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Research on the Interdependent Network of the Thermal Coal Price Based on Directed Limited Penetrable Visibility Graph

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ABSTRACT

This paper constructs a new directed limited penetrable interdependent network (DLPIN) for the thermal coal price (TCP) between the opening series and closing series based on the criterion of the visibility graph, which is better than the traditional method of the visibility graph to mine the price information for steam coal. According to the DLPIN by analyzing, the mechanism of the price fluctuation and information transmission for the thermal coal can be obtained, some references can be provided for the investors to reduce risk investment and increase revenue.

Keywords: visibility graph, interdependent network, thermal coal price, time series

NONMENCLATURE

Abbreviations	
DLPIN	Directed Limited Penetrable Interdependent Network
TCP	Thermal Coal Price
OPS	Opening Price Series
CPS	Closing Price Series

1. INTRODUCTION

As the core strategic resource of coal resources, thermal coal's dominant position determines that its price fluctuations can not only accurately reflect the trend of coal price changes [1], but also have an impact on the economic development [2-4] and ecological environment to a certain extent [5]. Therefore, the study of thermal coal price is of great significance for understanding the trend of coal price change, alleviating the contradiction between supply and demand, guaranteeing the power production system, protecting environment and promoting economic development [6].

With the coal playing an important role in the global energy field and the growth of international trade, the global thermal coal market is also emerging [7], and the research on the price of thermal coal has become a research hotspot. Zaklan et al. (2012) [8] conducted a comprehensive multi-co-integration analysis on the export, transportation and import prices in the value chain of thermal coal, and investigated whether the logistics entered the coal price dynamics through the transportation cost. Huang et al. (2016) [9] used the scenario analysis method to simulate the change rule of the factors affecting coal procurement, and established the model of the thermal coal procurement. Schernikau (2010) [10] analyzed the recent trend of the thermal coal market, studied the development of the coal derivatives and the possible scenarios of the future coal trading, and qualitatively analyzed the global thermal coal trading market with the help of a non-linear model.

Complex networks almost cover all levels of science and technology due to their unique and superior performance. In particular, the application of complex networks to time series analysis has attracted much attention. At the same time, a series of methods for time series mapping to complex networks have emerged [11, 12]. Among the many research methods, the most effective one is viewable network construction method.

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Its advantage is that the associated network not only inherits the inherent characteristics of the original time series, but also is convenient to analyze the dynamic characteristics of the time series. Therefore, visibility graph, horizontal visibility graph, penetrable visibility graph, directed limited penetrable visibility graph have gradually become important branches in the study of time series [13-16].

Combining the characteristics of visibility graph, especially the advantages of directed limited penetrable visibility graph, it will be helpful to analyze the trend of coal price more deeply and guarantee the normal operation of power production system when it is applied to the research of complex network on thermal coal price. However, there are few reports on relevant studies at present. Taking this as an opportunity, this paper studies the interdependent network of the thermal coal price based on directed limited penetrable visibility graph.

The content structure of this paper is as follows: the part 2, data and constructing network, which introduces the data and methods of the constructing network. The part 3, analyzing the difference of the TCP between the DLPVG and DLPIN. The part 4, the conclusions a are given.

2. DATA AND CONSTRUCTING NETWORK

2.1 The Data

The data is selected from the opening price series (OPS) and closing price series(CPS) (from September 26, 2013 to March 18, 2020) of main thermal coal futures in Zhengzhou Commodity Exchange in this paper, which is used to be the data of the research, and the fluctuation state and difference of which are shown in Fig 1.

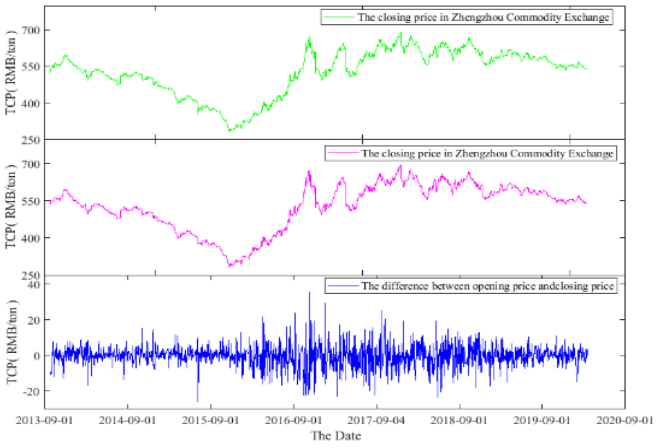

Fig 1 The fluctuation state and difference.

