Interconnectedness as a measure of systemic risk potential in the S&P 500

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**The views expressed are the author's own and do not necessarily reflect those of the Central Bank of Ireland*

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Introduction

- 2007–2009 global financial crisis has sparked a search for indicators to monitor and detect instabilities in financial markets.
- Procyclicality of the financial system can cause lead to feedback loops between asset prices and leverage leading to increased fragility of financial system and vulnerability to systemic event.
- Increase in interconnectedness may be detected as instabilities emerge.
- Minimum Spanning Tree analysis detects increasing interconnectedness, decreasing sectoral heterogeneity and large financial sector influence in price dynamics of the S&P 500 in the lead up to the crisis.
- Coupled with balance sheet valuation measures, dynamic Minimum Spanning Tree analysis can be a useful method in systemic risk detection and crisis monitoring.

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Systemic Risk

Systemic Risk has been defined by three major policy institutions, the [IMF, BIS & FSB, 2009], as the risk of

> *"the disruption to the flow of financial services that is (i) caused by an impairment of all parts of the financial system and (ii) has the potential to have serious negative consequences for the real economy."*

Systemic risk has both a cross-sectional and a time dimension. [Caruana, 2010]

- Cross-sectional dimension: risks are related to common exposures and to the complex network of transactions and balance sheet exposures.
- Time dimension: Procyclicality to systemic risk

Our Approach

We assess the suitability of a number of metrics for detecting and monitoring the build-up of systemic risk which considers both the cross-sectional and the time component by analysing the co-movement of stock prices using Minimum Spanning Tree (MST) analysis.

Point in time analysis can provide us with information regarding the interconnectedness, level of clustering and relative influence of sectors or individual stocks in the network.

By analysing changes changes in the MST over time we may be able to detect dynamical behaviour related to feedback loops and systemic risk.

Equity market based measures of systemic risk

- Forward looking
- Reflect correlation of firms' values
- Links to real economy: Wealth and financial accelerator effects

Literature

[Mantegna, 1999]: Static analysis using minimum spanning trees can detect sectoral clustering in stock markets.

[Onnela et al, 2003]: Shrinking of minimum spanning tree during stock market crisis.

[De Nicolo and Kwast, 2002]: Increased correlation means exogenous shocks can better propagate through the system.

[Lautier and Raynaud, 2013]: Minimum spanning tree identifes the shortest and most probable path for the transmission of price shocks throughout the system.

[Kennett et al, 2010]: Persistent dominance of financial sector over time in partial correlation network of stock market.

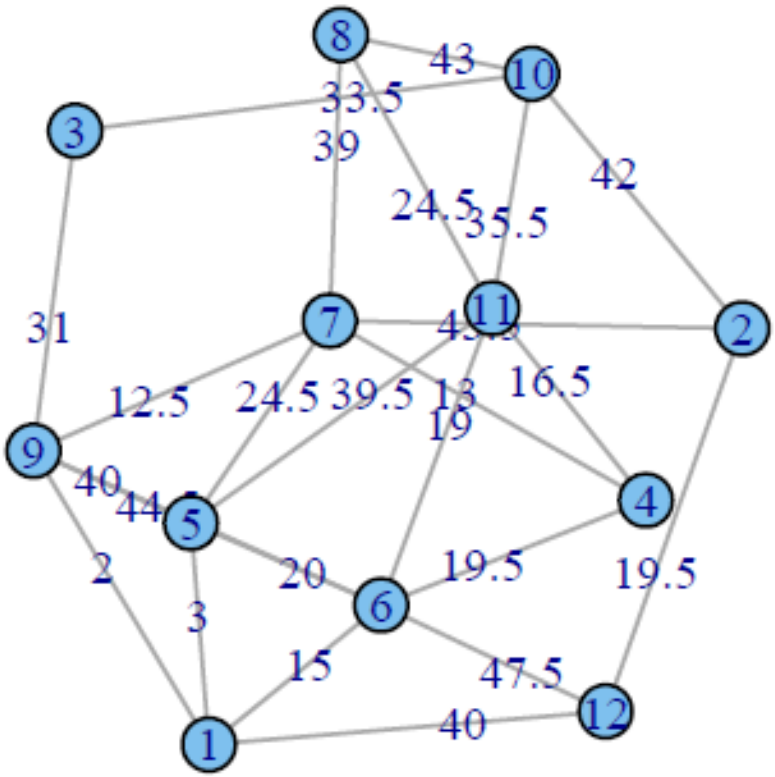
[Kaya, 2015]: Asset eccentricity as a early warning indicator of financial crises crises.

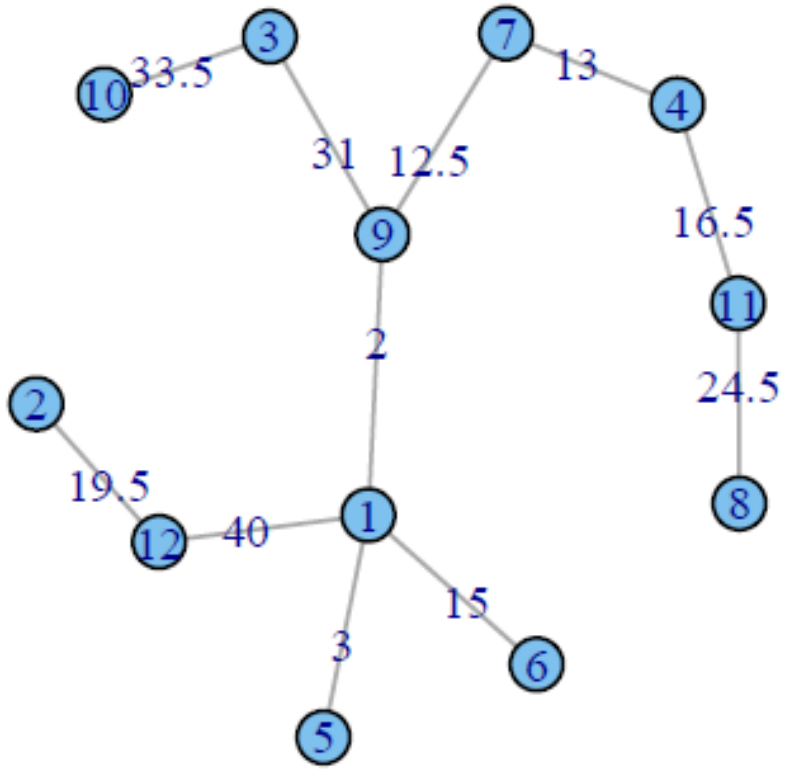
Data

Stock	Ticker	Industry Classification	Market Cap. US$	Stock	Ticker	Industry Classification	Market Cap. US$
Freeport-McMoRan	FCX	Basic Materials	56,742,525	**U.S. Bancorp**	USB	Financials	51,806,765
Amazon	AMZN	Consumer Cyclicals	81,180,000	**Wells Fargo**	WFC	Financials	163,078,157
Comcast	CMCSA	Consumer Cyclicals	60,999,687	**Abbot Laboratories**	ABT	Healthcare	74,116,001
Disney	DIS	Consumer Cyclicals	71,152,719	**Amgen**	AMGN	Healthcare	51,166,800
Ford	F	Consumer Cyclicals	63,511,717	**Johnson & Johnson**	JNJ	Healthcare	169,351,299
Home Depot	HD	Consumer Cyclicals	56,902,380	**Merck**	MRK	Healthcare	111,079,130
McDonald's	MCD	Consumer Cyclicals	80,874,336	**Pfizer**	PFE	Healthcare	140,290,120
Wal-Mart Stores	WMT	Consumer Cyclicals	189,617,880	**Boeing**	BA	Industrials	47,983,009
CVS Health	CVS	Consumer Non-Cyclicals	47,391,510	**Caterpillar**	CAT	Industrials	59,832,135
Coca Cola	KO	Consumer Non-Cyclicals	150,744,840	**E I DU Pont**	DD	Industrials	45,755,423
Altria	MO	Consumer Non-Cyclicals	51,424,771	**General Electric**	GE	Industrials	194,155,227
Pepsico	PEP	Consumer Non-Cyclicals	103,286,730	**3M**	MMM	Industrials	61,443,668
Procter & Gamble	PG	Consumer Non-Cyclicals	182,922,355	**United Parcel Services**	UPS	Industrials	71,926,780
Apache	APA	Energy	45,592,567	**United Technologies**	UTX	Industrials	72,522,296
ConocoPhillips	COP	Energy	99,947,356	**Apple**	AAPL	Technology	295,455,299
Chevron	CVX	Energy	183,182,621	**Cisco Systems**	CSCO	Technology	114,400,650
Occidental Petroleum	OXY	Energy	79,735,166	**EMC Corporation**	EMC	Technology	47,385,733
Schlumberger	SLB	Energy	113,657,814	**Hewlett-Packard**	HPQ	Technology	92,784,106
Exxon Mobil	XOM	Energy	364,064,480	**IBM**	IBM	Technology	180,220,333
American Express	AXP	Financials	51,375,240	**Intel**	INTC	Technology	115,896,330
Bank of America	BAC	Financials	134,535,965	**Microsoft**	MSFT	Technology	241,923,880
Berkshire Hathaway	BRK'B	Financials	198,516,054	**Oracle**	ORCL	Technology	157,313,800
Citigroup	C	Financials	137,446,045	**QUALCOMM**	QCOM	Technology	79,777,880
Goldman Sachs	GS	Financials	85,346,375	**AT&T**	T	Telecommunications	173,667,732
JP Morgan	JPM	Financials	165,874,676	**Verizon**	VZ	Telecommunications	101,188,427

