain some meaningful conclusions.

2. Methodology and materials

The four time macroeconomic series data used in our paper are from the statistical database of the China Economic Information Network [15]. The four series are as follows: quarterly growth rate of value-added of the primary industry series, quarterly growth rate of value-added of the secondary industry series, quarterly growth rate of value-added of the tertiary industry series and growth rate of the Gross Domestic Product series of China from the first quarter of 1992 to the third quarter of 2010. Each series contains 75 data.

First, we will convert the four series into graphs by the visibility graph approach. Second, we explore the topological properties of graphs associated with four macroeconomic series, namely, the degree distribution and relations, the clustering coefficient, the average path length, the community structure and so on. Third, we explore the dynamics of the four series based on complex network theory.

2.1. Visibility graph and its inheritance of the original time series

The visibility graph maps a time series into a network. Consider a macroeconomic series y_t with a length of N. We can convert the time series into complex networks by applying the visibility algorithm [5]. Each data point in the time series is regarded as a vertex in the associated network and an edge is drawn connecting two vertices according to the rule that the two corresponding data points can see each other in the vertical bar chart of the time series: that is to say, if there is a straight line that connects the series data, provided that this "visibility line" does not intersect any intermediate data height. More formally, a visibility graph is obtained from a time series according to the following visibility criterion [5]: two arbitrary data (t_a, y_a) and (t_b, y_b) where $y_a, y_b > 0$ in the time series have visibility, and consequently become two vertices in the associated graph, if any other data (t_c, y_c) such that $t_a < t_c < t_b$ fulfills

$$y_c < y_a + (y_b - y_a)\frac{t_c - t_a}{t_b - t_a}. \tag{1}$$

When we converted macroeconomic time series into graphs in the paper, there are some inevitable losses of information for the original data. But the associated visibility graph inherits some important features of the original time series and it is a new perspective to research time series. Some researchers have studied the relationships between degree distribution of the constructed network and Hurst index H of the original series. The Hurst exponent H, namely, the long-range correlation exponent is used as a measure of the long term memory of time series. Theoretically, the values of the Hurst exponent are in the range from 0 to 1 with a dividing point at 0.5, and the time series show distinct features upon the different value: (1) $H = 0.5$ means the time series are standard Brownian motions and the event is independent, random and uncorrelated. (2) When $0.5 < H < 1$, the time series show positive correlation and persistence which is characterized by the long-range memory effect. The persistence means that if the time series have been up or down, they are like to continue to be up or down in the future. (3) Conversely, the time series will have anti-persistence and anti-correlation.

The dependence and the degree distribution of the visibility graphs of several specific examples of time series and corresponding Hurst index H have been investigated [5]. For a random time series extracted from a uniform distribution in [0, 1], the degree distribution of the visibility graph has an exponential tail. Lacasa et al. [5] have pointed out how graph theory techniques can provide an alternative method to quantify long-range dependence in time series. For a fractal Brownian motion (FBM) with Hurst exponent H, the predicted degree distribution obeys a power-law $p(k) \propto k^{-\gamma}$ and we can estimate the value of the Hurst exponent by $H = (3 - \gamma)/2$. Ni et al. [13] investigate the visibility graphs extracted from fractional Brownian motions and multifractal random walks, and find that the degree distributions exhibit power-law behaviors, in which the power-law exponent γ is another different linear function of the Hurst index H of the time series.

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