According to the Fig 1, the statistical characteristics of the TCP in different times are shown in Table 1.

Table 1. The statistical characteristics of the TCP.

Different price	Opening Price	Closing Price
Max	690.4	695.6
Min	282.6	283.2
Mean	526.76	526.94
Std.Dev	94.40	94.47
Skewness	-0.7760	-0.7726
Kurtosis	2.7161	2.7080
Jarque-Bera	163.7695***	162.7030***

Note: *** denotes the significance level = 1%.

The closing price has a higher maximum, minimum, mean and a relativity high standard deviation. The opening and closing price are all negatively skewed, which shows that the price data on the left side of the average value is less than that on the right side, the intuitive performance is that the tail on the left side is longer than that on the right side, because there are a few variables whose values are very small, which makes the left tail of the curve drag very long. In addition, the opening and closing price distributions peak at a level lower than the normal distribution. According to the Jarquee-Bera test, the abnormal distribution of the opening and closing price is confirmed by the statistics.

2.2 Rules of the network constructed

The edge connecting the internal nodes of the sub-network is called the internal connection edge in the interdependent network, and the connection edge generated between the subnetworks is called the external connection edge, which together constitute the backbone structure of the interdependent network.

The criterion of the DLPIN: As for a time series $X=\{X_i\}, i=1,2,\cdots,n$, which is standardized, and N is the distance of the limited penetrable visibility, if the data points (t_a, X_a) and (t_b, X_b) separated by m data points are visible in the discrete time series X, then there are k data points between the two data points, which satisfy the following formula (1):

$$\begin{cases} \dfrac{X_i - X_a}{t_i - t_a} < \dfrac{X_a - X_b}{t_b - t_a}, t_a < t_i < t_b, \end{cases} \quad (1)$$

and other $m-k$ data points (t_j, X_j) satisfy the following formula (2):

$$\begin{cases} \dfrac{X_j - X_a}{t_j - t_a} > \dfrac{X_a - X_b}{t_b - t_a}, t_a < t_j < t_b, \\ b = a + m, m > 0, N \geq 0 \end{cases} \quad (2)$$

where $b = a + m, m > 0, N \geq 0$.

According to the formula (1) and formula (2) based on the criteria of the directed limited penetrable visibility graph [11, 12] and the irreversibility of the time series, the DLPIN of the opening and closing price of the thermal coal is constructed in this paper, and the rules of the network construction are as follows:

(1) Network construction with the same price series

According to the directed limited penetrable visibility algorithm, the networks of the OPS and CPS are constructed, and the visibility distance is *N*=1. (In order to show their rules and differences, the first six data in the OPS and CPS is taken as an example.)

According to the irreversibility of the time (That is, the early price can affect the later price, but the later price can't affect the earlier price), the node (N_1) of the OPS is selected to carry out directed limited penetrable criterion for the later nodes $(N_2, N_3, \cdots, N_6)$, respectively. Then the node (N_1) and the nodes (N_2, N_3, N_4) generate the connected edge, and the direction is from the node (N_1) to the nodes (N_2, N_3, N_4), as shown in Fig 2.

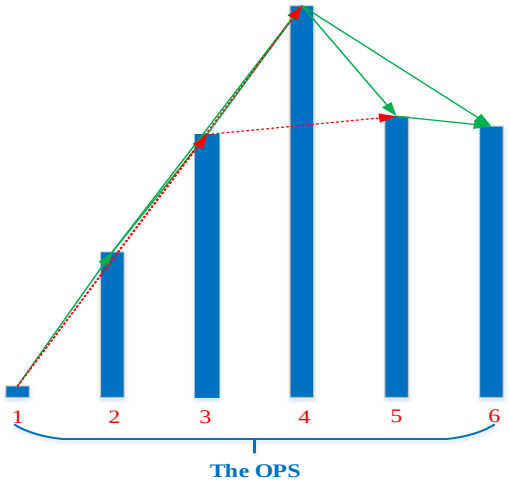

Fig 2 The DLPVG of the TCP in the same series.