Table: Basic Stock Information

Minimum Spanning Trees





Extracting the MST from a correlation matrix

Calculate a correlation matrix on the log-returns of all the stocks in the sample using pearsons correlation coefficient (ρ_{ij}).

[Mantegna, 1999] outline a distance metric between two stocks which can be calculated from ρ_{ij}

$$d_{ij} = \sqrt{2(1 - \rho_{ij})} \tag{1}$$

. This meets the three requirements for a Euclidean distance measure

1. $d_{ij} = 0 \Leftrightarrow i = j$
2. $d_{ij} = d_{ji}$
3. $d_{ij} \leq d_{ik} + d_{kj}$

Statistics

Normalised Tree Length

The Normalised Tree Length quantifies the level of interconnectedness of the MST

$$L = \frac{1}{N-1} \sum_{d_{ij} \in S} d_{ij} \tag{2}$$

Where S is the MST, L is the Normalised Tree Length, d_{ij} is the distance metric between stock i and stock j for $i, j = 1, ..., N$ and $i \neq j$

Average Level-Mean Occupation Layer

The mean occupation layer quantifies the spread of the minimum spanning tree [Onnela et al, 2003]

$$Lev(V_t) = \frac{1}{N} \sum_{V_i \in S} L(V_{i,t}) \tag{3}$$

Where S is the MST, Lev is mean occupation layer, $L(V_{i,t})$ is the level of node V_i with respect to the central node

Statistics

Sectoral Heterogeneity - Cluster Size

The cluster strength coefficient quantifies the degree to which stocks in the same sector are clustered together. $S(z)$ is a subgraph obtained from the MST with only the stocks from industry Z included.

$$C_z = \frac{1}{2(N_z - 1)} \sum_{i=1}^{N_z} Deg_{i,S(z)} \tag{4}$$

where C_Z is the sectoral clustering coefficient, $Deg_{i,S(z)}$ is the degree of stock i in subgraph $S(z)$. The overall sectoral clustering coefficient is simply the average of the sectoral clustering coefficients.

Average Sectoral Degree

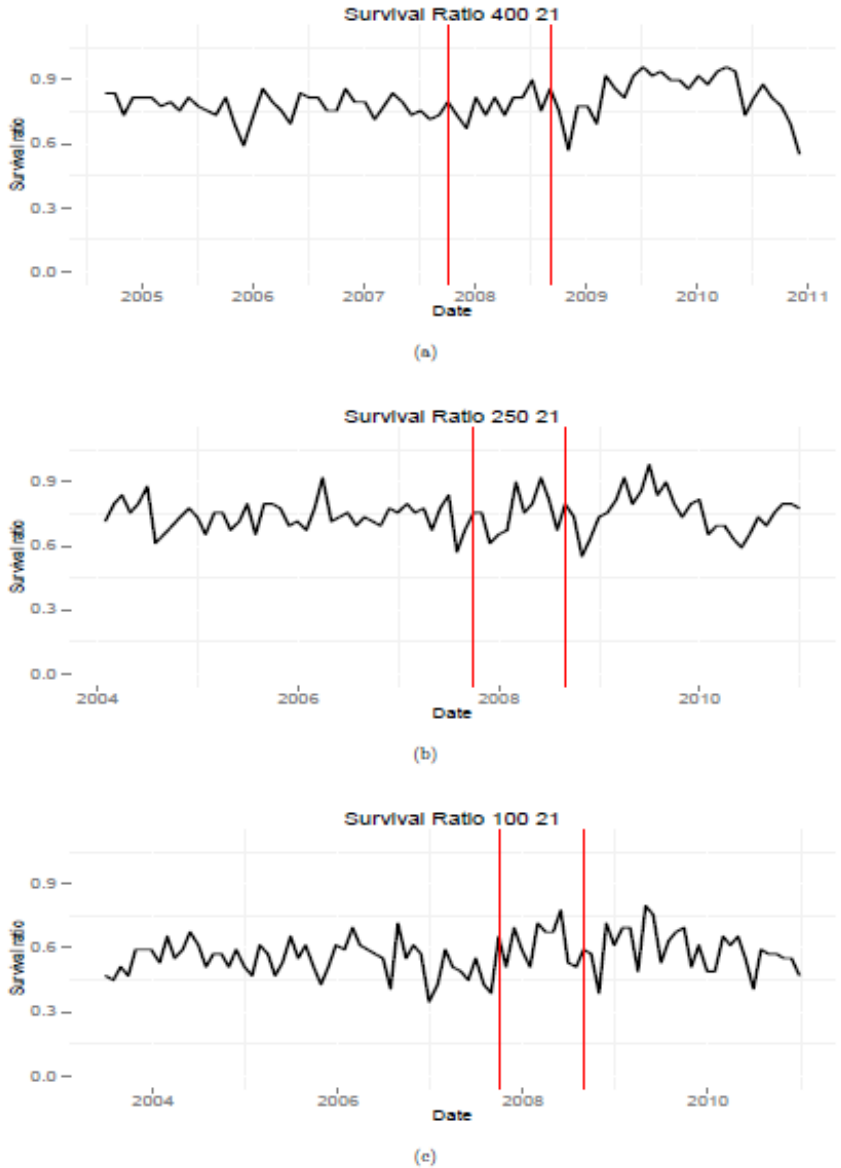
The Average Sectoral Degree quantifies the relative influence of each sector in the MST

