Physica A 492 (2018) 824–836

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Nonlinear complexity behaviors of agent-based 3D Potts financial dynamics with random environments

Yani Xing *, Jun Wang

School of Science, Beijing Jiaotong University, Beijing 100044, PR China

HIGHLIGHTS

- A financial price dynamics is modeled by 3D agent-based Potts model.
- Random coarse-grained Lempel–Ziv is applied to investigate the stock dynamics.
- CMSE is employed to explore the complexity of original and shuffled data.
- EMD method is used to show the feasibility of the proposed model.

ARTICLE INFO

Article history:
Received 26 June 2017
Received in revised form 11 October 2017
Available online 16 November 2017

Keywords:
Microscopic financial price series dynamics
3D Potts model
Shuffled time series
Random coarse-grained Lempel–Ziv complexity
Composite multiscale entropy
Empirical mode decomposition

ABSTRACT

A new microscopic 3D Potts interaction financial price model is established in this work, to investigate the nonlinear complexity behaviors of stock markets. 3D Potts model, which extends the 2D Potts model to three-dimensional, is a cubic lattice model to explain the interaction behavior among the agents. In order to explore the complexity of real financial markets and the 3D Potts financial model, a new random coarse-grained Lempel–Ziv complexity is proposed to certain series, such as the price returns, the price volatilities, and the random time d-returns. Then the composite multiscale entropy (CMSE) method is applied to the intrinsic mode functions (IMFs) and the corresponding shuffled data to study the complexity behaviors. The empirical results indicate that the 3D financial model is feasible.

1. Introduction

Research on the nonlinear properties of price fluctuations in financial markets has been a very important topic in recent years. Then various dynamic models have been established to simulate and explore the features of stock markets. As the main information series for financial markets, the return of stock price usually shows several common features, for example, fat tails for return time series, power law, volatility clustering, and multifractality of volatility, and so on, see [1–12]. Financial markets can be regarded as a complex interactive system that contains a lot of interactive particles, which have some similarity with certain particle physics systems [8,13,14], so some of the statistical physics methods have been applied to the financial markets, to measure the nonlinear behaviors of the stock price and stock indexes, for instance, the multifractal of stock markets is studied in [6,15,16], the entropy of return time series is researched in [17,18], and the correlation dimension of financial time series is calculated in [19,20]. The price changes of most models are based on the principle of information exchange, or based on the interaction between market investors, see [3]. For instance, there are some agent-based financial models of the statistical dynamic systems [21–23].

* Corresponding author.
E-mail address: yanixing@bjtu.edu.cn (Y. Xing).

https://doi.org/10.1016/j.physa.2017.11.013

In this paper, the 3D financial Potts model is proposed to simulate the fluctuation behaviors of financial time series. The 3D physical model is an extension of the famous two-dimensional (2D) Potts model [24,25], and the 2D Potts model which is used to characterize the interaction of spins on lattice in physics [26,27], has been used to describe the dynamic behaviors of financial markets. Now, based on its theory and structure, the new proposed 3D financial model provides us a new view to analyze financial markets. It is known that there are some differences between 2D Potts model and 3D Potts model. Firstly, there is a significant difference in the structure, since every spin locates on one of the sites of a cubic lattice in the 3D Potts model, and the spin can be regarded as a trader in financial markets, which indicates that the agents in this new model can change information with more agents in financial markets. Moreover, the critical value of 2D model is $\ln(1+\sqrt{3})$ with three different states of spins, while the critical value of 3D model is about 0.550565 when the states of spins are three. Secondly, in the theory, they have some different statistical properties, for instance in two states of spins, the fluctuations of interfaces of spins show the different statistical behaviors for 2D and 3D Potts models. In this work, we hope to view the financial market from all its aspects and from multiple perspectives, in some cases, the reflections of real markets are different from different models. From the above, it is of great significance to study the new 3D Potts financial model.

