Structural Change and Dynamics of Pakistan Stock Market during Crisis: A Complex Network Perspective

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Abstract: We studied the cross-correlations in the daily closing prices of 181 stocks listed on the Pakistan stock exchange (PSX) covering a time period of 2007–2017 to compute the threshold networks and minimum spanning trees. In addition to the full sample analysis, our study uses three subsamples to examine the structural change and topological evolution before, during, and after the global financial crisis of 2008. We also apply Shannon entropy on the overall sample to measure the volatility of individual stocks. Our results find substantial clustering and a crisis-like less stable overall market structure, given the external and internal events of terrorism, political, financial, and economic crisis for Pakistan. The subsample results further reveal hierarchical scale-free structures and a reconfigured metastable market structure during a postcrisis period. In addition, time varying topological measures confirm the evidence of the presence of several star-like structures, the shrinkage of tree length due to crisis-related shocks, and an expansion in the recovery phase. Finally, changes of the central node of minimum spanning trees (MSTs), the volatile stock recognition using Shannon entropy, and the topology of threshold networks will help local and international investors of Pakistan Stock Exchange limited (PSX) to manage their portfolios or regulators to monitor the important nodes to achieve stability and to predict an upcoming crisis.

Keywords: complex network; stock correlation network; Shannon entropy; threshold network; minimum spanning tree; crisis; Pakistan stock exchange

1. Introduction

Due to globalization and financial integration, stock markets throughout the world are strongly interconnected. For example, the Global financial crisis (hereafter, GFC) that begun from the USA in 2 April 2007 has affected almost all of the financial markets of the world [1]. The propagation of risks and the complex nature of external and internal events to a local stock market require a thorough study of the stock correlation networks and their structural dynamics. Introduced by Mantegna [2], the correlation-based networks are widely used in the financial network literature to quantify the impact of various crisis events [3–11]. An extension of the Minimum spanning tree (MST) method for the correlation network was later on presented by Tumminello et al. [12], known as planar maximally filtered graph (PMFG), and Boginski et al. [13] formed a correlation threshold (CT) network. The uncertainty of the stock market and the volatility in stock market returns can be measured with entropy-based approaches, as suggested by previous studies [14–19]. Most importantly, a complex system such as the stock market presents its structure better when it is under stress.

While studying the US stock market, Omnela et al. [20] discover structural changes and a shrinkage in the tree length due to crises by using the correlation network of dynamic asset trees. In addition, Vandewalle et al. [21] and Nobi et al. [22] found a power-law degree distribution of the US stock market.
Li et al. [23] show a star-like minimum spanning tree (MST) topology for the Euro Stoxx market during a crisis. Dimitrios and Vasileios [24] highlight the importance of a few stocks that can influence the entire Greek stock market. While examining the South African stock market, Majapa and Gossel [5] found a shrinkage in the tree length during a crisis and a growth afterwards. More interestingly, Kantar et al. [25], after applying MST, showed no impact of the global financial crisis 2008 on Turkish firms. Examining Asian capital markets, Bhattacharjee et al. [26] observed similar hubs and a decrease in the height of clusters during a crisis. Sensoy and Tabak [27] found a deteriorated network stability with the removal of the Hongkong stock market from the Asia Pacific spanning trees network. Using MST and a hierarchical tree, Yang et al. [28] mentioned the core nodes that should be monitored to maintain the stability and a slight increase in the clustering degree during a financial crisis for China’s stock market. Recently, Nie and Song [29] exhibited the integration of entropy and the dimension of financial correlation-based networks among stock markets of three countries: China, the UK, and the US. It is worth noticing that there are a lot of local stock markets that need to be explored via complex network methods, as past research is targeted at a few stock markets of the world.

In this article, we thoroughly analyze the correlation structure network and dynamics of $N = 181$ stocks from 33 sectors listed on the Pakistan stock exchange (PSX) over a wide period from 2007 to 2017. We observe that the Pakistan stock market experiences severe downward fluctuation due to a financial and trade contagion emerging from the GFC. Therefore, our main aim is to investigate the impact of GFC on the network structure of the Pakistan stock market by diving the timeline into three subperiods. The novelty of this research lies in the network analysis of an overall and period-wise comparison of the pre-financial crisis, the financial crisis, and the post-financial crisis of PSX; that, to best of our knowledge, has not been done in the literature. We first measure the individual stock volatility by applying Shannon entropy on all stocks. Thereafter, we construct the Pakistan stock market network using Pearson correlation coefficients and present the topological properties of nine threshold networks around the GFC. In addition, we apply a physics-derived technique of MST to the entire timeline and three targeted subperiods to study the overall and period-wise structures of PSX and to inspect the scale-free properties of four MST networks. Finally, we present time varying topological measures of the Pakistan stock market to inspect the dynamic evolution of the network.

The paper is organized as follows: Section 2 reviews the relevant prior work on financial market networks. In Section 3, we describe the data and methodology used in this work. Section 4 shows the empirical results and discusses the results. Finally, we conclude the paper in Section 5.

2. Literature Review

For a stock market, the network approach has appeared as a useful measure to analyze its static and dynamic properties [30–33]. With regards to the application of a network-based approach to examine the developed markets of the world, Bonanno et al. [34] applied an MST and hierarchical tree (HT) to investigate the major 100 stocks listed in the New York stock exchange (NYSE) over the period of 1995 to 1998. Their results showed clusters of stocks in their respective economic sector, and information on the tree topology led to a portfolio optimization. Similarly, Ulusoy et al. [35] used MST and HT on the top 40 companies of UK listed on the London stock exchange between January 2006 and November 2010. In addition to identifying the common clusters, their results also represented an important role of the economic factors influencing a special group of stocks. Onnela et al. [7] investigated the impact of the black Monday crisis on 116 companies of S&P 500 between 1982 and 2000, using the MST methodology. Their results showed a decrease in the normalized tree length and a reconfiguration of the stocks during the crisis time. Brida and Risso [36] analyzed 29 main German companies of the blue-chip DAX 30 index trading on the Frankfurt stock exchange between January 2003 and November 2008. After using MST and HT, their results revealed linkages among companies with the same branch of economy. Additionally, they found a structural break in the expansion of global distance after implementing bootstrap simulations. Lee et al. [37] examined the high-frequency data of 50 stocks listed in the Korean stock market over the period of January 2009 to December 2009. After constructing MST maps, their results found dense structures with a higher market volatility.
Regarding developing countries’ stock markets, Zhang et al. [38] found a power-law degree distribution and a small-world property of a high frequency time series of the Shanghai stock index between 5 March 2007 and 16 March 2007. Huang et al. [39] presented a structural and topological analysis of threshold networks among 1080 stocks listed in the Shanghai and Shenzhen stock markets of China between 2003 and 2007. Their results showed both a topological robustness and a fragility against random node failures. Nguyen et al. [40] examined companies listed on the Hochiminh Stock Exchange (HSX) of Vietnam over the period of 2008 to 2017. Their results showed star-like MST during a Vietnamese financial crisis period in the year 2011–2012. Bahaludin et al. [41] identified four highly dominant stocks of the Malaysian stock market by using the MST method on the top 100 companies from 2011 to 2013. Tabak et al. [42] applied MST on the Brazilian stock market and found a respective importance of various sectors by using the data of 47 stocks between January 2000 and February 2008.

To fix the distortion from correlation coefficients [43], Lyocsa et al. [32] constructed an MST from the dynamic conditional correlations (DCC) of the US stock market over various sample periods. With the exception of the oil and gas industry, their results revealed heterogeneity among various industry sectors. Additionally, they suggested the DCC approach over rolling correlations while describing the limitations of both methods. Examining nonstationary time series, Ferreira et al. [44] applied a detrended cross-correlation analysis (DCCA) method to study the financial integration among 10 Eurozone countries. Their results showed a dissimilar financial integration among a number of EU countries. Furthermore, Peron et al. [45] mentioned entropy-based methods to examine the topology and dynamic evolution of financial market networks, especially during crisis. However, we construct a network based on Pearson correlation coefficients because it is widely applied in the financial network literature. Additionally, a network based on the correlation of stock returns consists of all the information regarding the stock relationship, including investor expectations.

