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Innovations in Financial IS and Technology Ecosystems: High-Frequency Trading Systems in the Equity Market

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INNOVATIONS IN FINANCIAL IS AND TECHNOLOGY ECOSYSTEMS: HIGH-FREQUENCY TRADING IN THE EQUITY MARKET

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ABSTRACT

Technology-based financial innovations over the past four decades have led to transformations in the financial markets. Understanding technological innovations in financial information systems (IS) and technologies has been challenging for technology consultants and financial industry practitioners due to the underlying complexities though. In this article, we propose an ecosystem analysis approach by extending the *technology ecosystem paths of influence model* (Adomavicius et al. 2008a) to incorporate stakeholder actions, considering both supply-side and demand-side forces for technological change. Our ecosystem model brings together three original core elements: technology components, technology-based services, and technology-supported business infrastructures. We also contribute a fourth new element to this approach involving *stakeholder analysis*. We investigate innovations in the area of *high-frequency trading* (HFT) *technologies* as a basis for empirically validating the existence of several different patterns in the historical path of technology evolution. Our analysis results suggest that supply-side and demand-side forces influenced HFT technology innovations and contributed to changes in the financial markets. This research represents some of the first work that investigates financial market technology innovations at the technology and stakeholder levels. It also offers a useful and practical tool to help managers and analysts to understand the nature of technology-based financial innovations and the relationships between technology and financial markets that support their emergence.

Keywords: Algorithmic trading, financial markets, financial innovation, high-frequency trading, technology-based innovation, paths of influence, technology ecosystems

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1. INTRODUCTION

Information technology (IT) is important as a driver of product, service and business innovation in financial services and financial markets (Steiner and Teixeira 1989; Wriston 1988, 2007). When we consider their impacts on how securities and other financial instruments have been traded over the past four decades, the extent of IT-enabled innovations and transformations that have occurred has been dramatic and far-reaching (Mishkin and Strahan 1999, Stoll 2006). The rate of change in the core technologies of *algorithmic* and *high-frequency trading* (HFT) also has been rapid for market participants. Starting from the 1980s, program trading emerged and trades were sent to market with computers, diminishing floor trading at the exchange (Hasbrouck et al. 1993). The emergence of other fully-electronic trading venues, especially electronic communication networks (ECNs), further changed trading on the NASDAQ and New York Stock Exchange (NYSE) in the late 1990s (Weston 2002). This, in turn, led to the wider use of algorithmic trading and eventually the rise of HFT (Aldridge 2013). With HFT, proprietary trading firms known as *high-frequency traders* use computer systems to monitor market data, identify opportunities to make profitable trades, and submit large numbers of orders to the markets (SEC 2010).

Competition has been intense among rival trading firms in the equity markets. In 2005, the U.S. Securities and Exchange Commission (SEC) (2005) promulgated the Regulation National Market System (NMS) to improve price display and trading execution fairness, promote pricing in pennies instead of eighths and sixteenths, and democratized market-wide access to market data. These regulatory changes set the stage for the current electronic trading mechanisms, leading to rapid development of HFT technologies and enabling new trading strategies. HFT is characterized by: a dependence on high-speed and sophisticated computer programs; ultra-low latency in the delivery of orders to an exchange's computer systems; the submission of numerous orders that can be canceled shortly after submission; the limited shelf-life of the trading algorithms that are used; and trading in multiple asset classes involving numerous exchanges (McGowan 2010). In response to the automated process and winner-take-all nature of HFT, high-frequency traders have found it important to invest in hardware, software and network capabilities to minimize latency, which enable them to continue to refine their trading programs and algorithms, update their technology infrastructures, and be successful in the related "arms race."

In addition, these technological innovations have been supported by transformations in the operational practices and infrastructures over time. The relevant changes have included the immobilization and dematerialization of securities through the establishment of multi-tiered financial intermediation and centralized securities depositories, such as the Depository Trust and Clearing Corporation (DTCC 2012a). They make it possible for different kinds of organizations – retail investors and investment funds; institutional investors, hedge funds and exchange-traded funds; domestic and foreign brokers; commercial, savings and investment banks; and local and global custodian services providers – to share the same infrastructure (Chan et al. 2007, Russo et al. 2002). This allows the securities to be held in digital rather than physical form at one location, where they can be available for clearing and settlement. It also obviates the need for the costly exchange of physical certificates after trades are completed, improving efficiency and security, and increasing the likelihood that intraday settlement can be achieved (DTTC 2012b). Other recent developments further supported HFT diffusion. They include the deposit of securities at the DTCC (2013): via fully-automated straight-through agents; for provisional credit pending agent approval; and for immediate credit.