$$\bar{Deg}_z = \frac{1}{N_z} \sum_{i=1}^{N_z} Deg_{i,z} \tag{5}$$

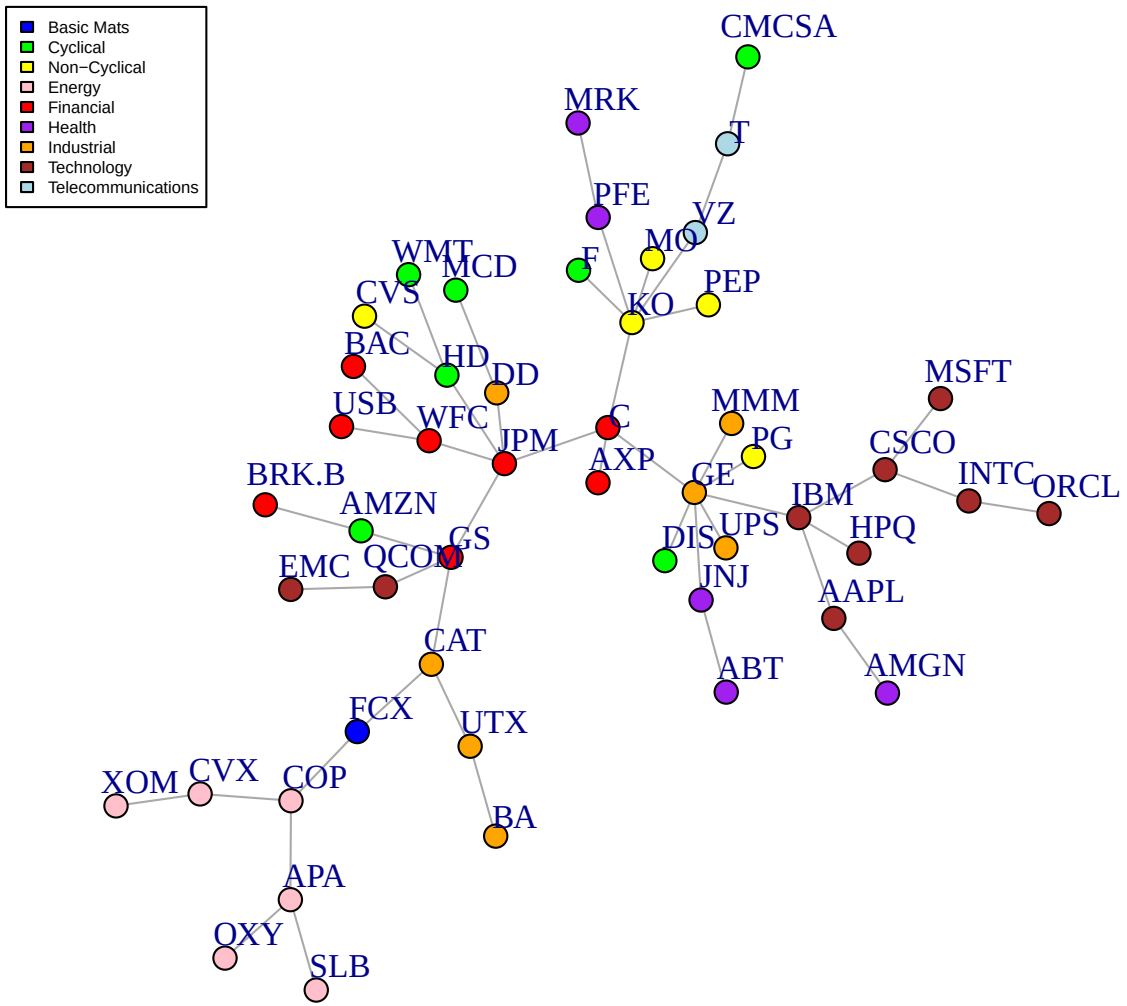
where N_z is the number of stocks in industry z and $Deg_{i,z}$ is the degree of stock i in industry z

Time Parameters

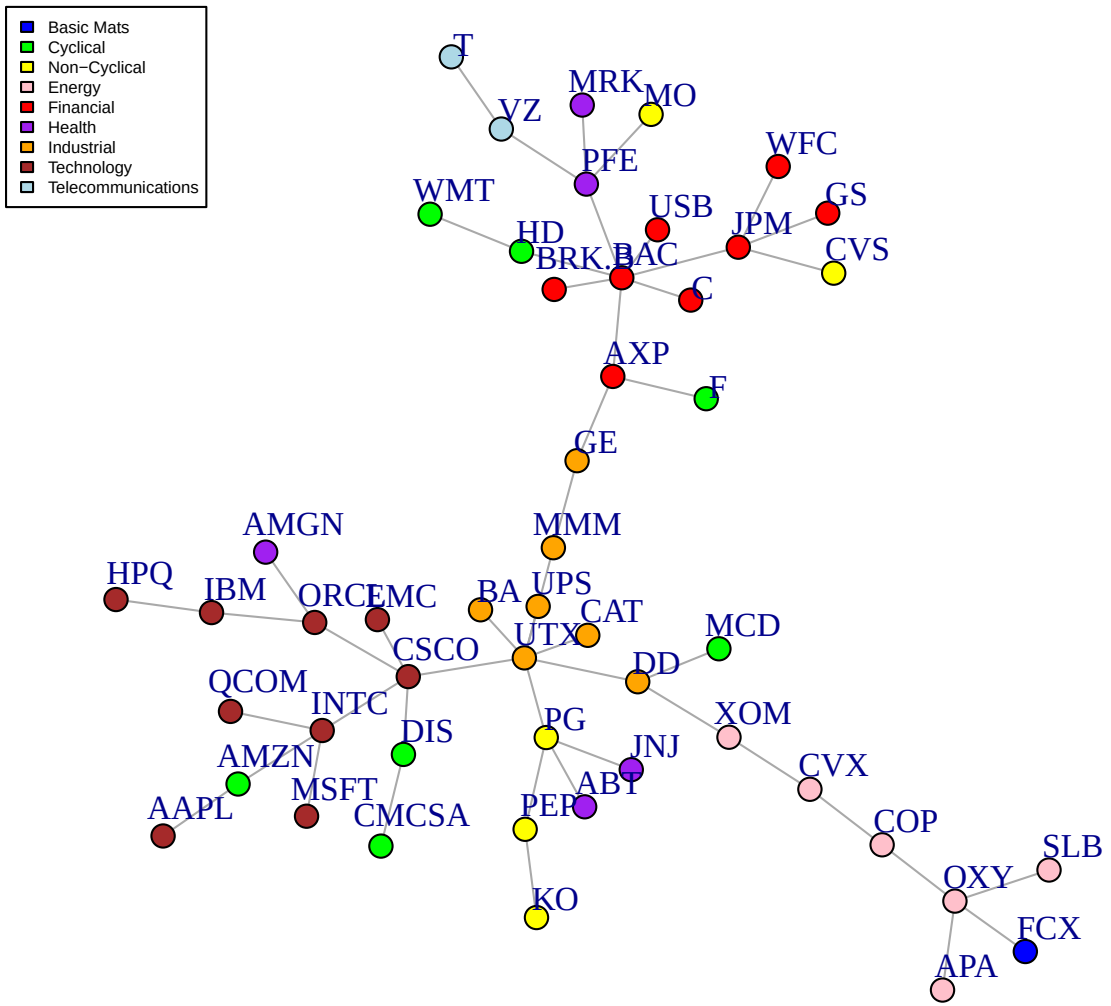
- Rolling window analysis: trade-off between stability and sensitivity
- Window size T and step size δT
- Single Step Survival Ratio [Onnela et al, 2003]