3. Data and Methodology

We analyze the daily closing prices for 181 stocks listed in the Pakistan stock market from 3 January 2007 to 29 December 2017, consisting of 2722 trading days. Previous studies mention a varied time period for GFC for Asian countries (see, for example, the Asian market Indices [46], Japan [47], China [48], Korea [22], and Malaysia [49]). However, the Pakistan stock market experienced severe turbulence and country’s benchmark Karachi stock exchange (KSE-100) index declined rapidly from 14,956.82 points on the first trading day of May 2008 to a plunge in the index value by almost 35.29% or by 5278 points within three months, representing a financial crisis hit. Thus, to capture the full essence of a topological evolution of GFC on PSX, we divide the overall time series into three subperiods: precrisis (8 March 2007 to 2 May 2008), crisis (5 May 2008 to 30 June 2009), and postcrisis (1 July 2009 to 19 August 2010); each subperiod comprises 285 trading days. Table 1 mentions 33 sectors under the investigation of the Pakistan stock market network. A complete list of 181 stocks acting as nodes of the PSX network in a chronological order and categorized by their respective industry sectors is mentioned in Appendix A.

Table 1. The Pakistan stock sectors and their respective color in the minimum spanning tree (MST).

| S. No | Sector                      | Color     | Number of Companies |
|-------|-----------------------------|-----------|---------------------|
| 1     | Automobile Assembler        | Purple    | 9                   |
| 2     | Automobile Parts and Accessories | Purple | 4                   |
| 3     | Cable and Electric Goods    | Cream     | 5                   |
| 4     | Cement                      | Blue      | 13                  |
| 5     | Chemical                    | Yellow    | 8                   |
| 6     | Close-End Mutual Fund       | Rose gold | 2                   |
| 7     | Commercial Banks            | Red       | 16                  |
| 8     | Engineering                 | Hazel Green | 4                   |
| 9     | Fertilizer                  | Olive     | 5                   |
| 10    | Food and Personal Care Products | Charcoal | 9                   |
Table 1. Cont.

| S. No | Sector                                      | Color      | Number of Companies |
|-------|---------------------------------------------|------------|---------------------|
| 11    | Glass and Ceramics                          | Gunmetal   | 4                   |
| 12    | Insurance                                   | Cyan       | 10                  |
| 13    | Inv. Banks/Inv. Cos./Securities Cos.        | Lime       | 7                   |
| 14    | Jute                                        | Black      | 1                   |
| 15    | Leasing                                     | Navy       | 2                   |
| 16    | Leather and Tanneries                       | Celeste    | 2                   |
| 17    | Miscellaneous                               | Brown      | 7                   |
| 18    | Modarabas                                   | Grey       | 7                   |
| 19    | Oil and Gas Exploration Companies           | Orange     | 4                   |
| 20    | Oil and Gas Marketing Companies             | Orange     | 6                   |
| 21    | Paper and Board                             | Silver     | 5                   |
| 22    | Pharmaceuticals                              | Green      | 7                   |
| 23    | Power Generation and Distribution           | Light blue | 6                   |
| 24    | Refinery                                    | Indigo     | 4                   |
| 25    | Sugar and Allied Industries                 | Magenta    | 6                   |
| 26    | Synthetic and Rayon                         | Platinum   | 2                   |
| 27    | Technology and Communication                | Teal       | 7                   |
| 28    | Textile Composite                           | Khaki      | 7                   |
| 29    | Textile Spinning                            | Khaki      | 4                   |
| 30    | Textile Weaving                             | Khaki      | 2                   |
| 31    | Tobacco                                     | Coral      | 2                   |
| 32    | Transport                                   | Maroon     | 3                   |
| 33    | Woollen                                     | Salmon     | 1                   |

A set of \( n \) stocks is represented by \( S = \{ i | i = 0, 1, \ldots, n \} \), where the individual stock corresponds to a numerical label \( i \) in \( S \). We define \( \{ P_i(t) \} \) as the stock \( i \) closing price, the log return \( r_i(t) \) of stock \( i \) after the time interval \( \Delta t \) can be calculated as

\[
r_i(t) = \ln(P_i(t)) - \ln(P_i(t-1))
\]

Since, the volatility of each stock is a latent variable, a proxy needs to be determined. A well-known proxy to examine stock market volatility has been the standard deviation \( \sigma \). However, we apply the Shannon entropy [50], an alternative way commonly used in the statistical physics of complex dynamics. Given the probability distribution of occurrence \( P_i(i = 1, \ldots, N) \), the Shannon entropy \( H(p_1, p_2, \ldots, p_n) \), reads

\[
H = - \sum_{i=1}^{N} p_i \log_2 p_i
\]

where \( 0 \log 0 \) is described as 0 and the normalized related probabilities is \( \sum_{i=1}^{N} p_i = 1 \). The base 2 for \( \log \) is drawn so that the computation is given concerning bits of information. We divide the log return \( r_i(t) \) of the stock into \( N \) different bins and then compute the probabilities of each state \( i \) divided by the total number of values of stock \( S \). We then apply the Shannon entropy depending upon the number of selected bins for each stock to measure the uncertainty and volatility (for a detailed study, please see Reference [51]).

Thereafter, we calculate the Pearson correlation coefficient among all pairs of daily returns of stock \( i \) and \( j \) in set \( S \), given as

\[
C_{ij} = \frac{\langle r_i r_j \rangle - r_i \langle r_j \rangle}{\sqrt{\langle r_i^2 \rangle - (\langle r_i \rangle)^2} \sqrt{\langle r_j^2 \rangle - (\langle r_j \rangle)^2}}
\]

where \( r_i \) and \( r_j \) are the returns of stock \( i \) and \( j \) and the notation \( \langle \ldots \rangle \) represents the mean value over the period of investigation. Following this method, we can obtain \( (181 \times 181) \) cross-correlation symmetric.
matrices among all nodes that vary from $-1$ (negatively correlated) to $+1$ (positively correlated). We obtain threshold network $\theta$ by assigning a certain value to $\theta$, $(−1 ≤ \theta ≤ 1)$, from the cross-correlation coefficients. If $C_{ij}$ between two stocks is greater than $\theta$, we build an undirected link between stocks $i$ and $j$. Perhaps, with same number of nodes for a certain $\theta$, we obtain different set of links [39,52].

In order to construct a minimum spanning tree (MST), we further transform the correlation matrix of $(181 \times 181)$ stocks to a matrix that apprehends the distance in the tree network, as proposed by Mantegna [2] and by Mantegna and Stanley [53]. It is defined as

$$d_{ij} = \sqrt{2(1 - C_{ij})} \quad (4)$$

The distance $d_{ij}$ among stocks $i$ and $j$, the MST, denoted as $T$, is then computed from a data metric of $N \times (N - 1)/2$ links to a minimized total weight of $V - 1$ isolated edges, using the Kruskal algorithm [54].

$$T = \sum_{(i,j) \in T} d_{ij} \quad (5)$$

### 4. Results and Discussion

In this section, we present findings of the Pakistan stock market correlation network of 181 stocks from 33 industry sectors between January 2007 to December 2017 measured by logarithmic returns.

#### 4.1. Correlation Coefficients and Distance Matrices

Figure 1 presents a graph of the average cross-correlation coefficients (CCC) for 181 stocks of the Pakistan stock market between 2007 and 2017. The average CCCs show a tremendous increase in the year 2008 when a GFC struck Pakistan and a decline abruptly after crisis. A local peak in the average CCC can be seen in the year 2017, when country experienced a severe political and economic crisis. The strong correlation among stocks is an indication that common shock was shared by all stocks during crisis period [55]. Pakistan’s economy was sternly hit due to GFC and the country’s GDP growth rate has shown a reduction from 4.833% in the year 2007 to 1.701% in the year 2008. Further, in Table 2, we mention statistics of the Pearson correlation and the distance metrics of the overall and three subperiods around the GFC of the Pakistan stock market. The full sample mean correlation among the stocks of PSX remain at 0.128 and the average distance remains at 1.319, which is marginally lower than the overall sample mean correlation of 0.145 for the South African stock market [5] and, therefore, shows a lower clustering and homogeneity on the Pakistan stock market compared to the South African stock market. In addition, the results reveal a lower mean correlation during the postcrisis period, thus showing comparatively weaker clusters. In contrast, the mean correlation among stocks increases around 39.42% during the crisis period compared to the precrisis period and stabilized to the mean correlation of 0.134 in the postcrisis period, moderately lower than the precrisis mean correlation of 0.137.