A related development is the specter of software errors in HFT operations that lead to dramatic, fast and irrecoverable losses. Examples include the May 2010 "flash crash" (Kirilenko et al. 2014) and Knight Capital's 2012 software glitch that caused US$460 million losses in its millisecond and microsecond trading, at a time when it held 15% to 20% market share of all HFT activities in the U.S., and ultimately this event led to Knight Capital's acquisition by another firm (SEC 2013a). A recent DTCC (2013) report includes a famous quote from Mahatma Gandhi of India, who said: "There is more to life than just increasing its speed." The regulatory agencies and financial intermediaries such as the SEC and DTCC in the U.S. have responded by discussing the possible requirement of having HFT firms submit data on their fast trades on a near real-time basis, and not permitting a practice known as *pre-netting*, which makes it much more difficult to monitor market quality (SEC 2013b).[1] There are no longer any technical difficulties for firms to selectively hold back the sharing of data on netted trades. This practice dramatically compromises the capacity of governmental financial intermediaries that are charged with market oversight. They need to effectively monitor market quality and performance, and ensure operational fairness and transparency while mitigating the major risks (MarketsMedia 2013). These things led to promulgation of detailed rules since the 1990s, for example, for fixed income securities trading (Fixed Income Clearing Corporation 2014).

The most impactful trading technology innovations in financial markets have been difficult for managers and industry observers to assess. Though there have been bellwether signs of technology-related developments in the high-tech industries, it has not been easy to characterize how they arose, or what was the extent of their impact.[2] The primary questions are: What have been the historical paths of technological innovation in financial markets? What shape have they taken, and what patterns seem to be present? Can they be identified based on relevant empirical observations? Is there a methodology that can be applied to cut through the complex relationships among technology, financial markets, and stakeholders so the ecosystem's evolution can be understood? Will this be helpful for looking ahead and trying to understand what ecosystem changes are likely to occur in the future?

In this article, we adopt a view that is focused on *technology components*, *technology-based services*, and *technology-based business infrastructure.* Adomavicius et al. (2008a) proposed an early image of this view in research they conducted on *paths of influence* models in *technology ecosystems.* We employ this view to address issues that financial decision-makers and analysts face, as they think through what will

[1] According to the U.S. National Securities Clearing Corporation (NSCC), *pre-netting practices* involve: "(i) *summarization* (i.e.,a technique in which the clearing broker nets all trades in a single CUSIP by the same correspondent broker into fewer submitted trades); (ii) *compression* (i.e., a technique to combine submissions of data for multiple trades to the point where the identity of the party actually responsible for the trades is masked); (iii) *netting*; and (iv) any other practice that combines two or more trades prior to their submission to NSCC ..."

[2] The *Journal of Technological Forecasting and Social Change* has published exemplary research that gets at different aspects of this problem. They include: (1) forecasting pathways in science and technology innovation based on identification of relevant technical elements, consideration of knowledgeable people and groups related to distinctive functions of new technologies, how various high-value functions are supported by applications, and what are the links between applications and commercial opportunities (Robinson et al. 2013); (2) understanding technological innovation through analysis of diffusion of relevant technical knowledge via patents, articles and institutional collaboration (Cunningham and Kwakkel 2010); and (3) through industry network structure that supports transmission of knowledge to where it can be creatively applied for technology, component, product, service, and infrastructure innovation (Van der Valk et al. 2011), and mergers and acquisitions (Chellappa and Saraf 2010).

drive key innovations in a financial market's technology ecosystem. Components, services, and infrastructure in financial IT are the key building blocks for the insights we offer. In addition to these, we also offer a new contribution by extending this approach to consider some other forces associated with the potential influences and actions of a range of stakeholders present in the financial markets. [3] These forces act as accelerators or decelerators of change when new IT-enabled innovations have the potential to transform the nature of economic exchange. The extended approach is intended to be general, so it is possible to treat other industry and technology settings, with different stakeholders and competitive conditions.[4]

