Structural analysis and evolutionary exploration based on the research topic network of a field: a case in high-frequency trading

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Abstract

This study aims to systematically analyze the distribution dynamics of research topics and uncover the development state of the research in the specific field, which will provide a practical reference for developing professional subject knowledge services in the era of big data. The research topic network is constructed and analyzed using methods and tools of scientometrics. Basic statistics on network characteristics are performed to reveal the research status. Community detection, node ordering, and other steps are conducted to generate the evolutionary alluvial diagram. Then, relevant results are analyzed to explore the knowledge structure of the specific field and evolutionary context of research topics. Visualization analysis on the network structure of the latest period is executed to distinguish related concepts and predict the research trends. Taking high-frequency trading (HFT) as a case, this study achieves diversified scientometrics analysis of the research topic network and multi-dimensional evolution exploration of the relevant research topics in the specific field, which obtaining some knowledge insights. (1) Six major topics in HFT: liquidity & market microstructure, market efficiency, financial market, incomplete market, cointegration & price discovery, and event study. (2) The research focus about markets gradually transferred from international to emerging, meanwhile continuous attention to volatility/risk related issues. (3) The emphasis will change from theory to practice, technologies (big data, etc.) and theories (behavioral finance, etc.) will have more interaction with HFT. An effective research idea is proposed to reveal the knowledge structure of field and analyze the evolutionary context of research topics, which demonstrating the knowledge insights.

Keywords

Research topic network; Evolutionary analysis; Scientometrics; *NEViewer*; *Gephi*; High-frequency trading; HFT; Emerging trends; Graphs.

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1. Introduction

Literature is the carrier and essential medium for disseminating technology and knowledge across time and space (**Li**; **Gong**; **Zhang**, 2011). With the increasing investment in research and development, scientific literature has expanded rapidly in scale and increased geometrically in quantity. Facing the massive data in the scientific field (**Guo** *et al.*, 2014), most scholars need faster and more intelligent methods to track the research hotspots in relevant fields and complete the understanding of emerging trends (**Howe** *et al.*, 2008). The knowledge networks formed by self-organization in scientific communication, such as citation networks and research topic networks, reflect the knowledge structure of the subject/field and its flow process. Toolkits such as *Citespace*, *VOSviewer*, and *NEViewer* (**Wang**; **Cheng**, 2013) systematically integrate the methods and technologies for exploring scientific datasets and enable scholars to achieve a variety of visualization analyses based on these knowledge networks (**Gu** *et al.*, 2019; **Moral-Muñoz** *et al.*, 2020; **Wang**; **Wang**; **Huang**, 2021). By analyzing the evolution of research topics in the specific subject/field, the research hotspots and the development state in the field can be uncovered effectively, it benefits scholars to quickly grasp the basic status and research progress of the subject/field, and it has gradually become an essential way for providing subject knowledge services in library and information science in the era of big data (**Huang**; **Wang**; **Wang**, 2020).

> Facing the massive data in the scientific field, most scholars need faster and more intelligent methods to track the research hotspots in relevant fields and complete the understanding of emerging trends

The constant development and widespread adoption of new-generation communication technologies, high-performance computing, artificial intelligence, and other technologies create new conditions for research in various subjects/fields. Meanwhile, a new research field in finance influenced by these, high-frequency trading (HFT), has drawn greater attention. Born out of computer-assisted trading and algorithmic trading (AT) (*Staff of the Division of Trading and Markets*, 2014), HFT is a trading method that uses computer systems to make trading decisions in a brief time after processing the relevant data and quantitative analysis and does not hold positions overnight (**Aldridge**, 2009), with high speed and low latency (**Currie**; **Seddon**, 2016). It began in 1998 after the *U.S. Securities and Exchange Commission* (*SEC*) officially authorized electronic trading (*IBISWorld*, 2012). After that, benefited by the development of communication networks, computer hardware, artificial intelligence, and other technologies, and the revolution of trading rules, like the *Alternative Trading Systems Regulation*, the *Regulation National Market System*, and the *tick size* (the minimum price amount a security can move in an exchange) regime, the proportion of HFT in the global financial market continues to increase (**Hoffmann**, 2014; **Biais**; **Foucault**; **Moinas**, 2015). That means a radical transformation in the way the stock market operates. Meanwhile, the "dark pool" developed by HFT has increased the opacity of market operations (**Zupko**, 2021); the implementation of HFT strategies has raised public concerns about market fairness; and occasional shocks and disruptive events have posed regulatory challenges (**Goldstein**; **Kumar**; **Graves**, 2014). The implications of these developments need to be studied, summarized, and addressed by scholars.

Gomber *et al.* (2011) believed that "Is HFT beneficial or harmful to the economy?" is the most prominent question in HFT-related research. Some scholars summarized relevant views on the impact of HFT on the quality of financial markets (**Chung**; **Lee**, 2016; **Linton**; **Mahmoodzadeh**, 2018; **Virgilio**, 2019), while others further discussed the technologies and regulatory rules involved in HFT and supplemented with interview data (**Currie**; **Seddon**, 2016). Many scholars have attempted to categorize the academic literature on HFT, such as **Gomber** *et al.* (2011), who consider three main issues: market quality, fairness & colocation, and market penetration & profitability; and **Goldstein**, **Kumar**, and **Graves** (2014), who classified the research on computerized and high-frequency trading in the past decade into six categories: market performance, strategies & practices, evolution, speed, fairness, and regulatory implications. These studies have explored the underlying logic of HFT for some specific issues based on literature and empirical data. However, since these studies usually focus on aspects, which are unable to analyze related concepts of HFT objectively, and the data used is limited in quantity and variety, existing studies fail to provide a comprehensive picture of the knowledge structure in the field of HFT. With the development of scientometrics, more research perspectives and analytical methods are applied to analyze the new phenomena and new problems (**Serenko**, 2021) in library science (**Garcia**; **Lueck**; **Yakel**, 2019), accounting (**Lei**; **Deng**; **Liu**, 2020) and other subjects, and analyze the knowledge structure and research trends in some emerging research fields, such as *Bitcoin* (**Yu**; **Sheng**, 2020), smart city (**Moradi**, 2020), cloud health care (**Gu** *et al.*, 2020), etc. As far as we know, there is not currently any systematic review or scientometrics analysis of HFT by scientometrics in published journal[1], whether in finance or library & information science, which has brought certain obstacles to scholars' research and practitioners' practice.

Taking HFT as a case, this study focuses on revealing and "distance reading" the knowledge structure of subject fields and the evolutionary context of research topics. *NEViewer*, *Gephi* (**Bastian**; **Heymann**; **Jacomy**, 2009) and other network visual analysis tools will be used to analyze the collected papers, and the status quo will be quantificationally depicted in this study. By using these tools, this study will systematically explore the main research topics in the specific field and their macroscopic changing process, as well as the transfer of research focus reflected by them. Meanwhile, this study will comprehensively uncover the micro details of the subject research field, distinguish the connotation of relevant concepts, and make a reasonable inference about the development state of pertinent research. These will provide an important reference for scholars and practitioners in the specific field. And it will demonstrate a new idea for obtaining knowledge insights by using the research topic network to analyze the distribution dynamics of subject research and the development state of related research. Specifically, this study will take HFT as a case to explore the following questions:

- What is the distribution structure and evolution dynamics of research topics in the specific field?
- How to explore the research development state of the field reflected by the above analysis results?