|        | Distance | Pearson Correlation Coefficient |
|--------|----------|----------------------------------|
|        | Mean     | Maximum | Minimum | Mean   | Maximum | Minimum |
| Precrisis | 1.311    | 1.744   | 0.635    | 0.137 | 0.799 | -0.521 |
| Crisis   | 1.265    | 1.585   | 0.641    | 0.191 | 0.795 | -0.255 |
| Postcrisis | 1.313    | 1.554   | 0.693    | 0.134 | 0.760 | -0.208 |
| Overall  | 1.319    | 1.450   | 0.786    | 0.128 | 0.691 | -0.051 |

Table 2. A summary of the observations covering the precrisis, crisis, postcrisis and overall sample period for Pakistan stock exchange (PSX).
4.2. Shannon Entropy

We calculate the Shannon entropy of $N = 181$ stocks of PSX with two different bin choices of sizes 0.01 and 0.05. Obviously, the result of the first bin size of 0.01 will always be higher than of the other bin size of 0.05 and contains more information than the second bin size [51,56]. The result of the overall sample period is presented in Figures 2 and 3, where a high value of the Shannon entropy represents the most volatile stocks. The results show prominent variation among stocks with a larger bin size; that is why it is preferred in literature. After ranking the entire sample based on the Shannon entropy score, we present the top five most and least volatile stocks of PSX in Table 3. The results show that Invest capital investment bank (ICIBL) carries the highest entropy score of 4.634 with a bin size of 0.01 and, therefore, is the most volatile stock in the PSX. Simultaneously, Pakistan services ltd. (PSEL) is the least volatile stock of PSX with a lowest Shannon entropy score of 1.694 among the entire sample. Furthermore, the average entropy of the investment and securities companies sector remains the highest among the entire sample, 3.923, with a bin size 0.01, followed by the textile weaving sector average entropy of 3.827, representing the most volatile sectors of the PSX.

![Figure 1. The average cross-correlation coefficients of 181 stocks of the Pakistan stock exchange (PSX).](image1)

![Figure 2. The Shannon entropies of 181 stocks on the PSX with bins of size 0.01.](image2)
4.3. Threshold Network

In this subsection, we present the topology of correlation threshold networks that have been achieved after analyzing three subperiod metrics (precrisis, crisis, and postcrisis). It means that a line is drawn acting as the undirected link for stocks at three different correlation $\theta$ values of $C_{ij} > 0.1$, $C_{ij} > 0.3$, and $C_{ij} > 0.5$ and that nine adjacency matrices are created for three different subperiods. The results in Table 4 exhibit a dense network for all the subperiods at $\theta > 0.1$, particularly for the crisis period with a high network density of 0.674 and with 67.37% of the retaining edges in comparison with the other two periods. However, the density of the threshold network reduces significantly at $\theta > 0.5$, since a higher threshold value corresponds to fewer edges [57]. The density of the crisis period at $\theta > 0.5$ remains high to 0.183 in comparison with the precrisis and postcrisis periods due to a tight correlation among stocks, which is a sign of instability because markets tend to act as one during crises [58]. In addition, a high number of 86 stocks acting as nodes in the threshold network are connected at $\theta > 0.5$ for the crisis period in comparison with 37 stocks in the precrisis and 49 stocks in the postcrisis periods. Regarding sectoral influence, the cement sector nodes of Fauji cement company (FCCL) and DG Khan cement company (DGKC) are key nodes in the threshold network during the precrisis period. Whereas, DGKC dominates in the crisis period threshold network by forming a major cluster at a $\theta$ value of 0.3 and higher, along with the fertilizer sector important node of Engro corporation (ENGRO). However, the period after crisis presents important nodes with many links from three sectors of investment companies, cement, and fertilizers.
Table 4. The topology of the threshold network before, during, and after a financial crisis for PSX.

|                     | Precrisis | Crisis | Postcrisis |
|---------------------|-----------|--------|------------|
|                     | $p > 0.1$ | $p > 0.3$ | $p > 0.5$ | $p > 0.1$ | $p > 0.3$ | $p > 0.5$ | $p > 0.1$ | $p > 0.3$ | $p > 0.5$ |
| Nodes               | 181       | 123    | 37         | 181       | 161       | 86        | 181       | 107       | 49        |
| Retaining Edges     | 9684      | 1250   | 74         | 10975     | 3891      | 669       | 9570      | 1421      | 94        |
| % of Retaining Edges| 59        | 8      | 0.45       | 67.37     | 23.89     | 4.11      | 57.52     | 8.72      | 0.58      |
| Average Degree      | 107.006   | 20.325 | 4          | 121.271   | 48.535    | 15.558    | 103.536   | 26.561    | 3.837     |
| Network Diameter    | 3         | 5      | 7          | 3         | 9         | 6         | 3         | 5         | 7         |
| Average Path Length | 1.411     | 2.163  | 2.545      | 1.329     | 2.245     | 2.399     | 1.431     | 1.964     | 2.777     |
| Graph Density       | 0.594     | 0.167  | 0.111      | 0.674     | 0.302     | 0.183     | 0.575     | 0.251     | 0.08      |
| Communities         | 5         | 8      | 8          | 4         | 5         | 5         | 5         | 5         | 9         |
| Modularity          | 0.044     | 0.134  | 0.459      | 0.09      | 0.167     | 0.273     | 0.041     | 0.109     | 0.417     |

4.4. Minimum Spanning Tree

We construct four minimum spanning trees of the Pakistan stock exchange network for three subperiods around a GFC and a full sample period to study the evolving connectivity and efficacy of nodes (all nodes are colored according to their respective sector (please see Appendix A) and are sized based on their centrality score) in the network. The precrisis minimum spanning tree map of PSX is presented in Figure 4. The results show an emergence of three major clusters belonging to the cement sector (blue), the oil and gas sector (orange), and the commercial banks (red). In terms of connectivity (the number alongside each node represents its degree of connections), there is one major hub node of DG Khan cement company (DGKC, 15), along with four minor hub nodes, which are Nishat mills (NML, 8), National bank of Pakistan (NBP, 7), Pakistan oilfields (POL, 7), and Sui northern gas pipelines (SNGP, 7). We can observe the scattered role of commercial bank nodes in the MST such as Soneri bank (SNBL), which is connected to the oil and gas exploration sector node POL; Samba bank (SBL) and SILK Bank (SILK), which are connected to the cement sector key nodes of DGKC and ACPL; United Bank (UBL) and Meezan bank (MEBL), which are connected to the textile composite sector key node of Nishat mills (NML); and so on. This shows that the commercial banks sector plays a lead role in spreading the financial crisis to other sectors in the Pakistan stock market network.

Figure 4. A precrisis minimum spanning tree map of 181 stocks on the PSX network (8 March 2007 to 2 May 2008).
A crisis period minimum spanning tree structure is presented in Figure 5. The results show the appearance of a similar major hub node of DG khan company (DGKC, 11) as in the precrisis period that plays a key role in resisting a crisis shock. Other key nodes with a high degree of connections in the MST are Askari bank (AKBL, 9), Pakistan refinery (PRL, 8), Dawood Hercules Corporation (DAWH, 7), and Oil and gas development company (OGDC, 7). Thus, a crisis MST of PSX reveals a weakening in the number of connections in comparison with the precrisis period, similar to the findings for the South African stock exchange network during crises [5]. In addition, the results also show the importance of the commercial banks sector node of Askari bank (AKBL) that holds the highest betweenness centrality score of 9464 in the crisis period MST of the Pakistan stock market, perhaps reflecting a strong intermediary role.

![Minimum Spanning Tree Map](image)

**Figure 5.** A crisis period minimum spanning tree map of 181 stocks on the PSX network (May 5, 2008 to June 30, 2009).

A postcrisis minimum spanning tree map of PSX network is presented in Figure 6. We can observe that DG khan company (DGKC, 6) is no longer a major hub node as observed in the precrisis and crisis period MST, possibly indicating a changing degree of diversification by the cement sector companies. In addition, there are seven principle nodes in the postcrisis MST, mainly Jahangir Siddiqui company (JSCL, 10), Adamjee insurance company (AICL, 8), ENGRO corporation (ENGRO, 8), ICI Pakistan (ICI, 8), Lucky cement company (LUCK, 8), Muslim commercial bank (MCB, 8), and Pakistan state oil (PSO, 7). The results also show an after-contagion effect in the form of rearrangement and reconfiguration in the MST structure, where commercial banks and cement sector nodes combine themselves among their respective clusters. Thus, a postcrisis MST reduces the impact of connectivity with the riskier sectors of the network. In addition, the results show a compact postcrisis MST structure mainly due to the presence of several hubs that indicate a metastable market structure in comparison with the crisis and precrisis period MSTs [11,59].
Figure 5. A crisis period minimum spanning tree map of 181 stocks on the PSX network (May 5, 2008 to June 30, 2009).