The above method is also the rules of constructing the DLPVG for the TCP.

(2) Network construction between the OPS and CPS

Since the correlation is relatively weak between the different price series, which reduces the tightness between the OPS and CPS. Therefore, the network is constructed based on the directed non-penetrable algorithm, where the visibility distance is *N*=0. Due to the difference in the opening and closing time of the day, there are differences in the connection of the directed edges among different price series, which should be noticed: (a) According to the OPS and CPS, it is found that the OPS of the day can affect the CPS of the day and after; (b) According to the OPS and CPS, it is found that the CPS of the day can just affect the OPS of the neat day and after, which is shown in Fig 3.

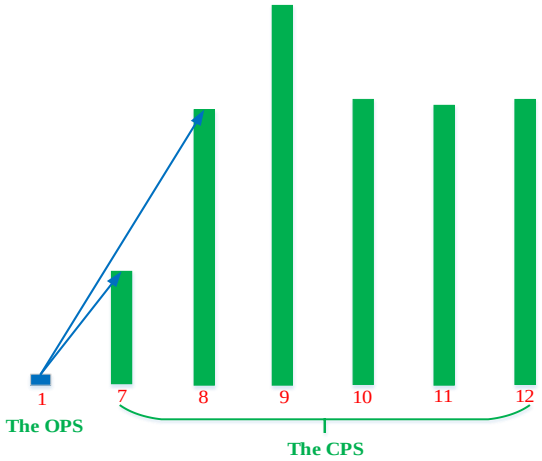

Fig 3 The directed non-penetrable visibility graph between the different series.

According to the above strategy of the network construction, the directed interdependent network of the OPS and CPS of the thermal coal can be obtained, as shown in Figure 4.

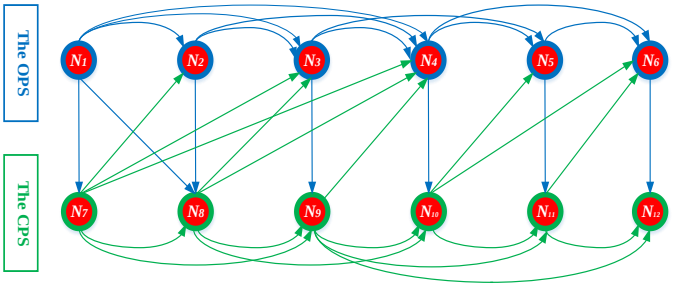

Fig 4 The directed interdependent network about the OPS and CPS of the thermal coal.

According to this process, the DLPIN can be obtained, and the directed limited penetrable visibility graph (DLPVG) of the TCP based on the visibility graph, which are shown in Fig 5. As for the DLPVG of the TCP, we recombine the opening price series and closing price series into a new time series of the TCP based on the time sequence, and construct the new time series, then the DLPVG is constructed by using the method of the directed limited penetrable visibility graph.