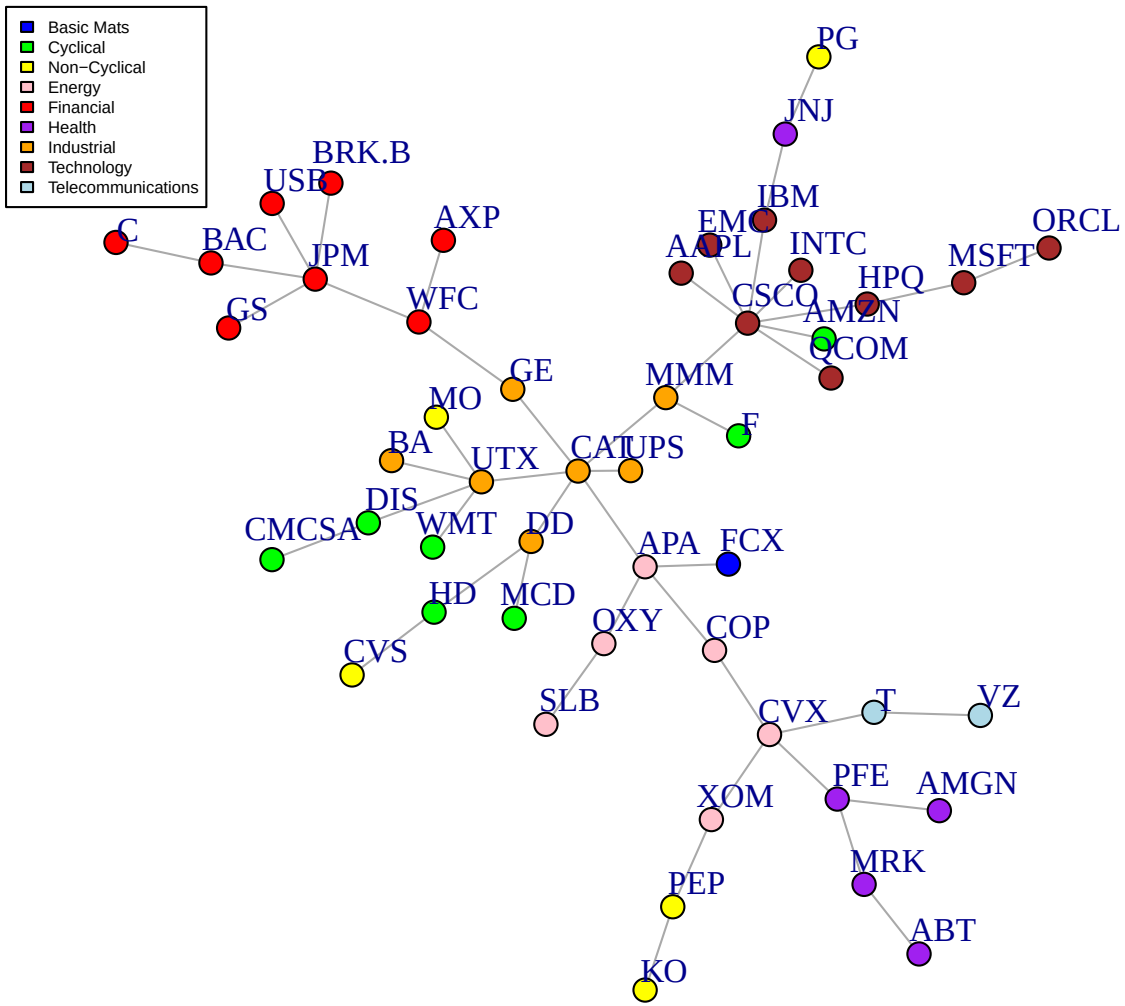
Minimum Spanning Tree 2006



Minimum Spanning Tree 2008



Minimum Spanning Tree 2010



Central Node

	Step 100 (% occurrence)	Step 250 (% occurrence)	Step 400 (% occurrence)		Step 100 (% occurrence)	Step 250 (% occurrence)	Step 400 (% occurrence)
FCX				**USB**			
AMZN				**WFC**	1.086956522	3.529411765	2.597402597
CMCSA				**ABT**			
DIS	6.52173910	3.529411765	2.597402597	**AMGN**			
F				**JNJ**			
HD	1.086956522			**MRK**			
MCD				**PFE**	1.086956522	1.176470588	
WMT	1.086956522			**BA**			
CVS				**CAT**	1.086956522		
KO	2.173910043	7.058823529	5.194805195	**DD**	2.173910043		
MO				**GE**	9.782608696	8.235294118	6.493506494
PEP				**MMM**	2.173910043		
PG	1.086956522			**UPS**	4.347826087		
APA				**UTX**	3.260869565	4.705882353	7.792207792
COP	1.086956522	3.529411765		**AAPL**			
CVX	6.52173910	3.529411765		**CSCO**	9.782608696	16.47058824	25.97402597
OXY				**EMC**			
SLB				**HPQ**	2.173910043	3.529411765	
XOM	2.173910043			**IBM**			
AXP	2.173910043	4.705882353	3.896103896	**INTC**	4.347826087		
BAC	8.695652174	4.705882353	6.493506494	**MSFT**	1.086956522		
BRK.B				**ORCL**			
C	8.695652174	17.64705882	18.18181818	**QCOM**	1.086956522	1.176470588	
GS	7.608695652	7.058823529	3.896103896	**T**			
JPM	7.608695652	9.411764706	16.88311688	**VZ**			

Table: Occurrence of central vertex as percentage of total time steps. Using a 400 day window the central vertex comes from companies within the financial sector approximately 52 % of time periods, 45% for 250 day and 35% for 100 day.

Normalised Tree Length:

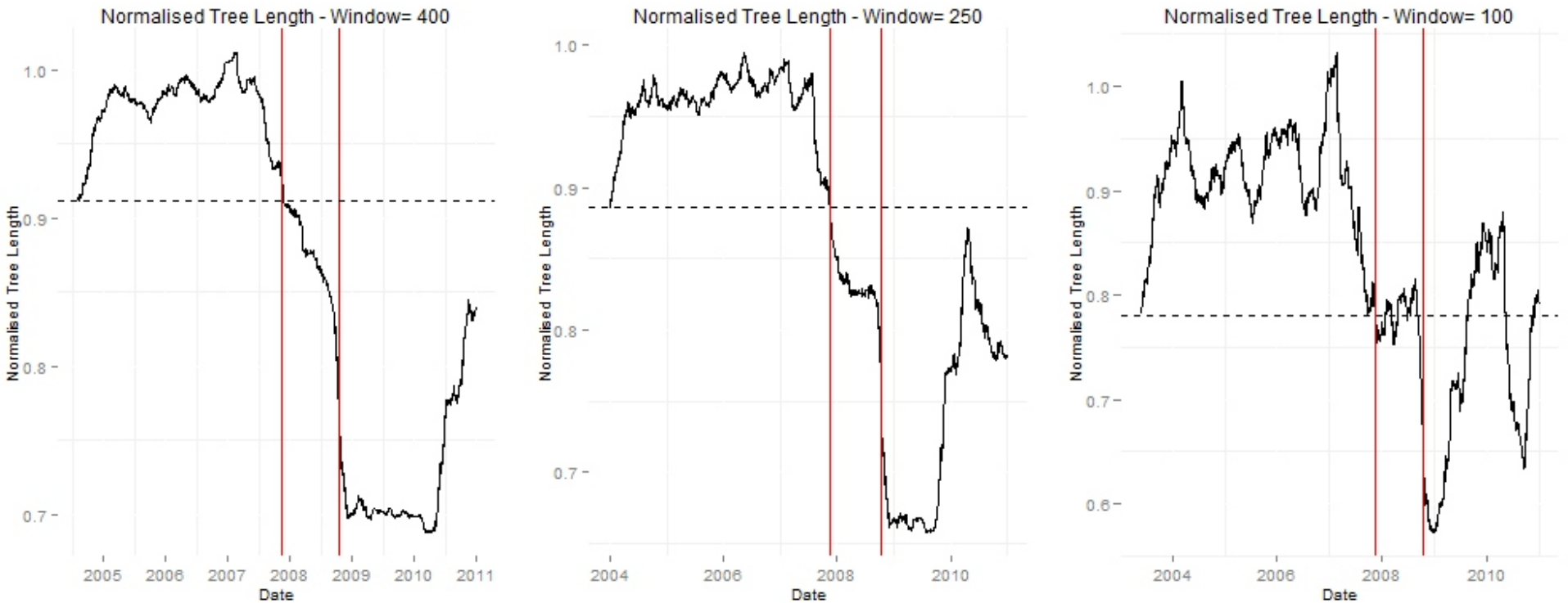
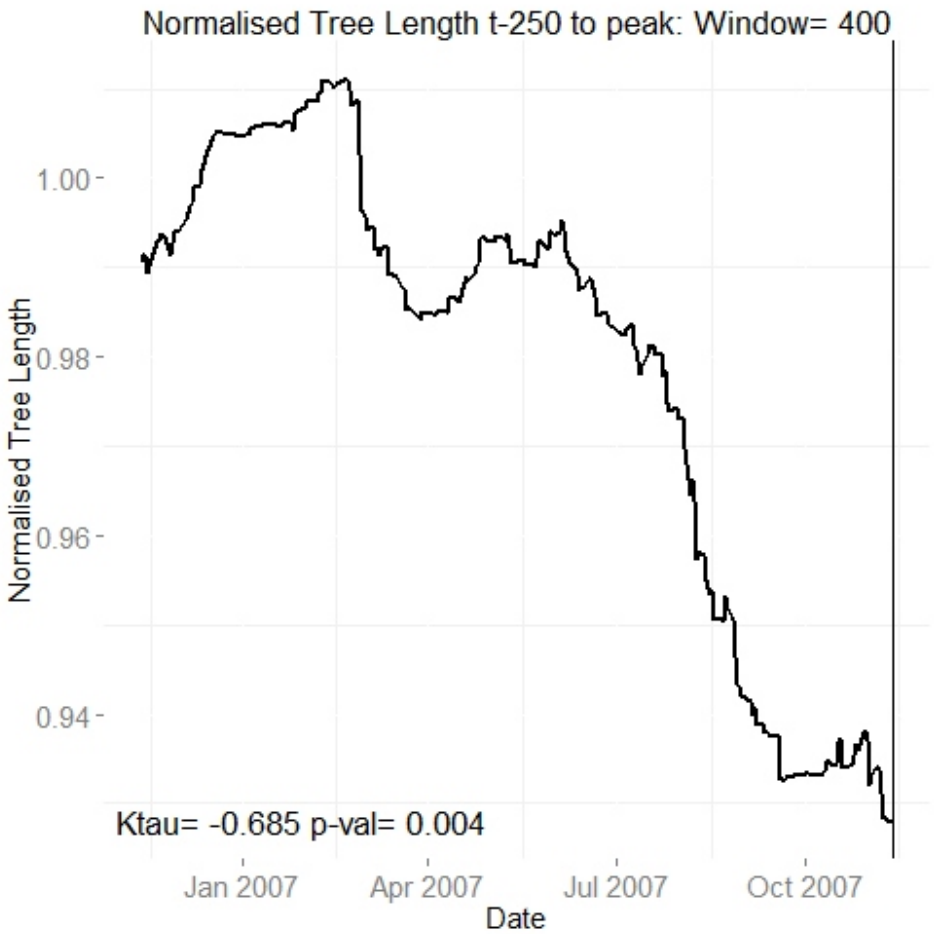