Figure 6. A postcrisis minimum spanning tree map of 181 stocks on the PSX network (1 July 2009 to 19 August 2010).

Figure 7 presents the overall MST structure of the Pakistan stock market. As can be seen, the whole structure of PSX network revolves around one super hub node of DG khan company having 42 connections, followed by the important nodes of Nishat mills (NML 12), Fauji cement company (FCCL 7), and Pakistan state oil (PSO 7). Hence, the rise and fall of DGKC will give a huge impact on the stability structure of the PSX network, as mentioned by Sharif et al. [60] for the HWAN and MRES nodes of the Malaysian stock market network. The results also reveal a star-like less stable market structure of PSX during the entire period of study, similar to the structures of the Vietnamese stock exchange [40] and German stock exchange [61] during crises. The crisis-like structure is well-suited, given the turbulent timeline of 11 years for Pakistan that posed various challenges and threats, among the major being GFC, terrorism, and economic and political crisis. Furthermore, the results show a substantial clustering on the Pakistan stock exchange network because stocks mostly tend to cluster based on their economic activity.
Figure 6. A postcrisis minimum spanning tree map of 181 stocks on the PSX network (July 1, 2009 to August 19, 2010).

Figure 7. An overall-period star-like minimum spanning tree map of 181 stocks on the PSX (3 January 2007 to 29 December 2017).

4.5. Scale-Free Structure of MSTs

We calculate the scale-free properties of the MST networks, a concept introduced by Barabasi and Albert in the year 1999 [62] and widely used in financial network literature [20,22,63,64]. The power-law degree distribution $p(k)$ of node $i$ and degree $k$ has a power tail, such as $p(k) \sim k^{-\alpha}$; the network is said to be scale-free. We apply a powerful tool introduced by Clauset et al. [65] to observe the degree distribution of subsamples and overall MST networks. To accept the power-law hypothesis, the goodness-of-fit $p$-value must be larger than 0.1 [65]. The fitting results for three subsample periods are presented in Figures 8–10. The $p$-value for three subsamples is larger than 0.1, which means that the degree distribution follows the power law. However, the $p$-value of the overall sample period stands at 0.037, shown in Figure 11, which implies not to accept the power-law hypothesis. Similarly, a star-like MST is also found by Nguyen et al. [40] for the Vietnamese stock market from the year 2011 to 2012, where the degree distribution does not fit with the power law distribution. In addition, the power-law exponent (the value of the power-law exponent $\alpha$ nearing 1.0 indicates the longer tail distribution) $\alpha$ for the crisis period is 3.430, which is higher than in the precrisis, $\alpha = 2.890$, and postcrisis, $\alpha = 2.810$, periods. Hence, a postcrisis degree distribution of MST has a longer tail distribution in comparison with the precrisis and crisis period MST networks. As can be seen in Figures 8–10, the degree distribution of the postcrisis period is more compact than the pre- and crisis period.
contain a relatively low number of linkages. This type of configuration represents several star-like core nodes are largely interconnected in a minor portion, whereas a large number of peripheral nodes.

Thereafter, we construct yearly MSTs and present their finding of degree distribution and normalized tree lengths. In addition, the power-law exponent (the value of the power-law exponent)

sample period stands at 0.037, shown in Figure 11, which implies not to accept the power-law hypothesis. Similarly, a star-like MST is also found by Nguyen et al. [40] for the Vietnamese stock market from the year 2011 to 2012, where the degree distribution does not fit with the power law.

The degree distribution

Figure 8. A precrisis minimum spanning tree degree distribution of 181 stocks on the PSX network: the p-value is 0.669, which means the stocks follow the power-law distribution.

Figure 9. A crisis period minimum spanning tree degree distribution of 181 stocks on the PSX network: the p-value is 0.764, which means the stocks follow the power-law distribution.

Figure 10. A postcrisis minimum spanning tree degree distribution of 181 stocks on the PSX network: the p-value is 0.112, which means the stocks follow the power-law distribution.
4.6. Dynamic Structures of MSTs

In order to examine the consistency and dynamic evolution of the Pakistan stock market network, we divide the overall data sample into $T = 11$ rolling windows of width $L$ (where $L$ is the daily returns of $N = 181$ nodes starting from the first trading day of the year in the month of January and ending on the last trading day of the same year in the month of December) [66]. Thereafter, we construct yearly MSTs and present their finding of degree distribution and normalized tree lengths.

4.6.1. Degree Distribution

The degree distribution $p(k)$ of dynamic MSTs of PSX is presented in Figure 12. We can observe a positively skewed degree distribution representing the heterogeneity of the system. However, the core nodes are largely interconnected in a minor portion, whereas a large number of peripheral nodes contain a relatively low number of linkages. This type of configuration represents several star-like MST structures, especially during the GFC in the year 2008 and the economic and political crisis in the year 2017 for the Pakistan stock market network.

![Figure 12](image-url)

**Figure 12.** A dynamic minimum spanning tree degree distribution of 181 stocks on the PSX network from January 2007 to December 2017: The x-axis, y-axis, and z-axis mention the degree (k), time (t), and probability $p(k)$, respectively.
4.6.2. Normalized Tree Length

According to Onnela et al. [67], the normalized tree length (NTL) of MST $T = (V, E)$ can be calculated as follows:

$$L(t) = \frac{1}{n-1} \sum_{i \neq j \in T} d_{ij}(t)$$

where $n$ is the nodes of the network in $T$ and $d_{ij}$ is the distance among nodes $i$ and $j$.

Figure 13 shows the time-varying result of a normalized tree length of the Pakistan stock market network. As can be seen, the lowest NTL curve during a GFC is observed for the PSX network in the year 2008 and implies a higher correlation among stocks. However, after getting a financial assistance package from the International monetary fund (IMF) to curb the GFC in the year 2008, the NTL curve shows a gradual increase and recovery that leads to expansion thereafter. In addition, the EU sovereign debt crisis appears to have no significant impact on the PSX network, and so, it is the flood and resultant property damages that affected 14 million people in the year 2010 [68]. To sum up, the results show that the crisis-related shocks of terrorism, politics, and economics resulted in the shrinkage of the PSX network.

![Figure 13. The normalized tree length of a dynamic minimum spanning tree of 181 stocks on the PSX network from January 2007 to December 2017.](image-url)

5. Conclusions

In summary, we have investigated the structural change and dynamic evolution of the Pakistan stock market from January 2007 to December 2017. We applied the Shannon entropy on all 181 stocks acting as nodes in our study to calculate the stock market volatility with two different bins and listed the top five most and least volatile stocks. However, the main aim of our study was to examine the structural change in the Pakistan stock market network around a GFC; therefore, we divided the whole timeline into three different subperiods around a GFC. We show that the correlation among stocks of the Pakistan stock market are at the highest level during the time period of global financial crisis in the year 2008. The subsample results of correlation and distance matrices also reveal a higher mean correlation and resultant lower distances during a crisis period in comparison with the pre- and postcrisis periods. From the topology of nine threshold networks of subperiods, we noticed a comparatively high network density for the crisis period at low thresholds. Similarly, at a larger correlation threshold, a great number of nodes connect with each other during the crisis period, representing a tight correlation and instable market state in comparison with the pre- and postcrisis periods.
periods. In addition, we observed scale-free MSTs during the three subperiods and the scattered commercial banking sector in the precrisis, implying that financial crisis spread to other sectors of the Pakistan stock market through the commercial banking sector. The results further showed a metastable market state structure of MST and a recovery in the postcrisis period. Given the turbulent timeline of the overall period of study for Pakistan, the MST of the entire sample period of the Pakistan stock market revealed a crisis-like less stable market structure and the emergence of a super hub node: DG Khan cement company (DGKC), belonging to the cement sector. However, a substantial clustering can be seen where nodes connect with each other based on their economic activity. To study the dynamic evolution of PSX, we presented a degree distribution and normalized tree length on 11 year rolling windows that showed several star-like positively skewed networks and a shrinkage of tree lengths due to the crisis-related shocks of terrorism, politics, economics, and finances.