2. Methodology

2.1. Research idea

This study proposes a general idea of analyzing the evolution of research topics based on the research topic network, as shown in Figure 1.

The following three stages are included in this idea.

Stage 1: Data collection and preprocessing

Web of Science (*WoS*) is one of the most widely used databases in academic circles, in which *Science Citation Index* (*SCI*) and *Social Sciences Citation Index* (*SSCI*) are internationally recognized authoritative indexes for scientific statistics and evaluation. Therefore, using papers published in journals indexed by *SCI/SSCI* to analyze the evolution of research topics can ensure the validity and reliability of its results. Specifically, take the selected terms in the specific field as "Topic," search in the *WoS* database, and set the year, language, document type, and other rules for filtering, thereout complete data export of the basic paper set of the field. The document information includes accession number, year published, publication, author, institution, author keywords and abstract, etc. The author keywords usually have some

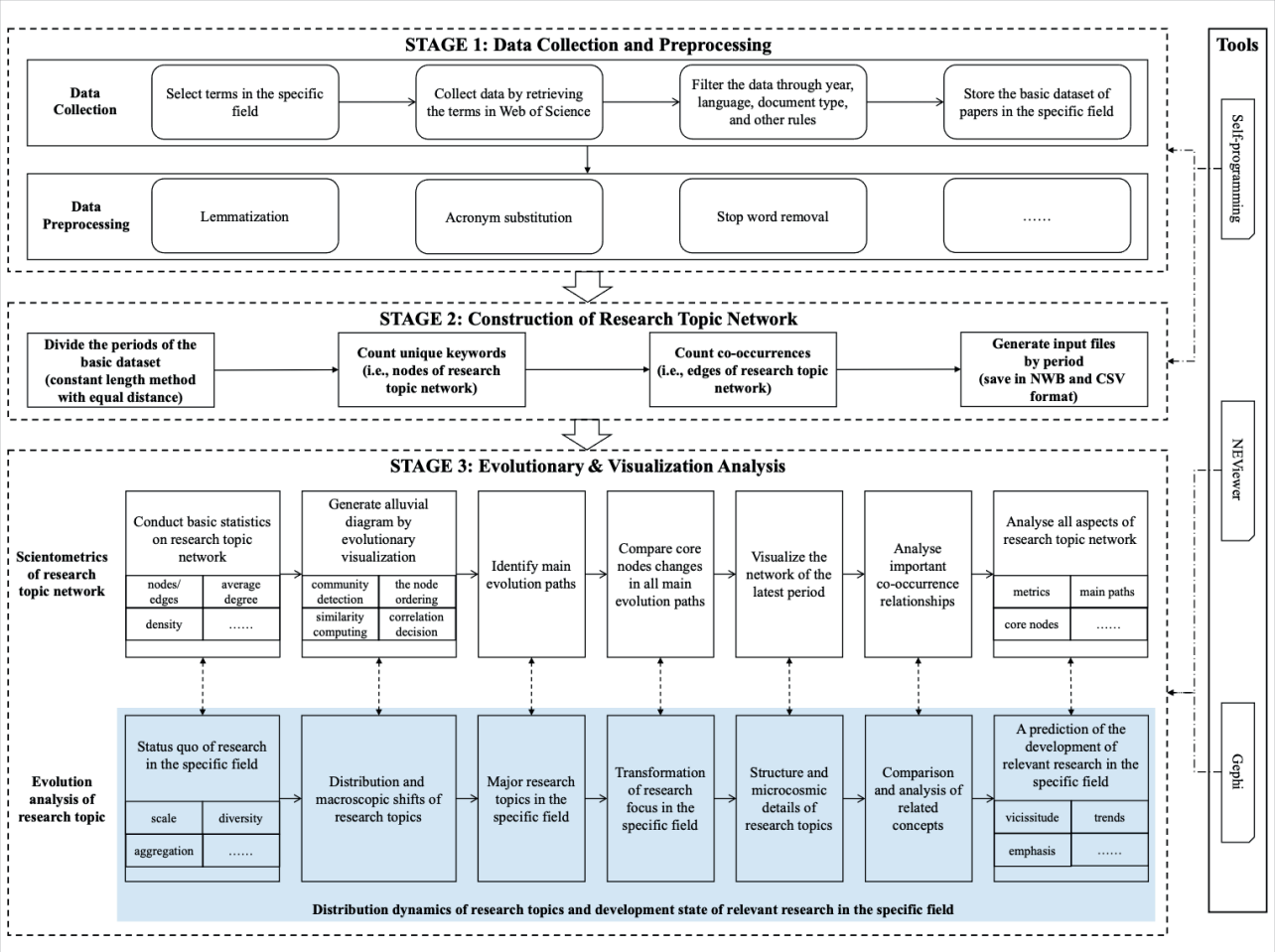

Figure 1. Research idea

formal problems such as morphology, abbreviation, and special character. Therefore, it is necessary to complete data preprocessing on the author keywords, such as lemmatization, acronym substitution, and stop word removal through self-programming.

> "This study proposes a new idea for obtaining knowledge insights by using the research topic network to analyze the distribution dynamics of subject research and the development state of related research"

Stage 2: Construction of research topic network

The research topic network is composed of continuous co-word networks of multiple periods, reflecting the correlation and the evolutionary context of related research topics. At this stage, firstly, the basic dataset is divided into several periods by combining the characteristics of field development and the constant length method with equal distance. Then the unique keywords and the co-occurrences among them in each period are counted as nodes and edges of the co-word network, respectively. Finally, according to the requirements of *NEViewer* and *Gephi*, the co-word network data of each period is saved into NWB and CSV formats, which are used as the input of the next stage.

Stage 3: Evolutionary & visualization analysis

Diversified scientometrics analysis of research topic network and multi-dimensional evolution exploration of research topic in the field corresponding to each other. From the perspective of the basic characteristics of network structure, community aggregation & association, nodes/edges, and other constituent elements, the research topic network is measured and analyzed, to scientifically explore the status quo and development trends of research in the field, and to visually reveal the macro process and micro details of the evolution of research topics. At this stage, the research topic network is measured scientifically through seven steps to realize the corresponding research topic evolution analysis. Finally, the distribution dynamics of the research topic are revealed, and the development state of the related research is uncovered.

1) Through the basic statistics of structure indicators such as nodes/edges, average (weighted) degree, and density of the research topic network, the development scale, diversity, and aggregation of research in the specific field is understood.

2) Through the detection of the research topic community, the node ordering, similarity computing, and correlation decision in *NEViewer*, an evolutionary visualization analysis tool, the evolutionary alluvial diagram of the research topic community is generated, to visualize the distribution of research topics and their macroscopic shifts (Birth, Growth, Merging, Contraction, Splitting, and Death).

3) Identify the main evolution paths formed by communities of research topics throughout the alluvial diagram, to know the major research topics in the specific field.