The contributions of this research to the literature on technology innovation and financial markets are twofold. We propose a contribution to theory involving a *supply-and-demand view* of the evolution of technology innovation in the financial market that emphasizes stakeholders. Technology is a supply-side force, but the more complex considerations arise around stakeholders, who act as a demand-side force for innovation. Little research has explored the complex interplay between financial markets and relevant technologies (Franke 1987, Saint-Paul 1992). Some exceptions are studies of technology-based financial innovations from an organizational perspective (Fichman and Kemerer 1999, Lyytinen and Rose 2003). And others (Adomavicius et al. 2008a, 2012) offered a technology ecosystem perspective that looks at how technology changes production in the general landscape of information systems (IS) and IT, based on interactions among different kinds of technological artifacts. This approach only emphasizes the supply-side forces of innovation evolution: it focuses on how the introduction and development of new technologies can lead to the initiation and diffusion of innovations. The demand-side forces of technology innovation were not considered though. Important stakeholders in financial market technology ecosystems, such

[3] Prior research by Adomavicius et al. (2008a, 2008b) characterized the building blocks as components, products and infrastructures, and they focused on technological innovations rather than process or services innovations. We emphasize services here. It is important for the reader to recognize that, had we identified the relevance of stakeholder analysis in the prior research some years ago, it would have offered other advantages and insights for that research that we did not have access to at that time. This might have led to other conclusions or insights that were somewhat different. Our primary intention here is to stress that, now that we are aware of the power of the demand-side and supply side forces for our analysis, we view this aspect of our extended approach as a general contribution for technology ecosystem evolution analysis. It is not specific to financial services or HFT innovations, even though it is applicable and insightful in terms of the findings it has produced for us.

[4] Some of the other settings in financial services involving technology innovation where the stakeholder analysis is likely to be useful, in addition to the basic elements we proposed of technology components, technology-based services and technology infrastructures, include: mobile payments (Au and Kauffman 2008); emerging forms of digital currency (e.g., Bitcoin, Litecoin, Primecoin, and Peercoin) (Gibbs 2013); supply chain management, trade finance, and bank payment obligations (International Chamber of Commerce 2014); and new mechanisms to support cross-border low-value payments (Park 2007).

as financial institutions and regulators, have great influence on the direction, speed, paths and outcome of technology innovation. The supply and demand-side forces can work together or in opposition, resulting in different outcomes. We propose a supply-and-demand perspective to retrospectively analyze and prospectively assess how technological changes can be interpreted in financial markets at the level of basic technologies, based on the stakeholders' actions, interactions and responses.

The second contribution of our work is empirical. To validate and support our approach, we conducted an empirical test by applying it to the HFT technology ecosystem, which has multiple stakeholders and is highly regulated. We identified the different roles that the related technologies play in the HFT innovation evolution process, and investigated the multiple stakeholders within the HFT ecosystem as well as their impacts on the historical evolution of HFT technology. For this aspect of the research, we collected and analyzed thirteen events, including historical trajectories of technology changes and stakeholder actions. Our analysis identified different patterns of innovations based on the disparate forces that seem to be associated with how they arose: supply-side forces, demand-side forces, or forces from both sides.

This article is organized as follows. Section 2 presents a review of relevant literature, including technology-based financial innovations, technology ecosystems, and the paths of influence model for technology evolution. It also provides appropriate historical background knowledge about HFT. Section 3 proposes the extended paths of influence model that incorporates stakeholder actions from our supply-and-demand view of the technology evolution process. Section 4 applies the proposed model to assess the historical evolution of the HFT ecosystem. We also discuss the details of our data collection, stakeholder and data analysis, and present the findings. Section 5 suggests the empirical results' implications from our analysis approach. Section 6 concludes, and offers comments on limitations and future work.

2. LITERATURE

Our work draws on existing literature on financial innovation, the path-dependent view of technology change, the technology ecosystem paths of influence perspective, and HFT technologies. We first discuss the importance of considering both supply-side and demand-side forces on technology-based financial innovation. We also will review the theory of technology evolution, and how it applies to financial markets. We then will discuss the technology ecosystem and paths of influence model and how the concepts can be adapted for empirical analysis. Finally, we will introduce the literature on HFT.

