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Q1 From time series to complex networks: The phase space coarse graining

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HIGHLIGHTS

- The novel algorithm that converts a time series into a complex network is proposed.
- The results of network analysis for four typical series are reported.
- The complex network mapped from gasoline spot price series is obtained.
- The dynamic characteristics of the gasoline spot price are identified.

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ABSTRACT

In this paper, we present a simple and fast computational method, the phase space coarse graining algorithm that converts a time series into a directed and weighted complex network. The constructed directed and weighted complex network inherits several properties of the series in its structure. Thereby, periodic series convert into regular networks, and random series do so into random networks. Moreover, chaotic series convert into scale-free networks. It is shown that the phase space coarse graining algorithm allows us to distinguish, identify and describe in detail various time series. Finally, we apply the phase space coarse graining algorithm to the practical observations series, international gasoline regular spot price series and identify its dynamic characteristics.

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1. Introduction

Time series is an emergent output of a system and contains much information about its microscopic details. A lot of valuable information can be obtained based on time series data mining and analysis. Therefore, nonlinear time series analysis has been an important branch in the field of nonlinear dynamics, which is of great theoretical and application significance in science, engineering, finance and economics, as well as life and medical science, etc.

Complex networks is a hot research topic in recent years, the main idea is to link between the real part of the system as a complex network, in the form of a network to describe the relationship between the real part of the system, so as to better understand the essence of reality system. With the development of the scale-free network model [1], the small-world network [2], the Newman and Watts network [3], and the random network model [4], complex network is applied in more and more fields, which provides us a new perspective and approaches to the study of the complexity problems. In recent years, complex network theory has flourished in the field of nonlinear time series analysis. The main idea of this

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method is to investigate the time series by mapping them to the complex networks. Representing the time series through a corresponding complex network, we can then explore the dynamics of the time series from network organization, which is quantified via a number of topological statistics. Currently, there are several algorithms for mapping the time series to complex networks. For instance, Zhang et al. [5–8] constructed complex networks from pseudoperiodic time series, with each cycle represented by a single node in the network. Xu et al. [9] introduced a transformation from time series to complex networks and studied the relative frequency of different subgraphs within that network. Lacasa L et al. [10] first presented a simple and fast computational method, the visibility graphs algorithm(VG), that converts a time series into a graph. Luque B et al. [11] presented a simplified version of VG, named the horizontal visibility graph algorithm (HVG). Donges J F et al. [12] proposed a new set of statistical tests for time series irreversibility based on standard and horizontal visibility graphs. For a given time series, the vertex sets of VG and HVG are the same, whereas the edge set of the HVG maps the mutual horizontal visibility of two observations x_i and x_j [12]. Later, Zhou et al. [13] proposed an improved visibility graph method, i.e., limited penetrable visibility graph, for establishing complex network from time series. This visibility graph method, as an efficient approach has been successfully used to characterize human strive intervals [14], occurrence of hurricanes in the United States [15], foreign exchange rates [16], energy dissipation rates in three-dimensional fully developed turbulence [17], human heartbeat dynamics [18,19], electroencephalogram series [20], daily stream flow series [21], stock indices [22,23], and gold price time series [24]. The method of reconstructing phase space was also the important method for mapping the time series to complex networks, in this method, the phase space embedding was first applied for the time series. Then each vector in the phase space was considered as a node in the network. Whether there is a link between two nodes or not depends on the distance (or correlation coefficient) in phase space between them [25–28]. And also some researches introduced coarse graining method for mapping the time series to complex networks [29–32].

To sum up, the previous works were very insightful and enlightening, the core point to construct a network from a time series is to define nodes and edges properly. So far, it is still an open question to reasonably map a time series into a network so that the latter could keep sufficient information to effectively exhibit the characteristics of the former. In this paper, we present a simple and fast computational method, the phase space coarse graining algorithm that converts a time series in a directed and weighted complex network. The constructed directed and weighted complex network inherits several properties of the series in its structure. Thereby, periodic series convert into regular networks, and random series do so into random networks. Moreover, chaotic series convert into scale-free networks. It is shown that the phase space coarse graining algorithm allows us to distinguish, identify and describe in detail various time series. Finally, we apply the phase space coarse graining algorithm to the international gasoline regular spot price series and identify the dynamic characteristics of the gasoline price.

Different from the previous studies, and four main novel contributions in our studies are as follows: (1) This paper combined the method of reconstructing phase space and the coarse graining techniques, and then proposed the phase space coarse graining algorithm for mapping the time series to complex networks. (2) Periodic time series, Gaussian white noise time series, Lorenz chaotic time series, and PSE chaotic time series were mapped into the corresponding directed and weighted complex networks, and the topological structures were contrastive analyzed. (3) The directed and weighted complex network mapped from the practical observations series, gasoline spot price series was obtained. (4) The dynamic characteristics of the gasoline spot price are identified based on network analysis. The advantages of this method are that it enables us to describe the evolution characteristics of time series more simply and reveal the underlying dynamics of time series more precisely. And the proposed method can be applied to many practical observations series to provide deep insights into the dynamics.

The outline of this paper is as follows: Section 2 introduces the phase space coarse graining algorithm; Section 3 reports the results of network analysis for four typical series. The international gasoline regular spot price series is analyzed using the phase space coarse graining algorithm in Section 4. The last section will make a summary.

2. Methods

2.1. Phase space reconstruction technique

The phase space is defined as the multidimensional space whose axes consist of variables of a dynamic system [25–28, 33–36]. An attractor can describe the asymptotic behaviors of the dynamic system. The dimensional of the attractor will provide a measure of the minimum number of independent variables that describe the dynamic system.

The basic idea of reconstruction phase space is that the scalar time series need to be embedded into a high dimensional phase space. The evolution characteristics of the scalar time series can be described in the reconstruction phase space. Theoretical basis of phase space reconstruction is Takens theorem [33]. Takens theorem is described as follows: Let M be a compact manifold of dimension d. For pairs (φ, h), where $\varphi : M \to M$ is a smooth (at least C^2) diffeomorphism and $h : M \to R$ a smooth function, it is a generic property that the $(2d+1)$-fold observation map $H_k[\varphi, h] : M \to R^{2d+1}$ defined by

$$x \mapsto (h(x), h(\varphi(x)), \ldots, h(\varphi^{2d}(x))) \quad (1)$$

is an immersion (i.e. H_k is one-to-one between M and its image with both H_k and H_k^{-1} differentiable).