All of these findings on the structural change and dynamic evolution will assist local and international investors of the Pakistan stock market in successfully managing their portfolios or to regulatory bodies to assess the stock market stability. In the future, we aim to explore the complexity and fractal dimensions of the PSX network.

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Appendix A

Table A1. A list of 181 stocks acting as nodes in the network of the Pakistan stock market classified by their respective industry sector and colored accordingly.

| Node | Ticker | Company Name                        | Sector               | Color  |
|------|--------|-------------------------------------|----------------------|--------|
| 1    | ABL    | Allied Bank Limited                 | Commercial Banks     | RED    |
| 2    | ABOT   | Abbots Laboratories (Pakistan) Limited | Pharmaceuticals | GREEN  |
| 3    | ACPL   | Attock Cement (Pakistan) Limited    | Cement               | BLUE   |
| 4    | ADOS   | Ados Pakistan Limited               | Engineering          | HAZEL  GREEN |
| 5    | AGTL   | Al-Ghazi Tractors Limited           | Automobile Assembler | PURPLE |
| 6    | AHCL   | Anil Habib Corporation Limited      | Fertilizer           | OLIVE  |
| 7    | AKCL   | Adapex Insurance Company Limited    | Insurance            | CYAN   |
| 8    | AKBL   | Askari Bank Limited                 | Commercial Banks     | RED    |
| 9    | ANL    | Azgard Nine Limited                 | Textile Composite    | KHAKI  |
| 10   | APL    | Attock Petroleum Limited            | Oil and Gas Marketing Companies | ORANGE |
| 11   | ATBA   | Atlas Battery Limited               | Automobile Parts & Accessories | PURPLE |
| 12   | ATLH   | Atlas Honda Limited                 | Automobile Assembler | PURPLE |
| 13   | ATRL   | Attock Refinery Limited             | Refinery             | INDIGO |
| 14   | BAFL   | Bank Al-Falah Limited               | Commercial Banks     | RED    |
| 15   | BAHL   | Bank Al-Habib Limited               | Commercial Banks     | RED    |
| 16   | BATA   | Bata Pakistan Limited               | Leather and Tanneries | CELESTE |
| 17   | BERG   | Berger Paints Pakistan Limited      | Chemical             | YELLOW |
| 18   | BIPL   | Bankislima Pakistan Limited         | Commercial Banks     | RED    |
| 19   | BNWM   | Bannu Woollen Mills Limited         | Woollen              | SALMON |
| 20   | BOK    | Bank of Khyber Limited              | Commercial Banks     | RED    |
| 21   | BOP    | Bank of Punjab Limited              | Commercial Banks     | RED    |
| 22   | BPL    | Burshane LPG (Pakistan) Limited     | Oil and Gas Marketing Companies | ORANGE |
| 23   | BRR    | B.R.R. Guardian Modaraba            | Modarbas             | GREY   |
| 24   | BWCL   | Bestway Cement Limited              | Cement               | BLUE   |
| 25   | BYCO   | Byco Petroleum Pakistan Limited     | Refinery             | INDIGO |
| 26   | CENI   | Century Insurance Company Limited   | Insurance            | CYAN   |
| 27   | CEPB   | Century Paper and Board Mills Limited | Paper and Board | SILVER |
| 28   | CFL    | Crescent Fibres Limited             | Textile Spinning     | KHAKI  |
| 29   | CHBL   | Chenab Limited                       | Textile Composite    | KHAKI  |
| 30   | CHCC   | Cherat Cement Company Limited       | Cement               | BLUE   |
| 31   | CJPL   | Crescent Jute Proucts Limited       | Jute                 | BLACK  |
| 32   | CLOV   | Clover Pakistan Limited             | Food and Personal Care Products | CHARCOAL |
| 33   | COLG   | Colgate Palmolive (Pakistan) Limited | Chemical            | YELLOW |
| 34   | CPPL   | Cherat Packaging Limited.           | Paper and Board      | SILVER |
### Table A1. Cont.