Figure: Normalised Tree Length $T = 400, 250, 100$ and $\delta T = 1$. The first red line indicates the peak of the market on 12 October 2007. The second red line indicates the Lehmann Brother's default

Normalised Tree Length Timing Analysis



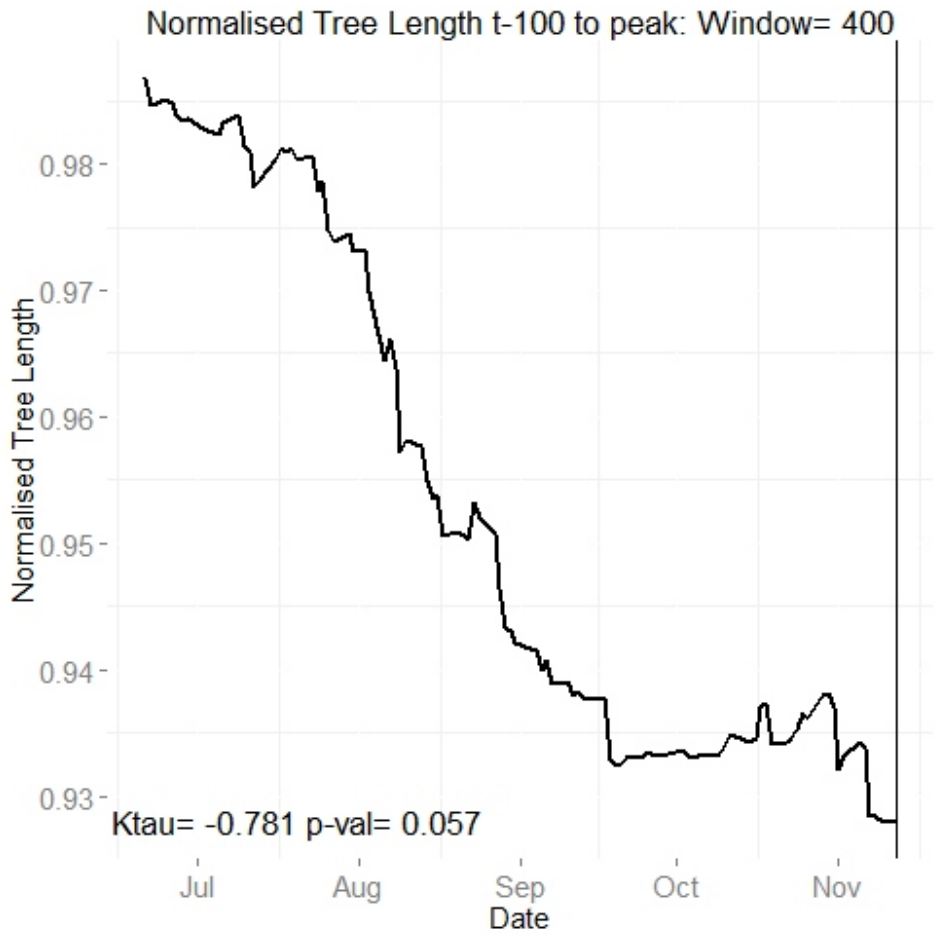


Figure: Normalised Tree Length Timing $T = 400$ and $\delta T = 1$. Kendall Tau coefficient p-value is calcualted based on 200 random segments from the normalised tree length time series from $t = 0$ to $t = peak - 250, 100$

Average Level

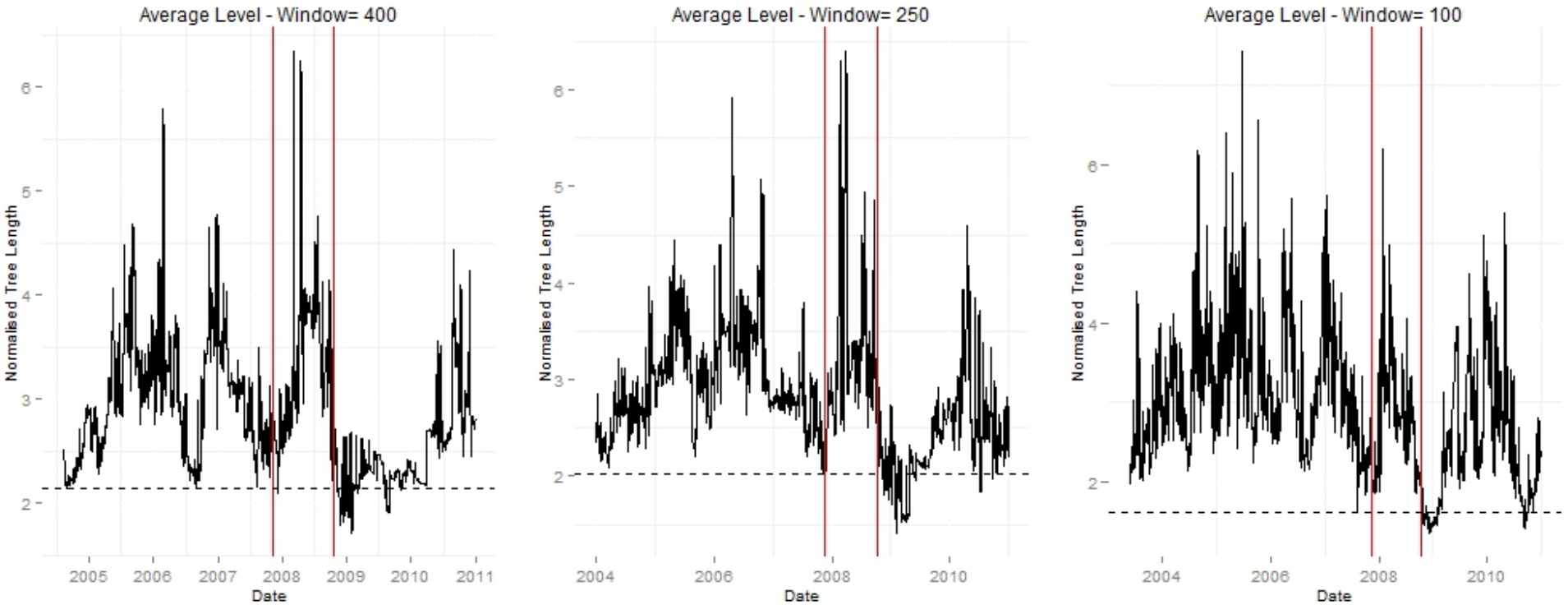
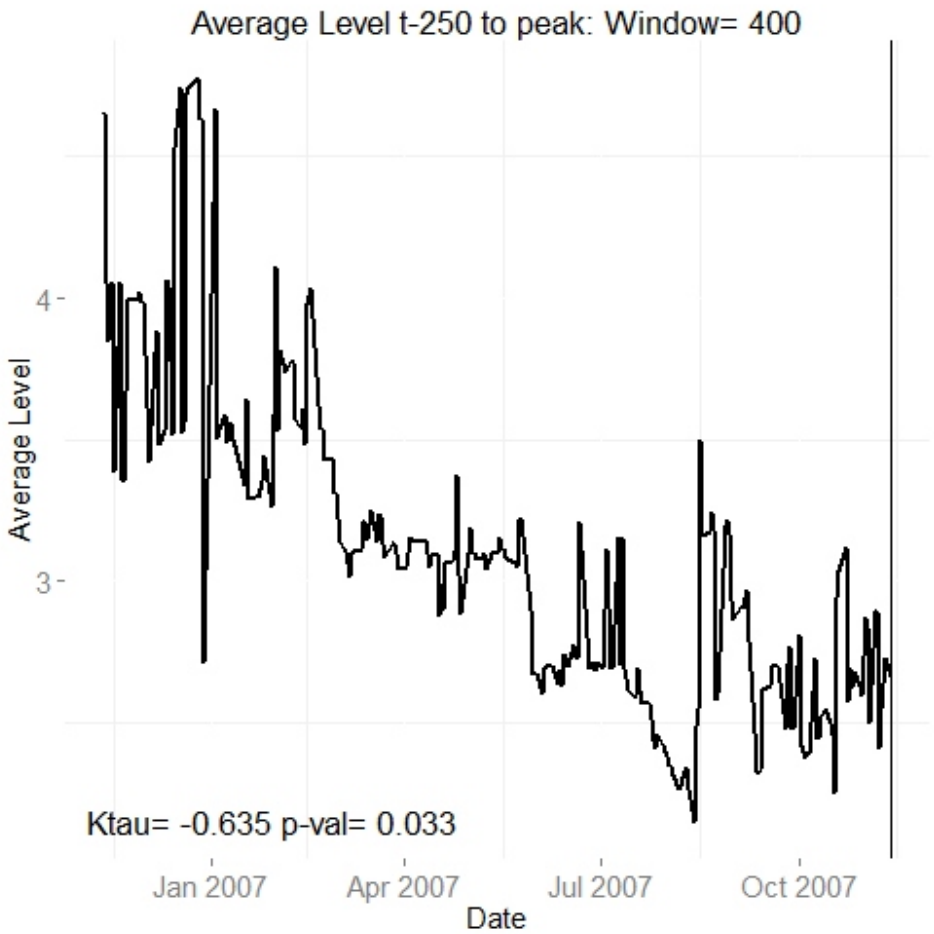