2.1. Supply and Demand-Driven Forces for Financial Innovation

The supply-side forces of financial innovation come from developments in the technical knowledge base that produces new technologies or recombines existing technologies to provide new applications for them in organizations (Tornatzky and Fleischer 1990). Gatignon and Robertson (1989), and Currie and Seltsikas (2001) have argued that entrepreneurial efforts to develop new technologies drive the technological change and adoption by organizations. Technology-based innovations in financial markets have influenced the value propositions that firms can offer to their clients. They support the management and administration of their businesses, and are critical and embedded elements of their core technology solutions (Swanson 1994). Understanding the sources of technology-based innovation and taking advantage of investment and market opportunities are crucial to a financial institution's success in the market. Not only do these innovations generate gains for the innovators and adopters (Tufano 1989), they also produce beneficial welfare effects for the market overall (Frame and White 2004). The literature on financial innovations mostly has focused on: the diffusion of these innovations; the characteristics of adopters; and the consequences of innovation for firm profitability, institutional changes, and the performance of financial markets (Merton 1995, Miller 1986, Kavesh et al. 1978). It has not concentrated on understanding how *organizational innovation* influenced technology changes in financial markets. This creates demand-side forces that support financial innovations though (Lerner and Tufano 2011, Lyytinen and Rose 2003).

There has been some recognition of the need to model push and pull forces in innovation adoption (Zmud 1984) – representing efforts on the supply and demand sides. We have observed that when there is strong demand for innovations from the stakeholders in the financial markets, technology providers will be motivated to put more effort toward innovating with new products and services. When stakeholders are not ready to adopt new innovations that are pushed to the market by technology advances, immature technologies are likely to be used inappropriately and eventually result in financial losses for early adopters.

The literature has not resolved whether the pull of demand, the push of supply, or a combination of the two is the fundamental driving force though (Adner and Levinthal 2001, Arthur 2009, Sahal 1985). A mixed perspective is appropriate for analyzing the delivery and evolution of technology-based innovations in the financial markets, so the interplay of the supply and demand sides can be observed. Hence, there appears to be a key opportunity to extend the current thinking by explicitly including stakeholder analysis.

2.2. Technology Evolution and the Paths of Technological Change

Research has debated how technology evolves and creates innovation. Is it a smooth evolution of changes due to a process of continual improvement in the performance of a technology (Basalla 1988, Henderson and Clark 1990)? Or does it involve a discontinuous evolution with big changes driven by other things than the technological change (Tushman and Anderson 1986, Eldredge and Gould 1972)? Even though the literature is inconclusive, understanding technological change in the financial markets requires a carefully constructed view of the paths that the change process trace over time (Boland et al. 2003, Sood et al. 2012).

Regulators have been cautious to observe what happens when new technologies enter the financial markets. Technology innovations have the potential to spur breakthroughs in trading practices, destabilize the overall market and economic environment, and in some extreme cases, the dark side of these new financial innovations also has the potential to create a financial crisis (Diaz-Rainey and Ibikunle 2012, Thakor 2012, Fostel and Geanakoplos 2012). In addition, competition among market participants also results in the accumulation of many minor improvements, instead of jumps in performance over time. Our approach adopts a *path-dependent view* similar to Paul David's (2007, p. 92), in which changes in a financial IS and technology follow "a dynamic process whose evolution is governed by its own history."

The hype cycle for emerging technology developed by Gartner (Fenn et al. 2000) describes technological innovations in terms of several patterns in their evolutionary process. All of them are associated with the shifting sentiments and expectations of industry and social observers – from initial discovery of rising potential, to over-inflated hype and on to diminished and more realistic expectations. Worlton

(1998) has observed that technological change occurs in four stages: invention, innovation, diffusion, and change of scale, and Sahal (1981, 1985) also identified specific evolutionary patterns associated with different stages of technological change. Baldwin and Clark (1997, 2000) noted that design rules make innovation patterns predictable due to increased *modularity*. These things stimulated us to identify evolutionary patterns in the technology change process through the analysis of historical data and to offer useful managerial perspectives on what happened.

2.3. The Technology Ecosystem and Paths of Influence Perspective

Lyytinen and Rose (2003) emphasized the interrelationship among innovations for system development, IT services, and the related installed base of IT. They investigated how disruptive ITs penetrate organizations with new computing, solution development and service delivery opportunities. This work motivated research on the *technology ecosystem view*. Adomavicius et al. (2007) considered a complex system of determinants for evolutionary outcomes in technology product and services settings, and explored an ecosystem approach to represent relationships that developed among different technologies. An *ecosystem* is a set of interrelated technologies with specific *technology roles* and overlapping *technology hierarchies*. The ecological term "ecosystem" emphasizes the organic nature of technology changes and interactions among stakeholders and technologies.