4) Among the main evolution paths, the node ordering in the topic community of different periods (especially the changes of core nodes) reflects the transformation of research focus of related topics. Thus, by comparing the changes of the core nodes in all main evolution paths, the transformation of research focus of the major research topics in the specific field is revealed.

5) Visually analyze the co-word network structure in the latest period by network exploration and visualization software *Gephi*, intuitively observe the co-occurrence relationship between related keywords, and then explore the topological structure and microcosmic details of the research topics in the latest period.

6) In the co-word network, a greater edge weight means a more critical co-occurrence relationship between the two related keywords. Analyze these important relations, explicitly understand the connotation and extension of specific concepts, and then distinguish the relevant concepts in the field.

7) Comprehensively analyze the overall situation of the research topic network in terms of structural metrics, main evolution paths, core nodes changes, etc., to study and judge the development state of relevant research in the specific field from the perspectives of vicissitude, trends, emphasis, etc.

After these stages,

- the status quo of research in the field can be quantitatively characterized;
- the major research topics and their macroscopic shifts process as well as the transfer of research focus reflected by the two can be systematically explored;
- the microscopic details of research in the field and the connotation of related concepts can be clearly analyzed; and
- the future development trends of the related research can be reasonably predicted.

To sum up, the idea proposed in this study will realize the dynamic analysis of the distribution of research topics and the uncover of related research development state in the specific field, to obtain some knowledge insights.

2.2. Data preparation

Through the advanced research function in *WoS*, the terms of HFT are selected as follows.

1) "High frequency trade" and "high frequency trading" are used as "Topic" to retrieval, then the author keywords included by the searched papers are collected.

2) Subject terms are covered from the relevant literature reviews (**Chung**; **Lee**, 2016; **Linton**; **Mahmoodzadeh**, 2018; **Virgilio**, 2019).

In terms of filtering rules set, the documents are restricted to research papers and reviews in English from 2000 to 2019 in this case. By this means, basic collected papers in the field of HFT were retrieved in *SCI*/*SSCI* and stored (including 20975 scientific papers[2]), then the author keywords were preprocessed.

Combining the timeline of HFT (**Budish**; **Cramton**; **Shim**, 2015; **O'Hara**, 2015) and the constant length method with equal distance, the duration is divided into four equidistant length periods of 5 years, namely 2000-2004 (Period I), 2005-2009 (Period II), 2010-2014 (Period III), and 2015-2019 (Period IV). The unique keywords and their co-occurrence relationship are counted through self-programming, and the research topic network data is saved in the required formats by period. The time-varying number of papers is shown in Figure 2. The number of relevant scientific papers in HFT is increasing year by year. According to the law of scientific literature growth and the Logistic Model of scientific literature (**Wang *et al.***, 2021), HFT is still developing. With the increasing number of papers, the connotation and extension of HFT are constantly enriched. Therefore, the revealing and "distance reading" of the knowledge structure of HFT and the evolutionary context of research topics are urgent needs for scholars and practitioners in HFT, and these are of great significance to its future development.

> "Taking HFT as a case, this study focuses on revealing and "distance reading" the knowledge structure of subject fields and the evolutionary context of research topics"

3. Results

Taking HFT as a case, three main results of the evolutionary analysis of the research topic will be presented in this section, and there will be a brief explanation of data input and the set of tools.

3.1. Basic statistics of the research topic network

This study constructed an undirected co-keyword network sequence based on the processed author keywords of four periods to form the research topic network. Table 1 presents the basic statistical indicators for the research topic network. Nodes and Edges measure the size of the network and indicate the number of nodes and edges, respectively. Density used to measure the network's completeness is calculated using the equation:

$$2*Edges/(Nodes*(Nodes-1))$$

Average Degree of the node represents the mean value about the number of all connected edges of the node in the network. Average Weight Degree extra considers the weight of edge (i.e., the number of co-occurrences among author keywords in this case). Clustering Coefficient demonstrates a general sign of clustering nodes in the network, whereas Connected Components refer to the number of disjoint subgraphs in the network.

The analysis of Table 1 and the distribution of the basic dataset reveal the following:

- With the increasing number of scientific papers in HFT from Period I to Period IV, Nodes and Edges rise accordingly, but the Density shows a downward trend. It means that the increasing number of related papers is accompanied by the gradual size enlargement of the corresponding co-keyword network, and the research topics in the field show a greater diversity but more scattered.

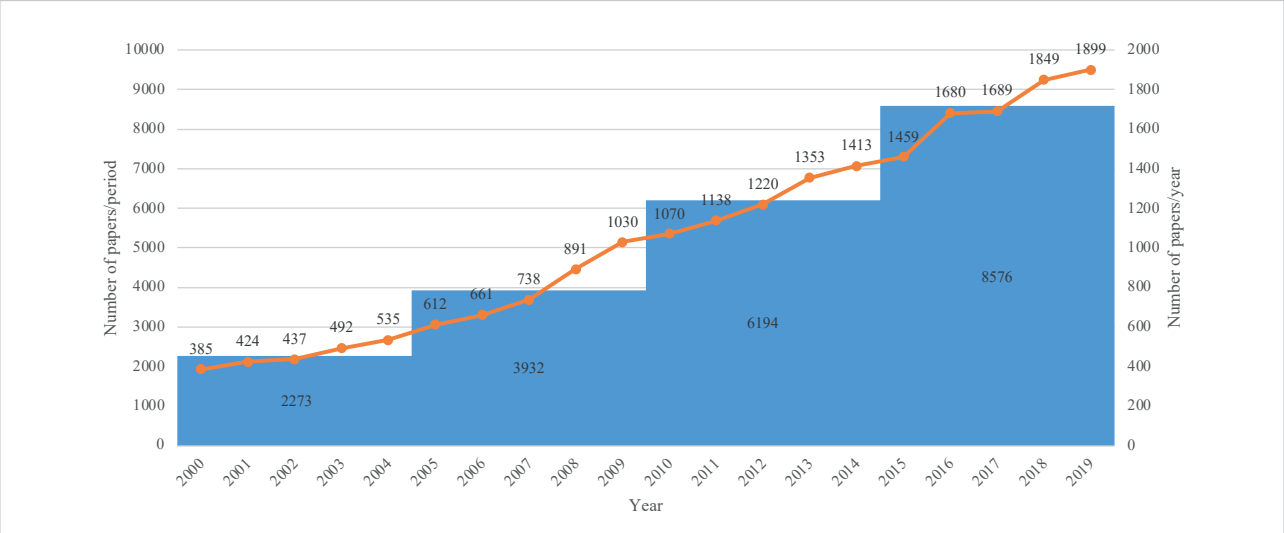

Figure 2. Distribution of scientific papers in HFT

Table 1. Basic statistics of the research topic network

Index	2000-2004	2005-2009	2010-2014	2015-2019
Nodes	675	1583	2793	4067
	--	(134.5%)	(76.4%)	(45.6%)
Edges	2607	8224	19883	32299
	--	(215.4%)	(141.7%)	(62.4%)
Average Degree	7.724	10.390	14.238	15.883
Average Weighted Degree	9.541	12.423	17.607	19.380
Density	0.01146	0.00657	0.00510	0.00391
Connected Components	14	8	11	15
Average Clustering Coefficient	0.398	0.375	0.444	0.435

Note: The numbers in parentheses in the table are the year-on-year growth rates of the corresponding indicators over the previous period.