| Node | Ticker | Company Name | Sector | Color |
|------|--------|--------------|--------|-------|
| 35   | CSAP   | Crescent Steel & Allied Products Limited | Engineering | HAZEL GREEN |
| 36   | CSMI   | Crescent Standard Modaraba | Sugar and Allied Industries | MAGENTA |
| 37   | DAWH   | Dawood Hercules Corporation Limited | Fertilizer | OLIVE |
| 38   | DCL    | Dewan Cement Limited | Cement | BLUE |
| 39   | DFML   | Dewan Farooque Motors Limited | Automobile Assembler | PURPLE |
| 40   | DGKC   | D.G. Khan Cement Company Limited | Cement | BLUE |
| 41   | DLL    | Dawood Lawrencepur Limited | Textile Composite | KHAKI |
| 42   | DNCC   | Dandot Cement Company Limited | Cement | BLUE |
| 43   | DSFL   | Dewan Salman Fibre Limited | Synthetic and Rayon | PLATINUM |
| 44   | DSL    | D.S. Industries Limited | Textile Spinning | KHAKI |
| 45   | DWSM   | Dewan Sugar Mills Limited | Sugar and Allied Industries | MAGENTA |
| 46   | DYNO   | Dynea Pakistan Limited | Chemical | YELLOW |
| 47   | ECOP   | Ecopack Limited | Miscellaneous | BROWN |
| 48   | EFUG   | EPU General Insurance Limited | Insurance | CYAN |
| 49   | EFUL   | EPU Life Assurance Limited | Insurance | CYAN |
| 50   | EMCO   | Emco Industries Limited | Glass and Ceramics | GUNMETAL |
| 51   | ENGRO  | Engro Corporation Limited | Fertilizer | OLIVE |
| 52   | EXIDE  | Exide Pakistan Limited | Automobile Parts and Accessories | PURPLE |
| 53   | FABL   | Faysal Bank Limited | Commercial Banks | RED |
| 54   | FCCL   | Fauji Cement Company Limited | Cement | BLUE |
| 55   | FCSC   | First Capital Securities Corporation Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 56   | FDBL   | First Dawood Investment Bank Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 57   | FECM   | First Elite Capital Modaraba | Modarabas | GREY |
| 58   | FECTC  | Fecto Cement Limited | Cement | BLUE |
| 59   | FEM    | First Equity Modaraba | Modarabas | GREY |
| 60   | FEROZ  | Ferrozns Laboratories Limited | Pharmaceuticals | GREEN |
| 61   | FFBIL  | Fauji Fertilizer Bin Qasim Limited | Fertilizer | OLIVE |
| 62   | FFC    | Fauji Fertilizer Company Limited | Fertilizer | OLIVE |
| 63   | FHAM   | First Habib Modaraba Limited | Modarabas | GREY |
| 64   | FNBM   | First National Bank Modaraba | Modarabas | GREY |
| 65   | FNEL   | First National Equities Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 66   | GADT   | Gadson Textile Mills Limited | Textile Spinning | KHAKI |
| 67   | GASF   | Golden Arrow Selected Funds Limited | Close-End Mutual Fund | ROSEGOLD |
| 68   | GATI   | Gatron Industries Limited | Synthetic and Rayon | PLATINUM |
| 69   | GATM   | Gul Ahmed Textile Mills Limited | Textile Composite | KHAKI |
| 70   | GHGL   | Ghani Glass Limited | Glass and Ceramics | GUNMETAL |
| 71   | GHNL   | Ghundara Nissan Limited | Automobile Assembler | PURPLE |
| 72   | GLAXO  | GlaxoSmithKline (Pakistan) Limited | Pharmaceuticals | GREEN |
| 73   | GTYR   | General Tyre and Rubber Co. of Pakistan Limited | Automobile Parts and Accessories | PURPLE |
| 74   | GWLC   | Gharibwal Cement Limited | Cement | BLUE |
| 75   | HABM   | Habib Sugar Mills Limited | Sugar and Allied Industries | MAGENTA |
| 76   | HAL    | Habib-ADM Limited | Sugar and Allied Industries | MAGENTA |
| 77   | HCAR   | Honda Atlas Cars (Pakistan) Limited | Automobile Assembler | PURPLE |
| 78   | HICL   | Habib Insurance Company Limited | Insurance | CYAN |
| 79   | HIFA   | HBL Investment Fund | Close-End Mutual Fund | ROSEGOLD |
| 80   | HINO   | HinoMotors Limited | Automobile Assembler | PURPLE |
| 81   | HINNO  | Highnoon Laboratories Limited | Pharmaceuticals | GREEN |
| 82   | HMB    | Habib Metropolitan Bank Limited | Commercial Banks | RED |
| 83   | HSPI   | Huffaz Seamless Pipe Industries Limited | Engineering | HAZEL GREEN |
| 84   | HUBC   | Hub Power Company Limited | Power Generation and Distribution | LIGHTBLUE |
| 85   | HUMNL  | Hum Network Limited | Technology and Communication | TEAL |
| 86   | ICI    | I.C.I. Pakistan Limited | Chemical | YELLOW |
| 87   | ICIBL  | Invest Capital Investment Bank Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 88   | IGHL   | IGI Holdings Limited | Insurance | CYAN |
| 89   | INDU   | Indus Motor Company Limited | Automobile Assembler | PURPLE |
| 90   | INIL   | International Industries Limited | Engineering | HAZEL GREEN |
| 91   | JGCL   | Jubilee General Insurance Company Limited | Insurance | CYAN |
| 92   | JILCL  | Jubilee Life Insurance Company Limited | Insurance | CYAN |
| 93   | JOPP   | Johnson and Phillips (Pakistan) Limited | Cable and Electric Goods | CREAM |
| 94   | JPGL   | Japan Power Generation Limited | Power Generation and Distribution | LIGHTBLUE |
| 95   | JSCL   | Jahangir Siddiqui Company Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 96   | JSGCL  | JSG Capital Limited | Inv. Banks/Inv. Cos./Securities Cos. | LIME |
| 97   | KAPCO  | Kot Addu Power Company Limited | Power Generation and Distribution | LIGHTBLUE |
| 98   | KEL    | K-Electric Limited | Power Generation and Distribution | LIGHTBLUE |
| 99   | KOHC   | Kohat Cement Limited | Cement | BLUE |
| 100  | KOHE   | Kohinoor Energy Limited | Power Generation and Distribution | LIGHTBLUE |
| 101  | KMTL   | Kohinoor Textile Mills Limited | Textile Composite | KHAKI |
| 102  | LUCK   | Lucky Cement Limited | Cement | BLUE |
| 103  | MACFL  | Macap Films Limited | Miscellaneous | BROWN |
| 104  | MARI   | Mari Petroleum Company Limited | Oil and Gas Exploration Companies | ORANGE |
| 105  | MCB    | MCB Bank Limited | Commercial Banks | RED |
| 106  | MEBL   | Meezan Bank Limited | Commercial Banks | RED |
| 107  | MERIT  | Merit Packaging Limited | Paper and Board | SILVER |
| Node | Ticker | Company Name                              | Sector                                      | Color   |
|------|--------|-------------------------------------------|---------------------------------------------|---------|
| 108  | MFPL   | Mitchells Fruit Farms Limited            | Food and Personal Care Products             | CHARCOAL|
| 109  | MLCF   | Maple Leaf Cement Factory Limited         | Cement                                      | BLUE    |
| 110  | MRNS   | Mehran Sugar Mills Limited                | Sugar and Allied Industries                 | MAGENTA |
| 111  | MLT    | Millat Tractors Limited                   | Automotive Assembler                        | PURPLE  |
| 112  | MUREB  | Murray Brewery Company Limited            | Food and Personal Care Products             | CHARCOAL|
| 113  | MSZM   | Mirza Sugar Mills Limited                 | Sugar and Allied Industries                 | MAGENTA |
| 114  | NATF   | National Foods Limited                    | Food and Personal Care Products             | CHARCOAL|
| 115  | NBP    | National Bank of Pakistan                | Commercial Banks                            | RED     |
| 116  | NCL    | Nishtat Chunian Limited                   | Textile Composite                           | KHAKI   |
| 117  | NESTLE | Nestle Pakistan Limited                   | Food and Personal Care Products             | CHARCOAL|
| 118  | NETSOL | NetSol Technologies Limited               | Technology and Communication                | TEAL    |
| 119  | NCLC   | Nimir Industrial Chemicals Limited        | Chemical                                    | YELLOW  |
| 120  | NML    | Nishtat Mills Limited                     | Textile Composite                           | KHAKI   |
| 121  | NRL    | National Refinery Limited                 | Refinery                                    | INDIGO  |
| 122  | OGCDC  | Oil and Gas Development Company Limited   | Oil and Gas Exploration Companies           | ORANGE  |
| 123  | OLPL   | Orix Leasing Pakistan Limited             | Leasing                                     | NAVY    |
| 124  | OTSU   | Otsuka Pakistan Limited                   | Pharmaceuticals                              | GREEN   |
| 125  | PBL    | Pak Electron Limited                      | Cable and Electric Goods                    | CREAM   |
| 126  | PAKD   | Pak Dacom Limited                         | Technology and Communication                | TEAL    |
| 127  | PAKOXY | Pakistan Oxygen Limited                   | Chemical                                    | YELLOW  |
| 128  | PAKRI  | Pakistan Reinsurance Company Limited      | Insurance                                   | CYAN    |
| 129  | PAKT   | Pakistan Tobacco Company Limited          | Tobacco                                     | CORAL   |
| 130  | PCL    | Pakistan Cables Limited                   | Cable and Electric Goods                    | CREAM   |
| 131  | PIAA   | Pakistan International Airlines Corporation | Transport                                  | MAROON  |
| 132  | PICT   | Pakistan International Container Terminal Limited | Transport                                  | MAROON  |
| 133  | PINL   | Premier Insurance Limited                 | Insurance                                   | CYAN    |
| 134  | PIUC   | Pioneer Cement Limited                    | Cement                                      | BLUE    |
| 135  | PKGS   | Packages Limited                          | Paper and Board                             | SILVER  |
| 136  | PMI    | First Prudential Modarba                  | Modarbas                                    | GREY    |
| 137  | PMPK   | Philip Morris (Pakistan) Limited          | Tobacco                                     | CORAL   |
| 138  | PNSC   | Pakistan National Shipping Corporation Limited | Transport                                  | MAROON  |
| 139  | POL    | Pakistan Oilfields Limited                | Oil and Gas Exploration Companies           | ORANGE  |
| 140  | TTL    | Pakistan Petroleum Limited                | Oil and Gas Exploration Companies           | ORANGE  |
| 141  | PRL    | Pakistan Refinery Limited                 | Refinery                                    | INDIGO  |
| 142  | PSEL   | Pakistan Services Limited                 | Miscellaneous                               | BROWN   |
| 143  | PSMC   | Pak Suzuki Motor Company Limited          | Automobile Assembler                        | PURPLE  |
| 144  | PSO    | Pakistan State Oil Company Limited        | Oil and Gas Marketing Companies             | ORANGE  |
| 145  | PTC    | Pakistan Telecommunication Company Limited | Technology and Communication                | TEAL    |
| 146  | QUICE  | Quice Food Limited                         | Food and Personal Care Products             | CHARCOAL|
| 147  | SAAPL  | Sanofi-Aventis Pakistan Limited           | Pharmaceuticals                              | GREEN   |
| 148  | SBL    | Samo Bank Limited                         | Commercial Banks                            | RED     |
| 149  | SEARL  | The Searle Company Limited                | Pharmaceuticals                              | GREEN   |
| 150  | SEPL   | Security Paper Limited                    | Paper and Board                              | SILVER  |
| 151  | SHEL   | Shell Pakistan Limited                    | Oil and Gas Marketing Companies             | ORANGE  |
| 152  | SHEZ   | Schez International Limited               | Food and Personal Care Products             | CHARCOAL|
| 153  | SHFA   | Shifa International Hospitals Limited     | Miscellaneous                               | BROWN   |
| 154  | SHSMIL | Shahrud Sugar Mills Limited               | Sugar and Allied Industries                 | MAGENTA |
| 155  | SIEM   | Siemens Pakistan Engineering Co. Limited | Cable and Electric Goods                    | CREAM   |
| 156  | SILK   | Silbank Limited                           | Commercial Banks                            | RED     |
| 157  | STIC   | Sita Chemical Industries Limited          | Chemical                                    | YELLOW  |
| 158  | SMTM   | Samin Textiles Limited                    | Textile Weaving                              | KHAKI   |
| 159  | SNAI   | Sana Industries Limited                   | Textile Spinning                             | KHAKI   |
| 160  | SNBK   | Soneri Bank Limited                       | Commercial Banks                            | RED     |
| 161  | SNGP   | Sui Northern Gas Pipelines Limited        | Oil and Gas Marketing Companies             | ORANGE  |
| 162  | SPCL   | Saudi Pak Leasing Company Limited         | Leasing                                     | NAVY    |
| 163  | SRVI   | Service Industries Limited                | Leather and Tanneries                       | CELESTE |
| 164  | SSGC   | Sui Southern Gas Company Limited          | Oil and Gas Marketing Companies             | ORANGE  |
| 165  | STCL   | Shabbir Tiles and Ceramics Limited        | Glass and Ceramics                           | GUNMETAL|
| 166  | STPL   | Siddirs Tin Plate Limited                 | Miscellaneous                               | BROWN   |
| 167  | TESTE  | Telecard Limited                          | Technology and Communication                | TEAL    |
| 168  | TGL    | Tariq Glass Industries Limited            | Glass and Ceramics                           | GUNMETAL|
| 169  | THALL  | Thal Limited                              | Automobile Parts and Accessories            | PURPLE  |
| 170  | TREET  | Treet Corporation Limited                 | Food and Personal Care Products             | CHARCOAL|
| 171  | TRG    | TRG Pakistan Limited                      | Technology and Communication                | TEAL    |
| 172  | TRIBL  | Trust Investment Bank Limited             | Inv. Banks/Inv. Cos. Securities Cos.        | LIME    |
| 173  | TRIPF  | Tri-Pack Films Limited                    | Miscellaneous                               | BROWN   |
| 174  | TSPL   | Tri-Star Power Limited                    | Power Generation and Distribution           | LIGHTBLUE|
| 175  | UBL    | United Bank Limited                       | Commercial Banks                            | RED     |
| 176  | UDPL   | United Distributors Pakistan Limited      | Miscellaneous                               | BROWN   |
| 177  | WAHN   | Wah Noble Chemicals Limited              | Chemical                                    | YELLOW  |
| 178  | WAVES  | Waver Singer Pakistan Limited             | Cable and Electric Goods                    | CREAM   |
| 179  | WTL    | WorldCall Telecom Limited                 | Technology and Communication                | TEAL    |
| 180  | ZIL    | Zil Limited                               | Food and Personal Care Products             | CHARCOAL|
| 181  | ZTL    | Zephyr Textile Limited                    | Textile Weaving                              | KHAKI   |
References