Figure: Average Level $T = 400, 250, 100$ and $\delta T = 1$. The first red line indicates the peak of the market on 12 October 2007. The second red line indicates the Lehmann Brother's default

Average Level Timing Analysis



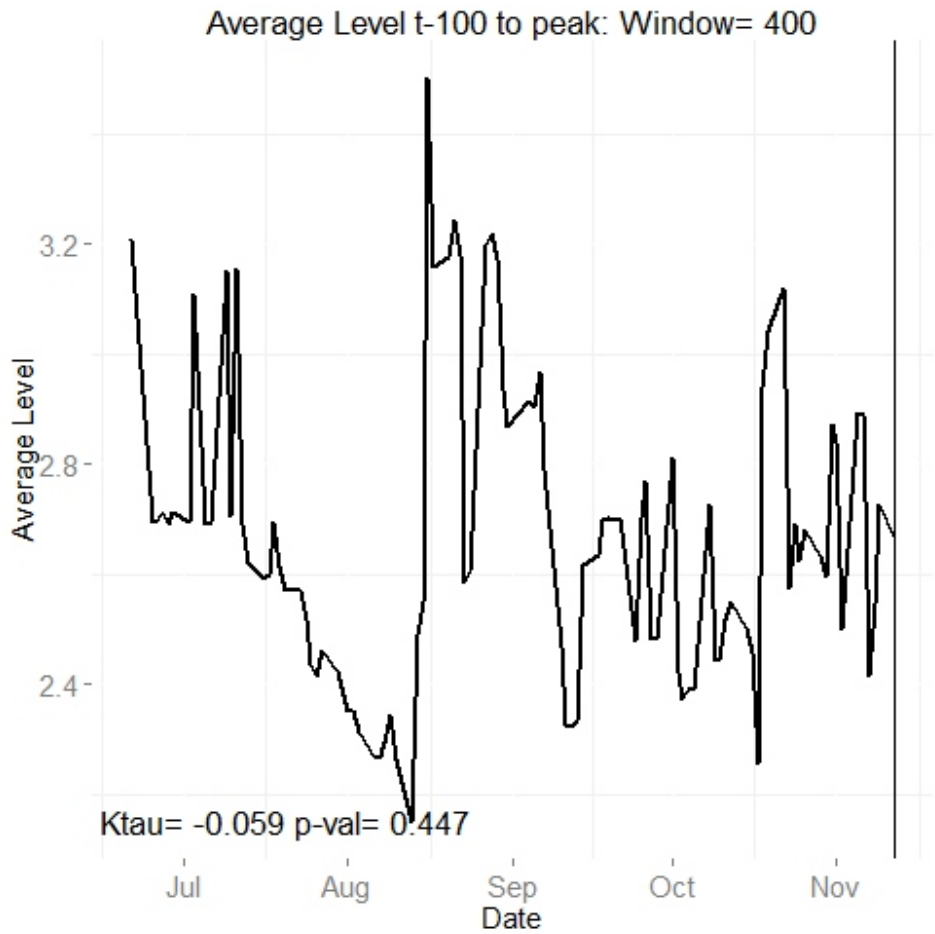


Figure: Level timing $T = 400$ and $\delta T = 1$. Kendall Tau coefficient p-value is calcualted based on 200 random segments from the average level time series from $t = 0$ to $t = peak - 250, 100$

Sectoral Heterogeneity

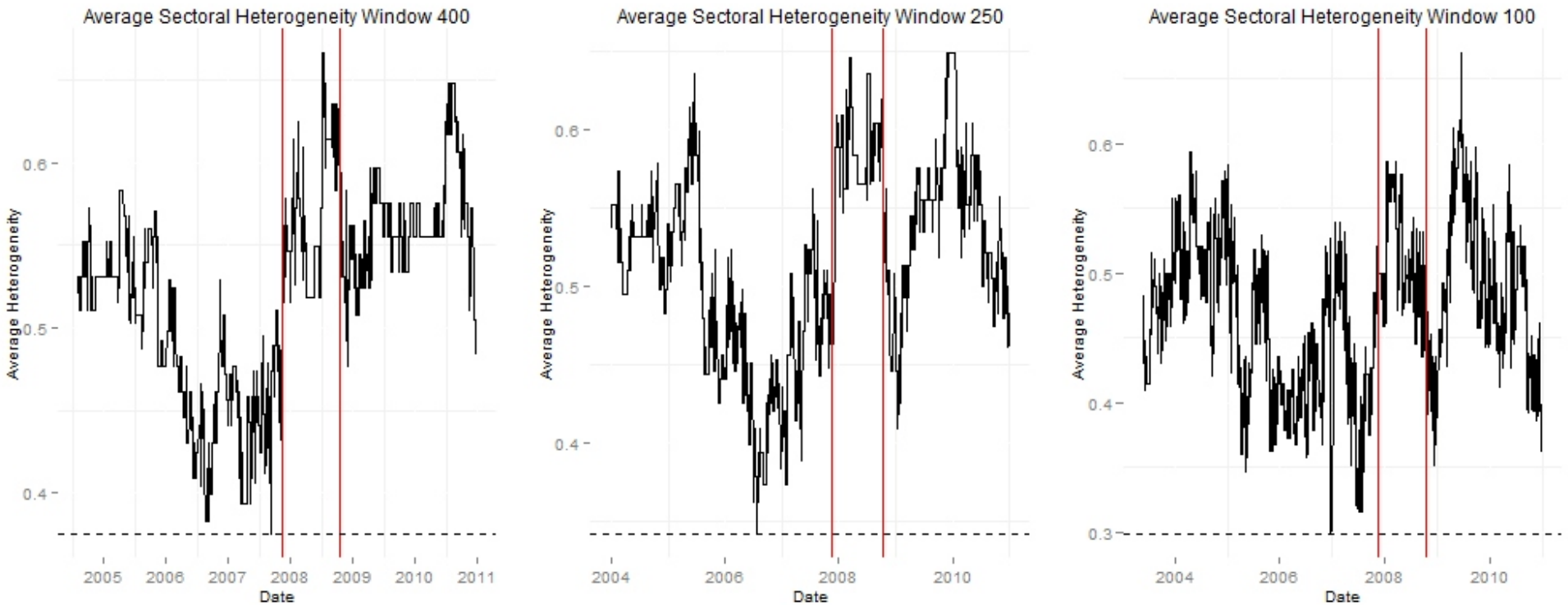
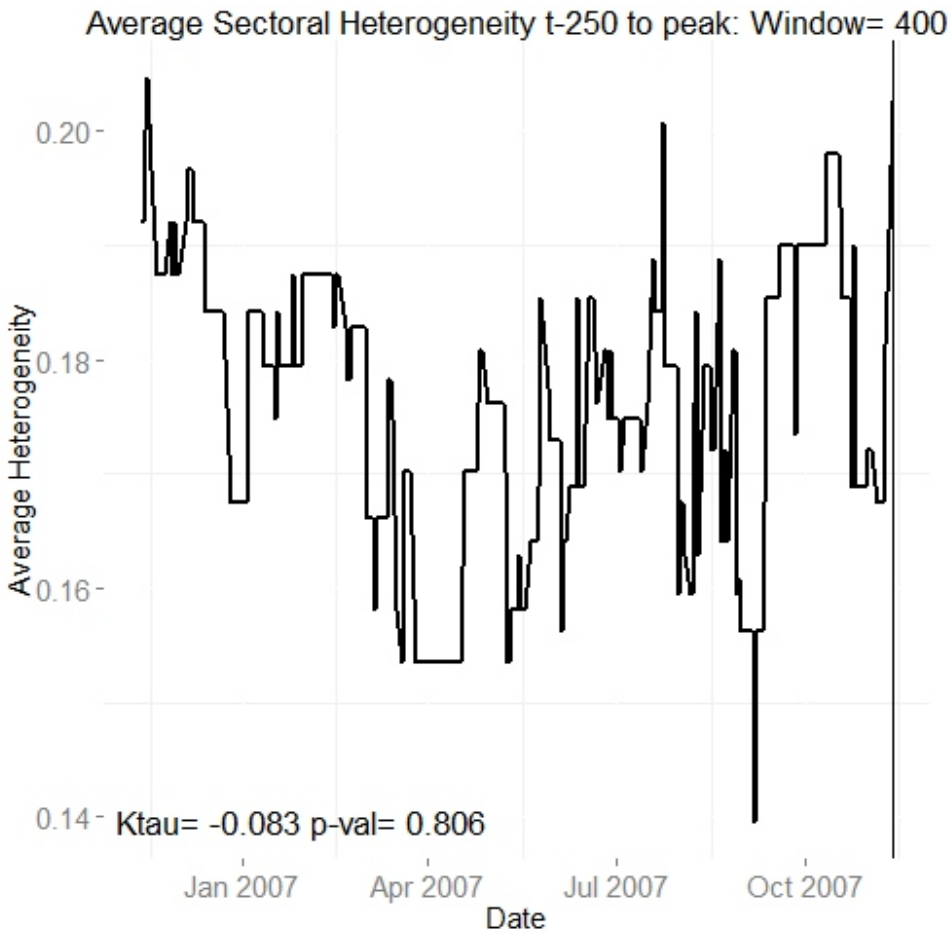