- Average (Weighted) Degree of four co-keyword networks increases over time, which means more frequent connections and co-occurrence relationships among the research topics in HFT. However, the Average Clustering Coefficient shows fluctuating changes, indicating that their overall degree of aggregation does not lead to a clear trend.
- The Connected Components of four co-keyword networks change in a "v" type. PeriodII has the lowest component but the highest yearly growth rate on co-keyword network size. It can be inferred that Period IIhad an explosion in the number of studies compared with Period I, and scholars took the cognizance of the previous period study and carried out much follow-up research. These studies initially showed systematic trends and clear connotations. Scholars further diffused these connotations in the subsequent two periods.

3.2. Distribution and evolution of research topics

The co-keyword networks of four periods were imported into the *NEViewer* toolkit for evolutionary visualization and analysis. Using the Blondel partitioning algorithm and Radical-Tree layout, the looking nodes backward were set up. The resulting alluvial diagram is shown in Figure 3.

Figure 3 shows that the community evolution of research topics in the field of HFT has a high degree of continuity across four periods, with a few communities splitting or merging in general. Specifically,

- "incomplete market" split into "systematic risk" and "portfolio optimization" in Period II, and the latter further split in Period III;
- Both "volatility" and "financial market," which were ranked high and had large nodes in Period IV were split from "financial market" in Period III;

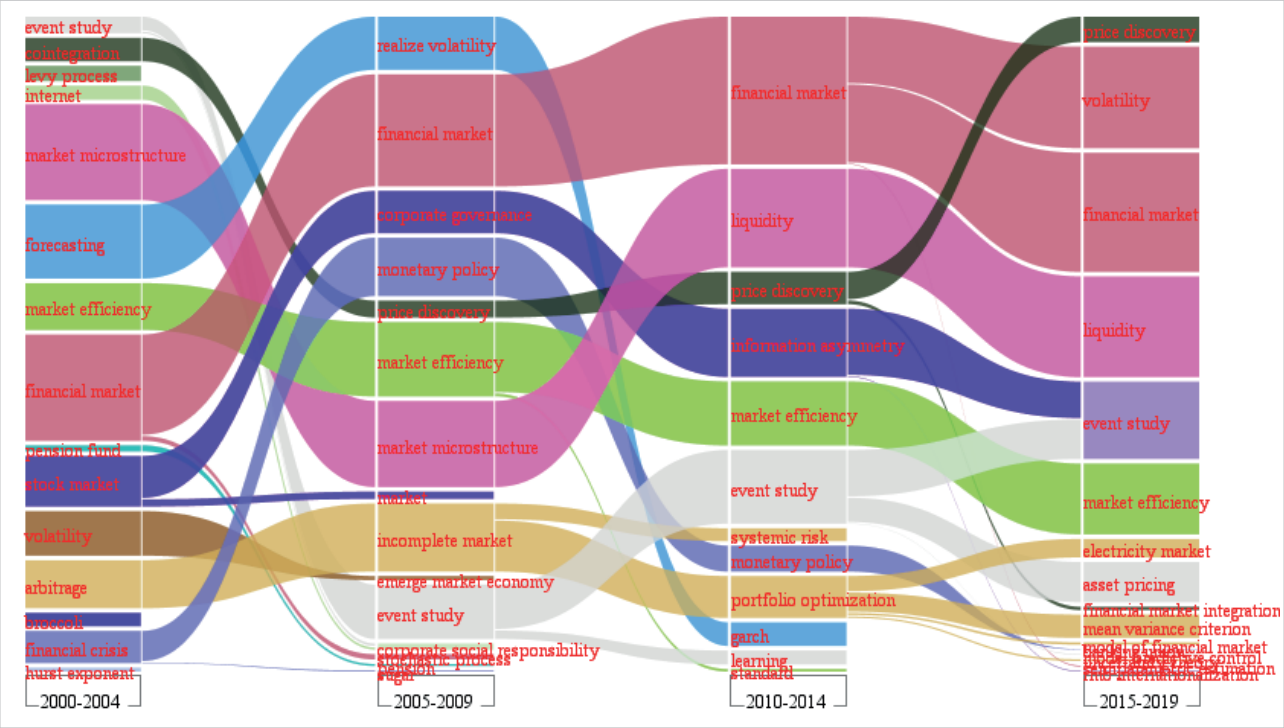

Figure 3. Alluvial diagram of community evolution on the research topics in HFT (Community similarity threshold equals 0.2)[3]

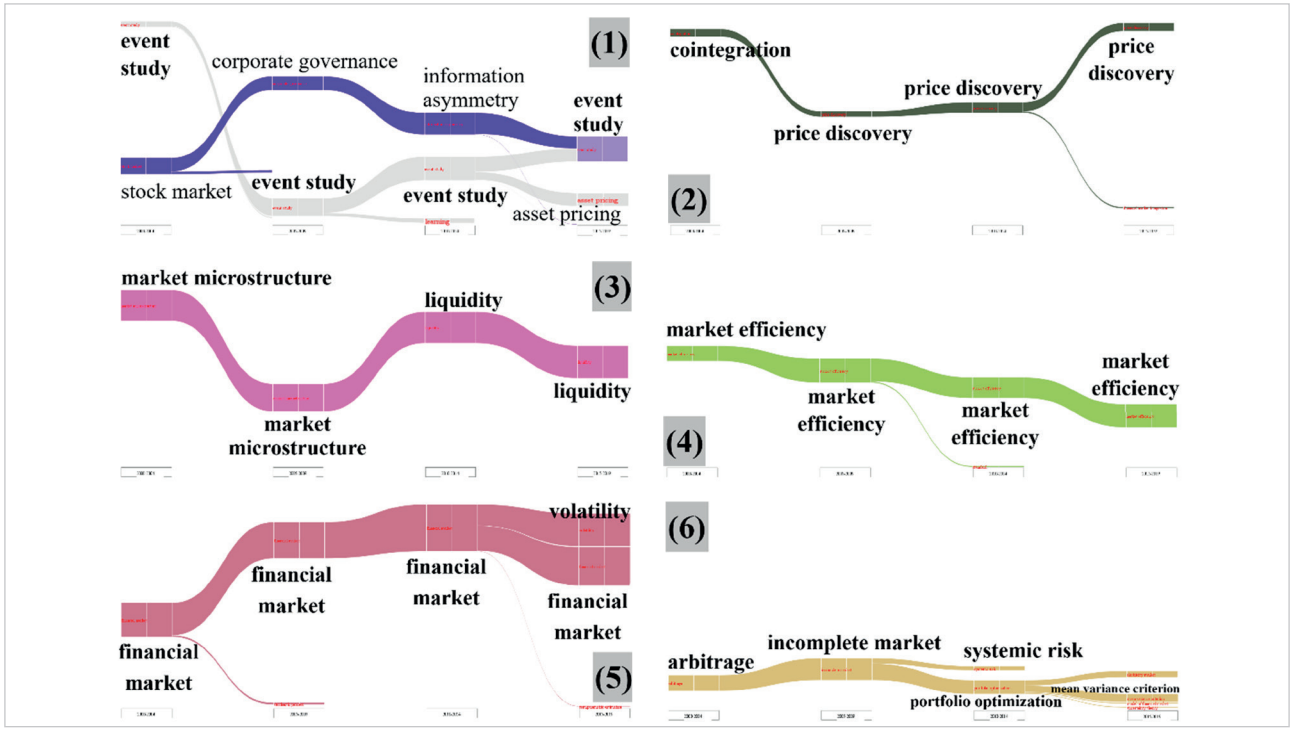

Figure 4. Main evolution paths of research topics in HFT

- In addition to the splitting in Period II and Period III, "event study" was also merging in Period IV, and it is the only convergence in the entire alluvial diagram.