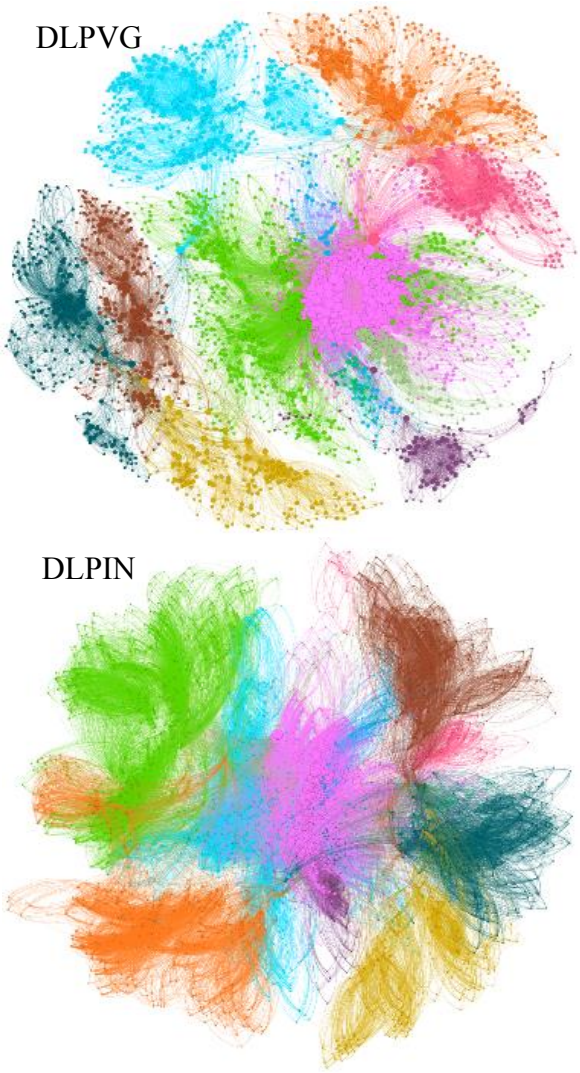

Fig 5 The DLPVG and DLPIN for the TCP.

As for figure 5, the size of the node denotes the size of the degree, and the nodes with the same color represent the same model. According to figure 5, it can be found that the community structure divided by the modular is clear and strong, showing good division quality, and the different communities are divided, which reflects the node concentration, rather than the random distribution among all modules. In addition, the number of the nodes in each community is different, that is, the possibility that each node belongs to a certain community is different, which shows that thermal coal price is similar in the whole, but different in the local part. Therefore, the community of the network is divided to determine whether the node belongs to a community based on the modularity, which is conducive to studying on the "mass generation" of the nodes in the network.
The relationships among the nodes of the network indicate that the changing state of the TCP, thus we can obtain the fluctuation laws of the TCP by analyzing the relationships of the nodes, such as, the changing relationship, the influences between the early price and the late price, and the trend of the price in the future.

3. ANALYSIS OF THE DLPVG AND DLPIN

From the above process, the price information of the thermal coal can be mined by constructing the DLPVG and DLPIN. However, there are some differences between the two networks, which will be discussed in the following part.

3.1 Statistical characteristics of the DLPVG and DLPIN

As for the DLPVG and DLPIN of the TCP, which are constructed by the same time series, thus they have the same node numbers. Since the method of the network constructed is different, which will cause the edges among the nodes will be different, and this is also the basis to compare the advantages and disadvantages of different network construction methods. In general, the greater the degree of the node is, the more importance of the node is, but it is a little one-sided to measure the importance of the nodes only from the degree of the nodes. Therefore, we give the quantitative research on the centrality of the nodes to mine the important nodes based on the shortest path method, then the value and potential value of the nodes are given and compared by analyzing in the DLPVG and DLPIN. The statistical characteristics of the TCP in the DLPVG and DLPIN are given, as shown in Table 2.

Table 2. The characteristics of the TCP in networks.

Different networks	DLPVG	DLPIN
Node numbers	3158	3158
Edges	54214	73470
Degree	108428	146940
Average degree	17.167	23.265
Diameter	14	12
Density	0.005	0.007
Average path length	5.304	4.657
Average clustering coefficient	0.3495	0.3057
Average betweenness centrality	0.0007	0.0006
Average closeness centrality	0.2159	0.2439
Average eigenvector centrality	0.0243	0.0273

Note: The diameter refers to the maximum distance between any two nodes in the network; The density can

describe the evolutionary trend of the connected edges among the nodes in the network; The average path length is one of the three most robust measures of network topology and distinguishes an easily negotiable network from one which is complicated and inefficient, with a shorter average path length being more desirable.