Figure: Sectoral Heterogeneity $T = 400, 250, 100$ and $\delta T = 1$. The first red line indicates the peak of the market on 12 October 2007. The second red line indicates the Lehmann Brother's default

Sectoral Heterogeneity Timing Analysis



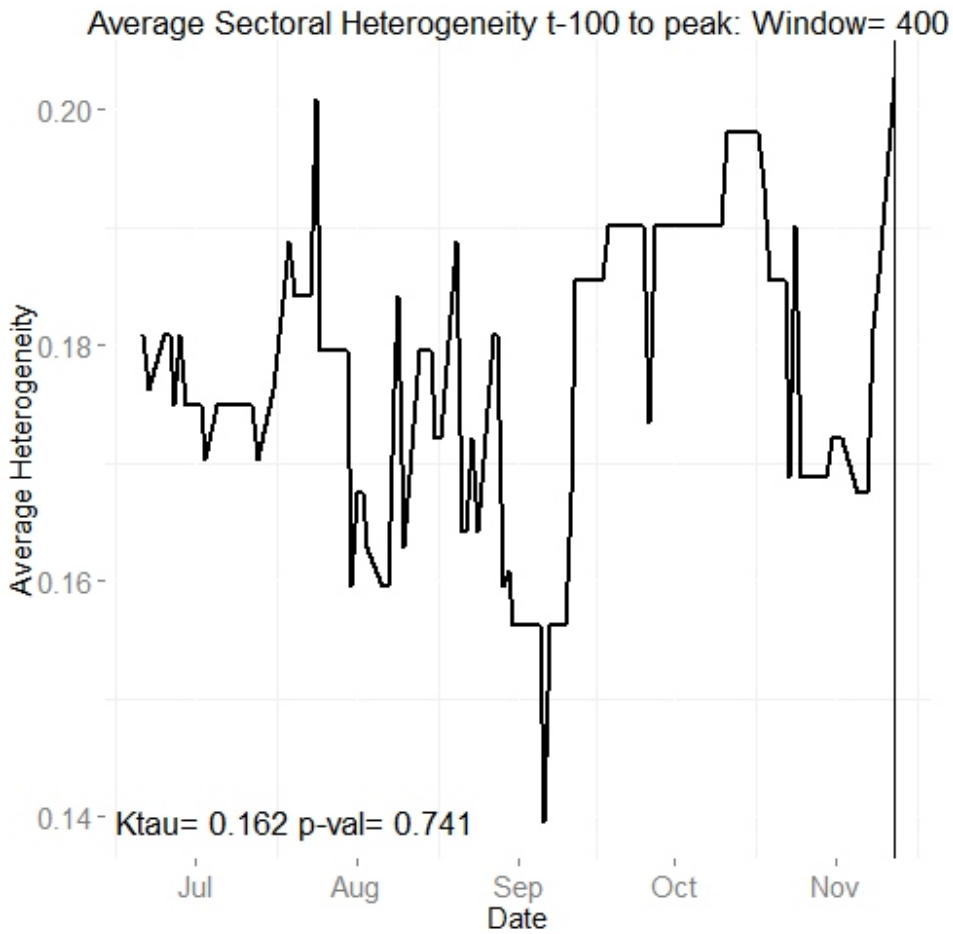


Figure: Heterogeneity timing $T = 400$ and $\delta T = 1$. Kendall Tau coefficient p-value is calcualted based on 200 random segments from the sectoral heterogeneity time series from $t = 0$ to $t = peak - 250, 100$