There are six main paths in Figure 3, namely

1) event study,

2) cointegration & price discovery,

3) liquidity & market microstructure,

4) market efficiency,

5) financial market, and

6) incomplete market, as shown in Figure 4.

In the *NEViewer* output, Z-Value measures how closely one node relates to others in that community. It is an indicator that reveals the importance of nodes at the local level instead of the global. For the related communities in the above main evolution paths, their nodes are ranked by Z-Value, and the corresponding core nodes are shown in Table 2.

3.3. The structure and analysis of the co-keyword network of the latest period

To dig adequate information deeper into the research topic network, this study imported the CSV data of Period IV into *Gephi*. In *Gephi*, this study carried out the following operations:

1) selected the modularization function to cluster the nodes in the network;

2) color rendering was done according to the clustering of the nodes;

3) filtered out the nodes whose values are greater than 42 (6.5%);

4) adjusted the node size according to the degree; and

5) selected "Fruchterman Reingold" to adjust the layout of the nodes to complete the final visualization.

The structure of the co-keyword network in Period IV is shown in Figure 5.

Compared Figure 5 with Figure 3, it can be observed that the node size ordering in Figure 5 is the same as that of the color block size of the alluvial diagram. The communities with more nodes such as "financial market," "volatility," "liquidity," "event study" and "market efficiency" in Figure 3 have specifically distributed in Figure 5. This study counted the weights (i.e., the number of co-occurrence) of the top 10 in the network and their corresponding co-occurrence nodes, shown in Table 3.

Table 2. Core nodes in six main evolution paths of research topics in HFT

	2000-2004	2005-2009	2010-2014	2015-2019
1)	**event study**, **international financial market**, electronic commerce, **asset pricing**, **information and market efficiency**, abnormal return, merger and acquisition, monitoring, market value, labor market regulation	**corporate governance**, regulation, disclosure, merger, merger and acquisition, takeover, acquisition, cost of capital, real estate, signaling	information asymmetry, ***corporate governance***, *insider trading*, *acquisition*, *merger*, *merger and acquisition*, restructuring, informed trading, initial public offering, takeover	***event study***, ***corporate governance***, abnormal return, ***information and market efficiency***, china, *insider trading*, *acquisition*, *merger and acquisition*, emerge market, *merger*
	stock market, economic growth, **corporate governance**, globalization, financial integration, market, develop country, shareholder value, intermediation, accountability	***event study***, ***asset pricing***, ***information and market efficiency***, *trading volume*, ***international financial market***, *portfolio choice*, *bond interest rate*, heterogeneous belief, capm, *general*	***event study***, ***information and market efficiency***, ***asset pricing***, *trading volume*, *bond interest rate*, *general*, ***international financial market***, *portfolio choice*, *investment decisions*, general financial market	***asset pricing***, *portfolio choice*, *trading volume*, *bond interest rate*, *investment decisions*, ***international financial market***, monetary policy, foreign exchange, financial market and the macroeconomy, time series model
2)	**cointegration**, **price discovery**, vector autoregression, equilibrium, exogeneity, error correction, error correction model, mechanism design, seasonality, negotiation protocol	**price discovery**, market integration, **cointegration**, japan, granger causality, vector autoregression, consumption, stock price, spillover, liberalization	**price discovery**, **cointegration**, future market, china, causality, volatility spillover, commodity market, information share, commodity, granger causality	**price discovery**, **cointegration**, information share, future, pair trading, etf, commodity future, granger causality, exchange trade fund, ornstein uhlenbeck process
3)	**market microstructure**, **liquidity**, information asymmetry, **bid - ask spread**, insider trading, spread, market maker, tick size, execution quality, microstructure	**market microstructure**, **liquidity**, **bid - ask spread**, information asymmetry, microstructure, market quality, limit order, limit order book, order flow, trading cost	**liquidity**, **market microstructure**, high frequency data, **bid - ask spread**, volatility, limit order book, realize volatility, price impact, market microstructure noise, transaction cost	**liquidity**, **market microstructure**, high frequency trading, limit order book, information asymmetry, **bid - ask spread**, transaction cost, algorithmic trading, price impact, high frequency data
4)	**market efficiency**, capital market, **behavioral finance**, earnings management, disclosure, investor psychology, learning, accrual, account regulation, limited attention	**market efficiency**, **behavioral finance**, random walk, experimental economics, capital market, risk, analyst forecast, mispricing, overreaction, anomaly	**market efficiency**, **behavioral finance**, efficient market hypothesis, nonlinearity, predictability, anomaly, fundamental analysis, short selling, adaptive market hypothesis, risk	**market efficiency**, technical analysis, **behavioral finance**, trading strategy, return predictability, momentum, efficient market hypothesis, machine learning, cryptocurrency, bitcoin
5)	**financial market**, econophysic, stochastic process, herd behavior, fat tail, economics, random graph, percolation, business, heavy tail	**financial market**, econophysic, volatility, stock market, financial crisis, bank, emerge market, hurst exponent, efficiency, economic growth	***financial market***, *financial crisis*, *stock market*, *regulation*, econophysic, *finance*, crisis, institution, *neoliberalism*, globalization	volatility, *stock market*, forecasting, garch, realize volatility, exchange rate, oil price, stock return, volatility spillover, spillover ***financial market***, financialization, *financial crisis*, *regulation*, *finance*, european union, innovation, *neoliberalism*, financial development, economic growth
6)	arbitrage, **incomplete market**, transaction cost, hedge, utility maximization, equivalent martingale measure, martingale measure, insurance, contingent claim, pricing	***incomplete market***, utility maximization, transaction cost, hedge, insider trading, *backward stochastic differential equation*, arbitrage, markov chain, *hamilton jacobi bellman equation*, levy process	systemic risk, financial innovation, securitization, financial stability, credit risk, derivative, bank regulation, financial literacy, performance, equity premium portfolio optimization, value at risk, ***incomplete market***, *backward stochastic differential equation*, risk management, optimization, algorithmic trading, *levy process*, *dynamic programming*, *hamilton jacobi bellman equation*	mean variance criterion, stochastic control, investment, *hamilton jacobi bellman equation*, partial information, optimal investment, mean variance, *dynamic programming*, ***incomplete market***, time consistency

Note: The red font in the table represents the community label corresponding to Figure 3 and Figure 4, bold indicates the node that appears in all four periods in the same path, italics means that the node is involved in the splitting or merging of the community, and the underscore denotes the node in the same path that appears in the first three periods or the last three periods.