From Table 2, there are 19256 more edges in the DLPIN than that in the DLPVG, and the degree is 146940 in the DLPIN but it is 108428 in the DLPVG, which indicate that the there is a close connection among the TCPs. According to the average degree and path length, it can be found that the DLPIN excavates the conduction distance and mechanism of frequent fluctuation for the TCP, which is helpful to explore the change trend for the future. It can be found that the average clustering coefficient and average betweenness centrality are larger in the DLPVG than that in the DLPIN, which means that the price information transmission of the DLPVG between a node and its neighbors is relatively close, and have a stronger influence on information flow. According to the density, average closeness centrality, and average eigenvector centrality, the transfer ability of the thermal coal price fluctuation can be more effectively identified in the DLPIN.

3.2 Degree distribution of the DLPVG and DLPIN

In order to further explore the degree, and their corresponding distribution of the nodes in the DLPVG and DLPIN, the analysis of the nodes is made by the logarithmic distribution and cumulative distribution, as shown in Fig 6.

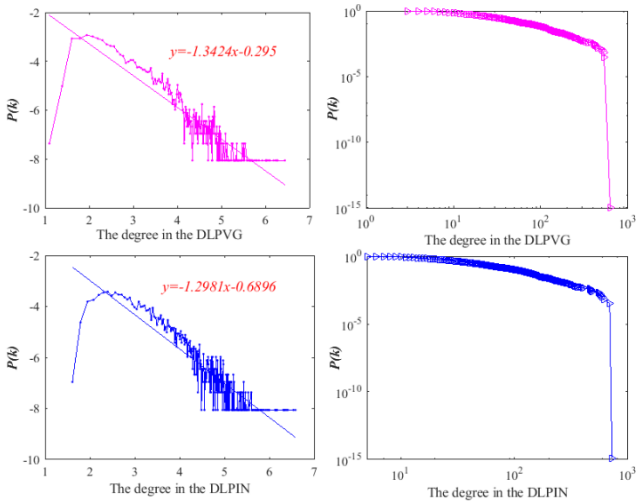

Fig 6 The logarithmic distribution and cumulative distribution of the degree about the nodes.

Figure 6 shows that the number of the nodes with a smaller degree is more (that is, most nodes in the DLPIN are only connected with few nodes), while the number of the nodes with a larger degree is less (that is, there are few nodes connected with many nodes), presenting long tail distribution, which has an obvious scale-free features. According to the construction rules of the DLPIN, the key node (i.e. the node with a larger degree) plays an important role in the connectivity, which existence makes the scale-free network have a strong ability to bear the impact of the emergencies, but it is fragile in the face of the collaborative attacks.

According to the least square method, the double logarithmic curve of the node for the degree of the DLPIN is regressed, and the regression equation of the DLPVG and DLPIN are y=-1.3424x-0.295 and y=-1.2981x-0.6896, respectively. The corresponding correlation coefficient of the trend line is 0.8059 and 0.8011, which shows that the degree of the nodes is power-law distribution, the corresponding power-law index is 1.3424 and 1.2981, and the fitting effect is good, but it does not belong to the common scale-free network power-law index range.

4. CONCLUSIONS

In recent years, the thermal coal price has always been the focus of the debate between coal mining industry and power industry with the increasing contradiction of the coal and power industry, which research has also been paid more attention. According to the criterion of the visibility graph, this paper constructs the DLPVG and DLPIN of the thermal coal price, and some results about the thermal coal price are given based on analyzing the networks, which are as follows:

(1) The thermal coal price data on the left side of the average value is less than that on the right side, the intuitive performance is that the tail on the left side is longer than that on the right side, and it is an abnormal distribution.

(2) The price information transmission of the thermal coal price between a node and its neighbors is closer, and has a stronger influence on information flow in the DLPVG that in the DLPIN.

(3) The transfer ability of the thermal coal price fluctuation can be more effectively identified in the DLPIN than that in the DLPVG.

The China's thermal coal industry is a typical demand-driven market, the thermal coal price is largely affected by the state of macroeconomic development

and the development of the related downstream industries, and thermal coal future prices is no exception. Meanwhile, studying on the overall-coordination-linkage mechanism between different coal product prices, and constructing a multilayer network between different coal market will be the focus in the future research.

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