1. Chen, Y.; Mantegna, R.N.; Pantelous, A.A.; Zuev, K.M. A dynamic analysis of S&P 500, FTSE 100 and EURO STOXX 50 indices under different exchange rates. PLoS ONE 2018, 13, e0194067. [PubMed]
2. Mantegna, R.N. Hierarchical structure in financial markets. Eur. Phys. J. B 1999, 11, 193–197. [CrossRef]
3. Dias, J. Spanning trees and the Eurozone crisis. Phys. A Stat. Mech. Its Appl. 2013, 392, 5974–5984. [CrossRef]
4. Matesanz, D.; Ortega, G.J. Sovereign public debt crisis in Europe. A network analysis. Phys. A Stat. Mech. Its Appl. 2015, 436, 756–766. [CrossRef]
5. Majapa, M.; Gossel, S.J. Topology of the South African stock market network across the 2008 financial crisis. Phys. A Stat. Mech. Its Appl. 2016, 445, 35–47. [CrossRef]
6. Zhao, L.; Li, W.; Cai, X. Structure and dynamics of stock market in times of crisis. Phys. Lett. A 2016, 380, 654–666. [CrossRef]
7. Önnlø, J.P.; Chakraborti, A.; Kaski, K.; Kertész, J. Dynamic asset trees and Black Monday. Phys. A Stat. Mech. Its Appl. 2003, 324, 247–252. [CrossRef]
8. Li, B.; Pi, D. Analysis of global stock index data during crisis period via complex network approach. PLoS ONE 2018, 13, e0200600. [CrossRef]
9. Xia, L.; You, D.; Jiang, X.; Guo, Q. Comparison between global financial crisis and local stock disaster on top of Chinese stock network. Phys. A Stat. Mech. Its Appl. 2018, 490, 222–230. [CrossRef]
10. Jang, W.; Lee, J.; Chang, W. Currency crises and the evolution of foreign exchange market: Evidence from minimum spanning tree. Phys. A Stat. Mech. Its Appl. 2011, 390, 707–718. [CrossRef]
11. Nobi, A.; Maeng, S.E.; Ha, G.G.; Lee, J.W. Structural changes in the minimal spanning tree and the hierarchical network in the Korean stock market around the global financial crisis. J. Korean Phys. Soc. 2015, 66, 1153–1159. [CrossRef]
12. Tumminello, M.; Aste, T.; Di Matteo, T.; Mantegna, R.N. A tool for filtering information in complex systems. Proc. Natl. Acad. Sci. USA 2005, 102, 10421–10426. [CrossRef] [PubMed]
13. Boginski, V.; Butenko, S.; Pardalos, P.M. Statistical analysis of financial networks. Comput. Stat. Data Anal. 2005, 48, 431–443. [CrossRef]
14. Risso, W.A. The informational efficiency and the financial crashes. Res. Int. Bus. Financ. 2008, 22, 396–408. [CrossRef]
15. Sönia, R.B.; Rui, M. Entropy: A new measure of stock market volatility? J. Phys. Conf. Ser. 2012, 394, 012033.
16. Sheraz, M.; Dedu, S.; Preda, V. Entropy Measures for Assessing Volatile Markets. Procedia Econ. Financ. 2015, 22, 655–662. [CrossRef]
17. Sönia, R.B. An entropy-based approach to stock market volatility: Evidence from the G7’s market indices. Int. J. Ind. Syst. Eng. 2016, 24, 158–177.
18. Oh, G.; Kim, H.-Y.; Ahn, S.-W.; Kwak, W. Analyzing the financial crisis using the entropy density function. Phys. A Stat. Mech. Its Appl. 2015, 419, 464–469. [CrossRef]
19. Huang, J.; Shang, P.; Zhao, X. Multifractal diffusion entropy analysis on stock volatility in financial markets. Phys. A Stat. Mech. Its Appl. 2012, 391, 5739–5745. [CrossRef]
20. Önnlø, J.P.; Chakraborti, A.; Kaski, K.; Kertész, J.; Kantó, A. Dynamics of market correlations: Taxonomy and portfolio analysis. Phys. Rev. E 2003, 68, 056110. [CrossRef]
21. VanDewalle, N.; Brisbois, E.; Tordoir, X. Non-random topology of stock markets. Quant. Financ. 2001, 1, 372–374. [CrossRef]
22. Nobi, A.; Maeng, S.E.; Ha, G.G.; Lee, J.W. Effects of global financial crisis on network structure in a local stock market. Phys. A Stat. Mech. Its Appl. 2014, 407, 135–143. [CrossRef]
23. Li, W.; Hommel, U.; Paterlini, S. Network topology and systemic risk: Evidence from the Euro Stoxx market. Financ. Res. Lett. 2018, 27, 105–112. [CrossRef]
24. Dimitrios, K.; Vasileios, O. A Network Analysis of the Greek Stock Market. Procedia Econ. Financ. 2015, 33, 340–349. [CrossRef]
25. Kantar, E.; Keskin, M.; Deviren, B. Analysis of the effects of the global financial crisis on the Turkish economy, using hierarchical methods. Phys. A Stat. Mech. Its Appl. 2012, 391, 2342–2352. [CrossRef]
26. Bhattcharjee, B.; Shafi, M.; Acharjee, A. Network mining based elucidation of the dynamics of cross-market clustering and connectedness in Asian region: An MST and hierarchical clustering approach. J. King Saud Univ. Comput. Inf. Sci. 2017. [CrossRef]
27. Sensoy, A.; Tabak, B.M. Dynamic spanning trees in stock market networks: The case of Asia-Pacific. *Phys. A Stat. Mech. Its Appl.* 2014, 414, 387–402. [CrossRef]
28. Yang, R.; Li, X.; Zhang, T. Analysis of linkage effects among industry sectors in China’s stock market before and after the financial crisis. *Phys. A Stat. Mech. Its Appl.* 2014, 411, 12–20. [CrossRef]
29. Nie, C.X.; Song, F.T. Relationship between Entropy and Dimension of Financial Correlation-Based Network. *Entropy* 2018, 20, 177. [CrossRef]
30. Namaki, A.; Shirazi, A.H.; Raei, R.; Jafari, G.R. Network analysis of a financial market based on genuine correlation and threshold method. *Phys. A Stat. Mech. Its Appl.* 2011, 390, 3835–3841. [CrossRef]
31. Onnela, J.-P.; Saramäki, J.; Kertész, J.; Kaski, K. Intensity and coherence of motifs in weighted complex networks. *Phys. Rev. E* 2005, 71, 065103. [CrossRef] [PubMed]
32. Lyócsa, Š.; Výrost, T.; Baumöhö, E. Stock market networks: The dynamic conditional correlation approach. *Phys. A Stat. Mech. Its Appl.* 2012, 391, 4147–4158. [CrossRef]
33. Brida, J.G.; Matesanz, D.; Seijas, M.N. Network analysis of returns and volume trading in stock markets: The Euro Stoxx case. *Phys. A Stat. Mech. Its Appl.* 2016, 444, 751–764. [CrossRef]
34. Bonanno, G.; Lillo, F.; Mantegna, R.N. High-frequency cross-correlation in a set of stocks. *Quant. Financ.* 2001, 1, 96–104. [CrossRef]
35. Ulusoy, T.; Keskin, M.; Shirvani, A.; Deviren, B.; Kantar, E.; Çağrı Dönmez, C. Complexity of major UK companies between 2006 and 2010: Hierarchical structure method approach. *Phys. A Stat. Mech. Its Appl.* 2012, 391, 5121–5131. [CrossRef]
36. Brida, J.G.; Risso, W.A. Hierarchical structure of the German stock market. *Expert Syst. Appl.* 2010, 37, 3846–3852. [CrossRef]
37. Lee, J.; Youn, J.; Chang, W. Intraday volatility and network topological properties in the Korean stock market. *Phys. A Stat. Mech. Its Appl.* 2012, 391, 1354–1360. [CrossRef]
38. Zhang, J.; Zhou, H.; Jiang, L.; Wang, Y. Network topologies of Shanghai stock index. *Phys. Procedia* 2010, 3, 1733–1740. [CrossRef]
39. Huang, W.-Q.; Zhuang, X.-T.; Yao, S. A network analysis of the Chinese stock market. *Phys. A Stat. Mech. Its Appl.* 2009, 388, 2956–2964. [CrossRef]
40. Nguyen, Q.; Nguyen, N.K.K.; Nguyen, L.H.N. Dynamic topology and allometric scaling behavior on the Vietnamese stock market. *Phys. A Stat. Mech. Its Appl.* 2019, 512, 255–243. [CrossRef]
41. Bahaludin, H.; Abdullah, M.H.; Salleh, S.M. Minimal spanning tree for 100 companies in Bursa Malaysia. *AIP Conf. Proc.* 2015, 1643, 609–615.
42. Tabak, B.M.; Serra, T.R.; Caujiero, D.O. Topological properties of stock market networks: The case of Brazil. *Phys. A Stat. Mech. Its Appl.* 2010, 389, 3240–3249. [CrossRef]
43. Forbes, K.J.; Rigobon, R. No Contagion, Only Interdependence: Measuring Stock Market Comovements. *J. Financ.* 2002, 57, 2223–2261. [CrossRef]
44. Ferreira, P.; Dionísio, A.; Zebende, G.F. Why does the Euro fail? The DCCA approach. *Phys. A Stat. Mech. Its Appl.* 2016, 443, 543–554. [CrossRef]
45. Peron, T.K.D.M.; Costa, L.D.F.; Rodrigues, F.A. The structure and resilience of financial market networks. *Chaos Interdiscip. J. Nonlinear Sci.* 2012, 22, 013117. [CrossRef] [PubMed]
46. Jin, X. The impact of 2008 financial crisis on the efficiency and contagion of Asian stock markets: A Hurst exponent approach. *Financ. Res. Lett.* 2016, 17, 167–175. [CrossRef]
47. Okubo, T.; Kimura, F.; Teshima, N. Asian fragmentation in the Global Financial Crisis. *Int. Rev. Econ. Financ.* 2014, 31, 114–127. [CrossRef]
48. Zhang, J.; Teng, F. Are China Stock Markets Efficient after the Global Financial Crisis? In Proceedings of the 2010 International Conference on Computational Intelligence and Software Engineering, Wuhan, China, 10–12 December 2010; pp. 1–4.
49. Mustafa, N.N.S.; Samsudin, S.; Shahadan, F.; Yi, A.K.J. Flight-to-Quality between Stock and Bond Markets: Pre and Post Global Financial Crisis. *Procedia Econ. Financ.* 2015, 31, 846–855. [CrossRef]
50. Shannon, C.E. A Mathematical Theory of Communication. *Bell Syst. Tech. J.* 1948, 27, 379–423. [CrossRef]
51. Sandoval, L. Structure of a Global Network of Financial Companies Based on Transfer Entropy. *Entropy* 2014, 16, 4443–4482. [CrossRef]
52. Lee, J.W.; Nobi, A. State and Network Structures of Stock Markets around the Global Financial Crisis. *Comput. Econ.* 2018, 51, 195–210. [CrossRef]
53. Mantegna, R.N.; Stanley, H.E. An Introduction to Econophysics: Correlations and Complexity in Finance; Cambridge University Press: Cambridge, UK, 2000.