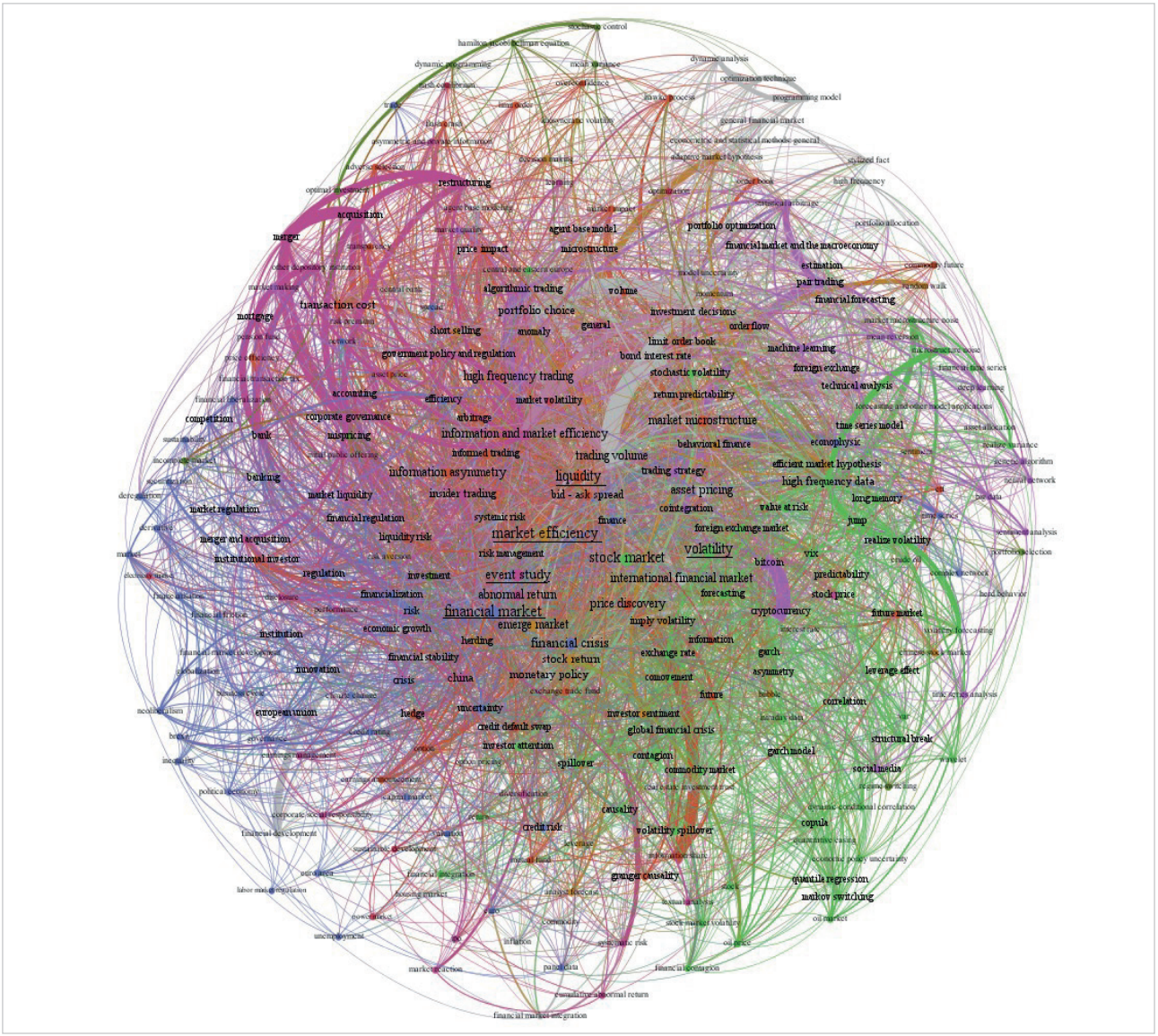

Figure 5. The co-keyword network topology of HFT in 2015-2019

Table 3. Top 10 co-occurrence in the co-keyword network of the last period

Rank	Node A	Node B	Weight
1	event study	information and market efficiency	69
2	asset pricing	bond interest rate	41
3	event study	abnormal return	40
4	asset pricing	trading volume	39
5	trading volume	bond interest rate	37
6	portfolio choice	investment decisions	32
7	high frequency trading	algorithmic trading	29
8	bitcoin	cryptocurrency	27
9	event study	trading volume	24
	price discovery	information share	
10	asset pricing	information and market efficiency	23

HFT and AT have the seventh-highest ranking of co-occurrences in the co-keyword network of Period IV. As discussed in the Introduction concerning HFT and AT, a deeper distinction between the two is necessary for relevant research and practice. To distinguish the two concepts objectively, co-occurrence times of them with other nodes were ranked in descending order, and the top 10 are shown in Table 4.

Table 4. Core nodes in co-occurrences with HFT or AT

Node A	Node B	Weight	Node A	Node B	Weight
high frequency trading	algorithmic trading	29	algorithmic trading	high frequency trading	29
	liquidity	17		**liquidity**	5
	market microstructure	13		market regulation	4
	limit order book	12		neural network	4
	market quality	9		machine learning	4
	market efficiency	8		**market efficiency**	4
	financial market	8		**market quality**	4
	price impact	6		**limit order book**	4
	flash crash	6		**price impact**	3
	statistical arbitrage	6		agent base model	3

Note: Bold indicates that nodes appear in both co-occurrence relationships.

Given 1) the current state of imbalance research and practice in HFT between emerging and international financial markets, 2) the ongoing societal discussion on the relationship of HFT with flash crash events, 3) the fact that behavioral finance always serves as the core node in the main paths and focused by several winners of the Nobel Economics Prize, 4) the continuing interest of relevant personnel in the accuracy and timeliness of forecasts on volatility, trends, and prices, etc., this case also uncovered the nodes frequently co-occurring, as shown in Table 5.

Table 5. Some important co-occurring relationships

Node A	Node B	Node A	Node B
emerge market	market efficiency	international financial market	asset pricing
	liquidity		portfolio choice
	international financial market		information and market efficiency
	event study		bond interest rate
	asset pricing		event study
	market microstructure		trading volume
flash crash	high frequency trading	machine learning	algorithmic trading
	limit order book		statistical arbitrage
	agent base model		big data
	systemic risk		high frequency trading
	herding		forecasting
behavioral finance	investor sentiment		trading strategy
	market efficiency		portfolio allocation
	financial crisis	deep learning	machine learning
	financial market		volatility prediction
	portfolio choice		high frequency trading
	efficient market		algorithmic trading
forecasting	volatility	big data	trading strategy
	realize volatility		machine learning
	stock market	neural network	algorithmic trading
social media	sentiment analysis		forecasting

4. Discussion

4.1. The distribution structure and evolution dynamics of research topics

The visualization analysis of the research topic network can reveal the knowledge structure of the specific field in periods and the evolutionary context of the research topics in this field. During 2000-2019, the research in HFT focused on event study, cointegration & price discovery, liquidity & market microstructure, market efficiency, financial market, incomplete market, and other research topics.