Average Degree of Financial Sector

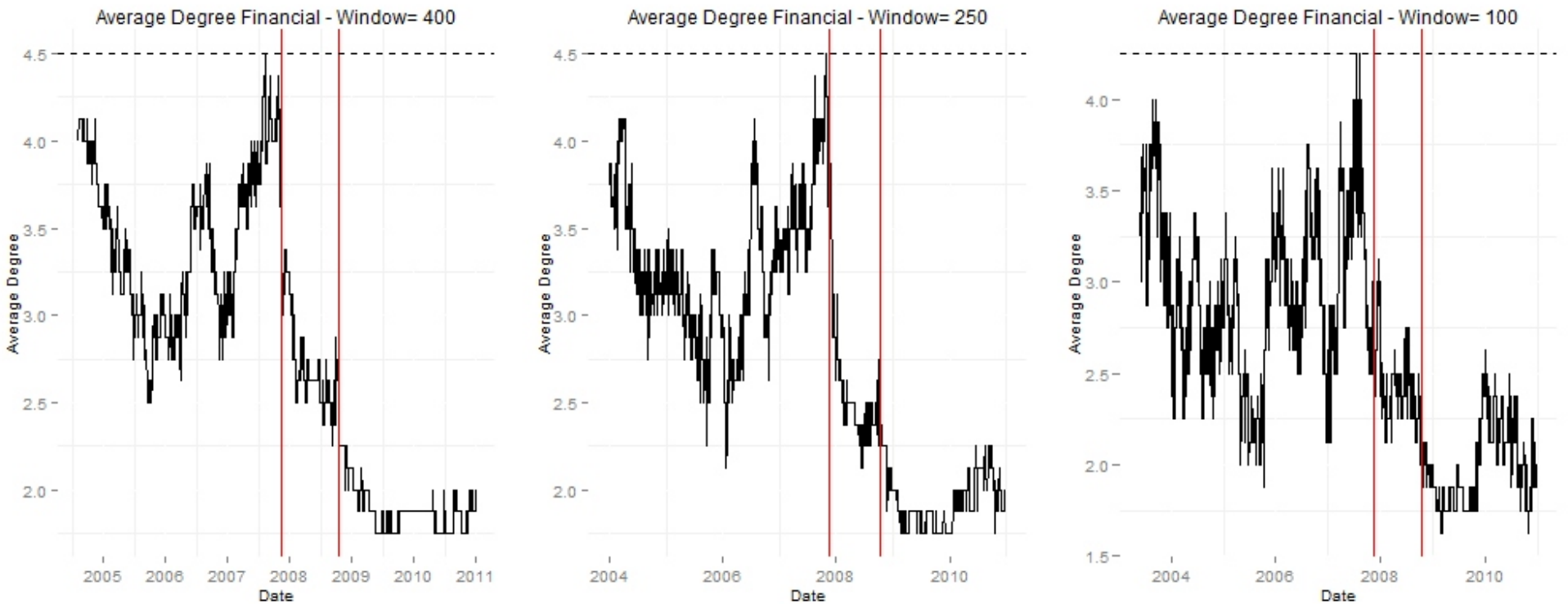
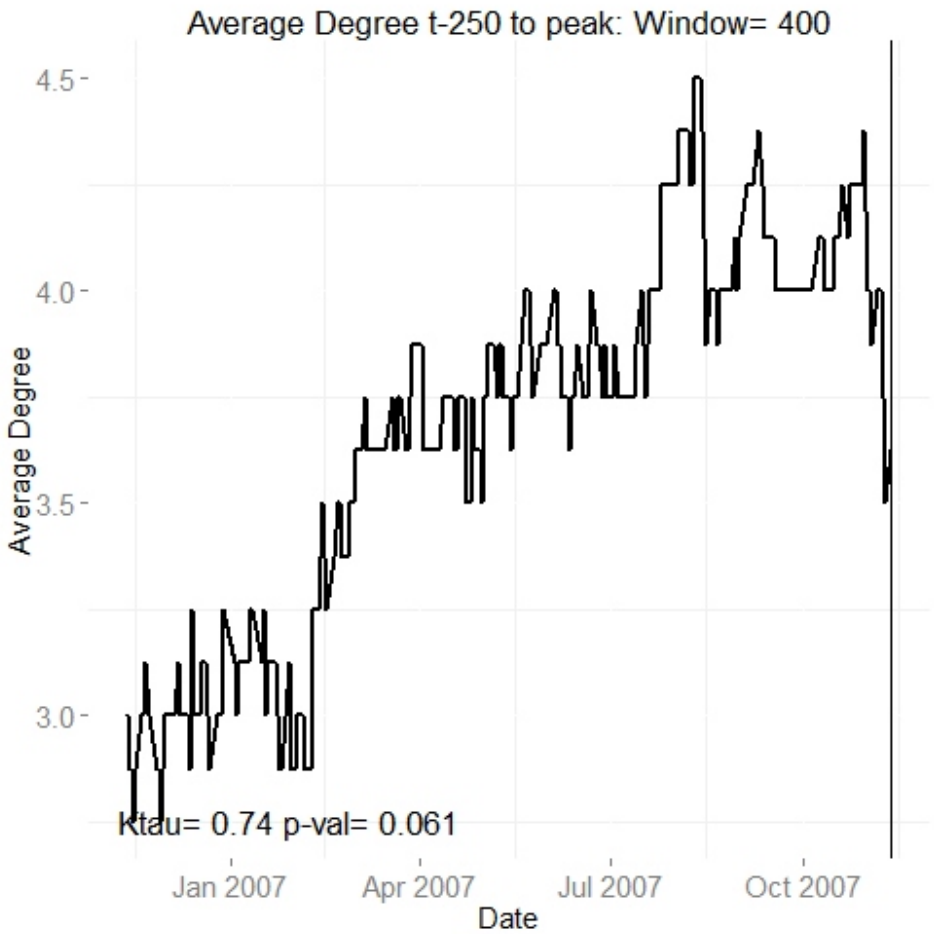


Figure: Average degree of the financial sector $T = 400, 250, 100$ and $\delta T = 1$. The first red line indicates the peak of the market on 12 October 2007. The second red line indicates the Lehmann Brother's default

Average Degree of Financial Sector Timing Analysis



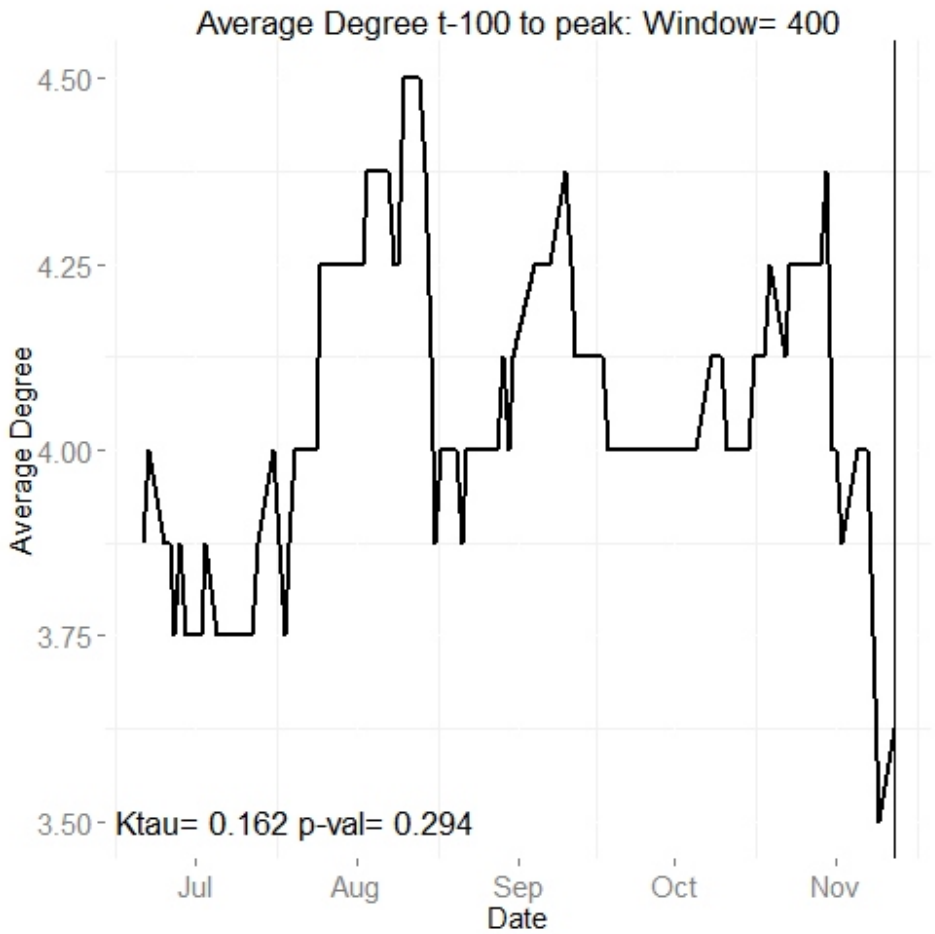


Figure: Average degree of financials timing $T = 400$ and $\delta T = 1$. Kendall Tau coefficient p-value is calcualted based on 200 random segments from the average degree time series from $t = 0$ to $t = peak - 250, 100$

Summary of Results

- From January to October 2007 there is a sharp increase in the interconnectedness of the market leaving it more vulnerable to systemic events.
- The financial sector holds an increasingly dominant position in the MST in the lead up to the crisis
- A decrease in sectoral clustering prior to the crisis points to the erosion of sectoral heterogeneous factors in stock price dynamics.
- With the onset of the crisis in late 2007, the centrality of the financial sector collapsed and the level of sectoral clustering increased sharply.

Discussion

- The dominant‘position of the financial sector coupled with a decrease in the level of sectoral clustering from early 2006 provides some indications that markets dynamics may being driven by market factors related to credit availability
- The increased dispersion of stocks in the system points to the erosion of sectoral heterogeneous factors and an increase in non-diversifiable market factors driving stock price behaviour.
- With the onset of the subprime crisis the interconnectedness of the system increases sharply indicating increased vulnerability of the market to a systemic event.
- As developments in the subprime mortgage market took hold and credit became scarcer, the centrality of the financial sector collapsed and the level of sectoral clustering increased sharply as sectoral differences came to the fore as investors sought safe havens from the distress in the financial sector.
- MST methodology, alongside balance sheet and credit based indicators, can form a useful toolbox for financial regulators and central banks for monitoring financial market stability.

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