54. Kruskal, J.B. On the Shortest Spanning Subtree of a Graph and the Traveling Salesman Problem. *Proc. Am. Math. Soc.* 1956, 7, 48–50. [CrossRef]

55. Jiang, Y.; Yu, M.; Hashmi, S.M. The Financial Crisis and Co-Movement of Global Stock Markets—A Case of Six Major Economies. *Sustainability* 2017, 9, 260. [CrossRef]

56. Pele, D.T.; Lazar, E.; Dufour, A. Information Entropy and Measures of Market Risk. *Entropy* 2017, 19, 226. [CrossRef]

57. Xu, R.; Wong, W.-K.; Chen, G.; Huang, S. Topological Characteristics of the Hong Kong Stock Market: A Test-based P-threshold Approach to Understanding Network Complexity. *Sci. Rep.* 2017, 7, 41379. [CrossRef]

58. Sandoval, L.; Franca, I.D.P. Correlation of financial markets in times of crisis. *Phys. A Stat. Mech. Its Appl.* 2012, 391, 187–208. [CrossRef]

59. Heiberger, R.H. Stock network stability in times of crisis. *Phys. A Stat. Mech. Its Appl.* 2014, 393, 376–381. [CrossRef]

60. Sharif, S.; Ismail, S.; Zurni, O.; Theng, L.H. Validation of Global Financial Crisis on Bursa Malaysia Stocks Market Companies via Covariance Structure. *Am. J. Appl. Sci.* 2016, 13, 1091–1095. [CrossRef]

61. Wilinski, M.; Sienkiewicz, A.; Gubiec, T.; Kutner, R.; Struzik, Z.R. Structural and topological phase transitions on the German Stock Exchange. *Phys. A Stat. Mech. Its Appl.* 2013, 392, 5963–5973. [CrossRef]

62. Barabási, A.-L.; Albert, R. Emergence of Scaling in Random Networks. *Science* 1999, 286, 509–512.

63. Wang, G.-J.; Xie, C.; Chen, Y.-J.; Chen, S. Statistical Properties of the Foreign Exchange Network at Different Time Scales: Evidence from Detrended Cross-Correlation Coefficient and Minimum Spanning Tree. *Entropy* 2013, 15, 1643–1662. [CrossRef]

64. Górski, A.Z.; Drożdż, S.; Kwapień, J. Scale free effects in world currency exchange network. *Eur. Phys. J. B* 2008, 66, 91–96. [CrossRef]

65. Clauset, A.; Shalizi, C.R.; Newman, M.E.J. Power-Law Distributions in Empirical Data. *SIAM Rev.* 2009, 51, 661–703. [CrossRef]

66. Wang, G.-J.; Xie, C. Correlation structure and dynamics of international real estate securities markets: A network perspective. *Phys. A Stat. Mech. Its Appl.* 2015, 424, 176–193. [CrossRef]

67. Onnela, J.P.; Chakraborti, A.; Kaski, K.; Kertesz, J.; Kanto, A. Asset Trees and Asset Graphs in Financial Markets. *Phys. Scr.* 2003, T106, 48. [CrossRef]

68. Gaurav, K.; Sinha, R.; Panda, P.K. The Indus flood of 2010 in Pakistan: A perspective analysis using remote sensing data. *Nat. Hazards* 2011, 59, 1815–1826. [CrossRef]