Compared with other main paths, the "event study" path has the most significant evolution process of splitting and merging. Scholars have made an extensive analysis of asset pricing and information & market efficiency in the international financial markets by event study method. There is a sub-path "corporate governance," where the related research concentrates on the financial condition, regulations, disclosure, insider trading, and merger & acquisition of the listed companies. Through the distribution dynamics of the corporate governance node and the comparison of related core nodes in Period I and IV, it can be found that the focus of related research has gradually transferred from international financial markets to emerging markets such as China.

The node size of related communities in "cointegration and price discovery" path is smaller, and its core nodes do not change much over four periods, which indicates that the related research topics of it are more concentrated. Besides, "price discovery" became the top community of the alluvial diagram in Period IV, suggesting that it was the most closely related to other research topics of HFT in 2015-2019. This path involves some financial mathematical and econometric analysis methods of price discovery and formation. The foci have gradually shifted from vector autoregression, equilibrium method, and error correction model to causality, information share model, and stochastic process. During 2000-2014, externalities, mechanism design, (volatility) spillover studies, and other issues were at the center of related research, while in 2015-2019, studies on the practice and application of pair trading and financial derivatives such as futures and exchange-traded funds were hot. Moreover, China was at the forefront of the core nodes during Period III, indicating that price discovery in emerging markets received extra attention from academia in 2010-2019.

The "market microstructure and liquidity" path is the only one without any split or merged, and its related topics have formed a more independent range of research. Bid ask spread received constant attention from scholars, but its enthusiasm had declined slightly in Period IV compared to other periods. It may be the result of an increase in the popularity of limit order, HFT, and other issues in 2015-2019. In 2000-2014, relevant research centered on the concepts of market microstructure such as market maker, tick size, limit order, order flow, trading cost, high-frequency data, and transaction cost, which may be one of the reasons for the increase in the heat of concepts such as HFT during 2015-2019. Besides, scholars kept a watchful eye on the concepts at the transaction-level, such as insider trading, limit order book, and transaction cost, and conducted research related to information asymmetry. Although some nodes like information asymmetry have emerged in the sub-path of event study, they underlined firm-level concepts, such as corporate governance and merger & acquisition. In addition, volatility and market microstructure noise also attracted the attention of academia from 2010 to 2014.

In the "market efficiency" path, the community centrality reduces over time, i.e., the interaction between market efficiency and other research topics in HFT is decreasing. This is contrary to the rise of the centrality of related communities in the "financial market" path, which may indicate that their evolution has a moderate correlation. Since the behavior of market participants affects the market efficiency, extensive research has been done on investor psychology, limited attention, random walking, overreaction, anomaly, efficient market hypothesis, adaptive market hypothesis, and other issues from the analytical perspective of behavioral finance. In 2000-2004, scholars paid attention to finance accounting related concepts such as earnings management, disclosure, accrual, and accounting regulation. Accordingly, they analyzed the impact of changes in factors such as financial behavior and accounting regulation of listed companies on market efficiency. During 2005-2009, experimental economics methods received attention from scholars. Several studies related to forecasting have been done in 2010-2019, including analyst forecasting, (return) predictability, etc. In addition, it could be found that the dominant approach to forecasting is gradually shifting from fundamental analysis to technical analysis. The overall research during 2015-2019 is biased towards the practice in the field of HFT, with concepts such as trading strategy, momentum, machine learning, cryptocurrency, bitcoin, and genetic algorithm gaining in popularity.

The node size of the relevant communities of the "financial market" is the largest in every co-keyword network, and its centrality in the research topic network is also relatively higher. However, perhaps because of the broad concept of the financial market, no other concepts of sustained interest are noticed in this path. From 2000 to 2004, scholars were concerned with concepts of mathematical characteristics such as stochastic process, fat tail, and heavy tail. Whereas, in the following 15 years, more attention was laid on concepts of market environments such as financial crisis, emerging market, stock market, economic growth, financial development, and globalization. Econophysics was the core node for the relevant communities in all the first three periods but did not sustain in the fourth. The reason may be that scholars paid more attention to the application of econophysics achievements in Period IV (e.g., prediction of the market volatility variation due to financial

> "Six major topics in HFT: liquidity & market microstructure, market efficiency, financial market, incomplete market, cointegration & price discovery, and event study"

crises by the dynamics). Overall, the nodes directly related to volatility, such as actual volatility and volatility spillover, only appeared in Period II and IV. Besides, "volatility" split from the presequence "financial market," became the second-largest community in Period IV. In 2015-2019, the relevant research on volatility concentrated on the measurement, forecasting, and the associated stock return and spillover. In addition, it also included the analysis of the stock market, exchange rate, oil price, and other research objects.

> "The research focus about markets gradually transferred from international to emerging, meanwhile continuous attention to volatility/risk-related"

The overall centrality of the "incomplete market" is the lowest among six main paths, and its associated communities split twice in Period II and III, suggesting that scholars are still exploring it. The sub-directions such as stochastic process, optimal control, and dynamic programming in operational research have been widely used in the research of incomplete market. In this path, the "portfolio optimization" community, which was split for the first time, continued the relevant research on stochastic processes and optimal control from 2005 to 2009. Its core nodes are backward stochastic differential equation, levy process, and Hamilton Jacobi Bellman equation, while also focusing on risk measurement and risk management. In 2010-2014, the "mean variance criterion" from the second splitting followed the middle Hamilton Jacobi Bellman equation and dynamic programming. Besides, financial innovation, securitization, financial stability, credit risk, financial literacy, and other issues attracted great attention to the community "systemic risk" from splitting in Period III, which were rarely covered by the relevant research in other periods, probably because of the sudden series of disruptive market events during 2010-2014.

4.2. Development state of the research in the field

By comprehensive analysis of the scale, main paths, and core nodes of the research topic network, reasonable study and judging of the development state of relevant research in the specific field can be realized. Related research during 2000-2019 in the field of HFT focuses on market microstructure, market efficiency, financial market, incomplete market, and other market-level research topics, as well as cointegration & price discovery, asset pricing, and others of price-formation-level. Event study is a common method in HFT. Volatility/risk is a concept commonly involved in all the above research topics. In recent years, the emphasis of research in HFT has gradually shifted from theory to practice and paid more attention to the related issues of financial innovation, behavioral finance, and operational research. Moreover, besides the research of the overall environment of international financial markets, emerging markets such as China have attracted more and more interest from scholars in recent years, especially in the related topics of event study and price discovery.

Additional details of the co-keyword network in the last period were also observed in this study.