To prove the feasibility of the proposed model, the complexity and the nonlinear characters of the simulated data and the real data from Shenzhen Stock Exchange (SZSE) Component Index and Shanghai Stock Exchange (SSE) Composite Index are investigated. To make an approach on the complexity of those series, the novel method coarse-grain Lempel–Ziv complexity with random environments is applied to the returns series, the absolute returns and the random time d-returns. Furthermore, the composite multiscale entropy (CMSE) analysis [28], which is developed from the multiscale entropy [29–33] is introduced to calculate the complexity and the periodicity for the real time series and the simulated time series. And the empirical mode decomposition (EMD) [34,35] method is applied to decompose these time series into intrinsic mode functions (IMFs), the CMSE results of the original time series, the series sorted in an ascending order, the random shuffled EMD time series, and the EMD time series sorted in an ascending order are compared and investigated.

2. A novel financial model based on 3D Potts dynamics

2.1. Description of 3D Potts model

So far, the study of 3D Potts model has made some achievements. As a statistical physical model, 2D Potts model [21,22,36] is the generalization of the famous Ising model, and compared to Ising model, the 2D Potts model extends the states of the particles that located on two-dimensional lattice into three or more, and it has already been explored in modeling financial model in [22], and the multiscale entropy of the model is investigated in this study. In [18], the weighted fractional permutation entropy and fractional sample entropy of 2D Potts model are calculated. Based on 2D Potts model, the 3D Potts model extends the system to a cubic lattice, which means that each interacting spin in 3D model has six nearest neighbors instead of four in 2D model. As a three-dimensional lattice system containing a large number of spins, each spin is equal pointing to one of the directions of 1 to q. In the q-state 3D Potts model, we denote the three-dimensional integer lattice as $\mathbb{Z}^3$. Let $\Omega_{\mathbb{Z}^3} = \{1, 2, \ldots, q\}$ stand for the space of spin configurations on $\mathbb{Z}^3$, and $\sigma = \{\sigma_i : i \in \mathbb{Z}^3\}$ stands for the element of $\Omega_{\mathbb{Z}^3}$. The values of spin σ_i range from 1 to q, where q is the number of different states of the model. Then for each $\sigma \in \Omega$, the Hamiltonian [37] of 3D q-state Potts model is

$$H_{\mathbb{Z}^3,h}(\sigma) = -\beta \sum_{\langle i,j\rangle} \delta_{\sigma_i,\sigma_j} - h \sum_{i} \delta_{\sigma_i,\sigma_g} \tag{1}$$

where δ is the Kronecker symbol, $h > 0$ favors magnetization in the direction of the other spin σ_g. The first sum of the formula is the interactions among six nearest neighbors (represented by $\langle i, j\rangle$) on the cubic lattice and the last sum represents the interactions over the whole lattice system. For any fixed site (x, y, z), the nearest neighbors of it are defined as $\mathbb{N}(x, y, z) = \{(x_1, y_1, z_1) : \|x - x_1\| + \|y - y_1\| + \|z - z_1\| = 1\}$. On a finite cubic lattice, the partition function is

$$Z_{\mathbb{Z}^3,h}(\sigma) = \sum_{\sigma} \exp(\beta \sum_{\langle i,j\rangle} \delta_{\sigma_i,\sigma_j} + h \sum_{i} \delta_{\sigma_i,\sigma_g}). \tag{2}$$

In the followings, we mainly investigate the 3-state 3D Potts model that has no external magnetic field (i.e., $h = 0$ and $q = 3$). And for $d \geq 2$, the model keeps an order–disorder transition, and for the case of $d = 3$, the critical value is about 0.550565 according to [37].

2.2. Construction of financial price model

Based on the above statistical physics model, we propose a microscopic financial agent-based price model called 3-state 3D Potts model on $L \times L \times L$ lattice. Here in this model, the strength of interaction between each particle is one of the leading cause of price changes, and it varies with the relative location on the 3D lattice. In China's stock markets, generally, we can divide the investors into three categories, namely, large institutional investors, institutional investors and retail private investors. And, since the herding effect, they change their investment attitude based on the information they get in the markets. The retail investors due to the lack of effective information, will be more inclined to follow large institutional