- In the field of HFT, asset pricing, bond interest rate, and trading volume are closely related to each other.
- Among issues related to AT and HFT, liquidity is of prime concern to scholars. Meanwhile, concepts such as limit order book, market quality, market efficiency, and price impact often appear alongside AT and HFT. While discussing AT, the relevant research focuses more on market rules and technology. In comparison, research of HFT is concentrated more on market microstructure.
- In emerging markets, research on market efficiency is more prominent, while in the case of international financial markets, the research of asset pricing is the most preferred. Thus, the research on emerging markets in the field of HFT is more inclined to the market-level, while the research on major international financial markets was more inclined to the transaction-level.
- In addition to HFT, the research on the flash crash involves systemic risk and herding (effect) and other concepts.
- The relevant research on behavioral finance in HFT mainly examines its impact on market efficiency and efficient market.
- Volatility forecasting is more common in HFT than price and trends forecasting.
- Research related to social media within HFT focused on sentiment analysis. The common idea is to analyze investor sentiment and monitor the fundamental information through the algorithm models based on the public opinion data in social media and then apply it to the trading strategy and forecasting model to improve the return of the strategy and the accuracy of the model.
- Machine learning and other emerging technologies are widely used in the research and practice of HFT, referred to statistical arbitrage, forecasting, trading strategy, portfolio allocation, etc. Regarding prediction related research, it includes the application of deep learning technology and neural network model. Besides, the development and computation of HFT strategies utilize techniques such as big data and high-performance computing, which can give useful information in a large amount of information flow in a fast and timely manner.

Combined with the above discussion, this study can reasonably uncover the development state of research and practice in HFT. Research in the field of HFT is still developing, and the paper counts will continuously increase in the coming years. Market-level research on market microstructure, market efficiency, financial market, incomplete market, and price-formation-level research on cointegration & price discovery, asset pricing price, etc., still are the focuses of future research in the field of HFT. These studies will pay more attention to emerging markets in the overall international financial market environment. The achievements in the fields of behavioral finance, econophysics, and operations research, as well as techniques such as big data, machine learning, and deep learning, will be further applied in the research

and practice of HFT, such as forecasting, trading strategy formulation, portfolio allocation, and risk management. The relevant research and practice of predicting will use more technical analysis methods and fundamental analysis methods combined with macroscopic, mesoscopic, and microscopic factors in the future. With a series of landmark financial events that occurred in recent years, such as the meltdown of U.S. stocks and the dive in oil prices, it is expected that future research in HFT will be more concentrated on the consideration of systemic risk in terms of financial innovation and market stability.

> "The emphasis will change from theory to practice, technologies (big data, etc.) and theories (behavioral finance, etc.) will have more interaction with HFT"

5. Conclusions

This study proposed a general idea for the evolution analysis of research topics based on the research topic network. Taking the emerging field of HFT as a case, the distribution dynamics of the research topic in HFT are systematically uncovered, and then the development state of the relevant research is comprehensively studied and judged, which proved the effectiveness of the proposed idea.

Concretely speaking, a variety of methods and tools of scientometrics are used to analyze the 20975 papers of HFT published in journals indexed by *SCI*/*SSCI* from 2000 to 2019. This study,

- quantitatively characterized the status quo of research in the field;
- systematically explored the major research topics and their macroscopic shifts process as well as the transfer of research focus reflected by the two;
- clearly analyzed the microscopic details of research in the field and the connotation of related concepts; and
- reasonably inferred and predicted the future development state of the related research.

Furthermore, this study has found that

1) the knowledge structure of specific field reflected by the community distribution of research topics, that is, the research of HFT focuses on six major topics related to market-level and price formation (liquidity & market microstructure, market efficiency, financial market, incomplete market, cointegration & price discovery, and event study).

2) The evolutionary context and focus transformation of related research in the field is reflected by the main evolution paths of the research topic and the changes of its core nodes. The focus of HFT research has gradually transferred from international financial markets to emerging markets such as China, but volatility/risk-related studies have been continuously concerned by the academe and the industry. The emphasis of research in the field of HFT has been changing from theory to practice and paid more attention to the related topics of financial innovation, behavioral finance, and operations research.

3) The structure of the network in the latest period reflected that the focus of future research in the HFT field will gradually shift from theory to practice. Relevant technologies such as big data, machine learning, and deep learning, and theories such as behavioral finance, econophysics, and operations research will have more interaction with the research and practice of HFT in the future. The related research and practice of predicting in HFT will use more technical analysis methods and fundamental analysis methods combining macroscopic, mesoscopic, and microscopic factors.

4) The results of this case indicate that in the next few years, an emerging research field in finance-HFT will be paid more attention by scholars, and the number of relevant scientific papers will continue to increase accordingly. The research in HFT will continue to focus on the related topics of market-level and price formation and be more concentrated on the consideration of systemic risk, while the further development of emerging markets in the overall international financial market environment will attract more attention from academia and industry.

The research idea proposed in this study, through the scientometrics analysis of the research topic network in the field, effectively reveals the distribution dynamics of the research topics and scientifically uncovers the development state of related research in the specific field. Since this, professional knowledge and insights can be obtained. This paper focuses on the production dimension in scientometrics without further consideration of the impact, and there are limitations in the case analysis. On the one hand, the choice of data may be conservative. This case only analyzed the scientific papers published in the *SCI* and *SSCI* journals and did not consider other scientific literature, such as conference papers, working papers, and monographs, etc. In addition, there are some journals that do not require authors to provide keywords, therefore this case failed to include papers in these journals. On the other hand, although this case has adopted a diversified way to select the terms in HFT, there is still no guarantee that some other topics associated with HFT have not been omitted, which may limit the depth of the analysis and discussion in this case to a certain extent. Overall, the research idea proposed in this study provides an effective reference for the development of professional subject knowledge services such as topic selection guidance, hotspot recommendation and trend analysis in the era of big data.

6. Notes

1. We note that a conference paper (**Chou**; **Lee**; **Hung**, 2016) presents the objectives of a study using bibliometric analysis of HFT without specific study content and findings.

2. Among *WoS* Index, 24250 papers were obtained by search formula TS=("high frequency trad*" OR "algorithmic trad*" OR "alternative trading" OR "alternative trading system" OR "electr* trad*" OR "dark pool*" OR "dark liquidity" OR "market microstructure" OR "market quality" OR "pair* trad*" OR "flash* trad*" OR "flash crash" OR "insider trad*" OR "tick size" OR "market maker*" OR "market making" OR "informed trad*" OR "bid-ask spread*" OR "exchange server*" OR "market volatility" OR "abnormal profit*" OR "abnormal return*" OR "order-to-trade ratios" OR "financial transaction tax" OR "Regulation NMS" OR "MiFID II" OR "minimum order resting time*" OR "floor trading" OR "price discovery" OR "limit order book" OR "market efficiency" OR "flow toxicity" OR "financial market*" OR "market regulation*") AND PY=2000-2019 AND LA= "English" AND DT=("Article" OR "Review") NOT DT= "Early Access", and 21083 papers remained after screening. After data inspection, 108 papers from 2020 were identified and excluded, and the final dataset contained 20975 papers.

3. The rectangular color blocks represent communities, the red label is the node with the highest Z-Value in the community, and the size of the color block means the number of nodes contained in the community. The colored streamlined curves between the blocks in each period show the splitting and merging process of a community in a specific time, which makes people understand more vividly the evolutionary trajectory and trend of the research direction. The vertical order of the color blocks in the period indicates the centrality of the research topic, and the corresponding community at the top is most closely related to other communities.

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