Adomavicius et al. (2008a, 2008b) developed useful tools for IT analysts and decision-makers to identify past and assess future IT innovations, with an emphasis on digital music and wi-fi technologies. Adomavicius et al. (2012) demonstrated cross-level effects in wireless networking, and validated the existence of *paths of influence* for the impacts of innovations across technology roles within the ecosystem. This approach only models supply-side forces of new IT components, products and infrastructure, but ignores the demand side, so it is less generalizable. In settings with financial IS and technologies, stakeholders play a critical role in the evolution of technology. We also consider influences and actions of a range of stakeholders in financial markets. They act as accelerators or decelerators of industry changes.

2.4. High-Frequency Trading Technology

Algorithmic trading is commonly defined as the use of computer algorithms to automatically make trading decisions, submit orders, and manage orders after submission. Algorithmic trading has improved market liquidity and enhanced the informativeness of price quotes in the market (Hendershott et al. 2011). HFT is a type of algorithmic trading that differs from others due to its use of technology for processing information that supports very fast trade execution, and its implementation of trading strategies that result in a large number of trades being made on a daily basis (Brogaard et al. 2014, SEC 2010).

HFT has received attention from academic researchers in recent years. Their articles have focused on how HFT impacts market conditions, such as liquidity (Hendershott et al. 2011, Hendershott and Riordan 2013), price discovery (Brogaard et al. 2014), and prices (Hagstromer and Norden 2013, Kirilenko et al. 2014). Brooks (2012) pointed out that the increased trading volumes with HFT technology deserve more careful analysis. They change over time and may provide a misleading indicator of the health of the underlying financial market. Moreover, the veiled relationship between electronic trading technology innovations and market performance has not been studied in depth yet. We fill this gap by augmenting technology ecosystems theory with a stakeholder analysis and applying it in an historical assessment of the evolution of HFT technology.

3. ANALYSIS APPROACH AND KEY CONSTRUCTS

We next will define a financial IS and technology ecosystem in greater depth.

3.1. Financial IS and Technology Ecosystem

Uncertain technological changes and complex market hierarchies contribute to the difficulty of analyzing technology evolution in financial markets. To address these problems, we introduce the *financial IS and technology ecosystem*, a set of technologies related to one another through some functionality or services, and incorporating various *stakeholders* such as customers, financial firms, or regulators. Stakeholders affect one another through their actions, and are affected by technology innovations. They are not unique to financial IS and technology ecosystems, but instead occupy a role that is important in many different kinds of technology innovation settings. This is important for the broader contribution of this work.

3.2. Technology Roles

Technologies play three roles in an ecosystem: *components*, *services*, and *business infrastructure*.

The component role. The components represent technologies necessary to support the functionality of financial services. If various technologies (encryption algorithms, access controls) act as components for financial markets, only certain components may be necessary for electronic trading: the order book, computer programs and algorithms, telecomm network support, etc. The difference between technology components and services is that the former act as sub-units or sub-systems of the latter. Designers combine components and modules of multiple components into services to address users' financial needs.[5]

The service role. The service role of technology is customer-facing, and provides customers with access to a broad spectrum of financial services. We typically see a *focal technology* and other related technologies in direct competition in the financial industry. An example in electronic trading is HFT. It accounts for more than half of all trades in the U.S. stock market (McCrank 2014). HFT is user-facing and performs a service role, supporting low-latency arbitrage, front-running and liquidity rebate trading, and directional trades based on news releases, order flows, or other trading signals (McGowan 2010). Other e-trading technologies, such as program trading, and manual trading with automated data monitoring and consolidation of information, compete with HFT and act as competing technologies in the ecosystem.

The business infrastructure role. This role identifies technologies that add value to the functionality or performance of the service role. Business infrastructure technologies create the basis for the provision of services to customers. ECNs perform in this role as financial market trading systems, for example. They facilitate trading on major exchanges during market hours, and are used for after-hours and foreign currency trading too. Business infrastructure capabilities also extend the functionality and provide additional value-added capabilities and services to customers. An example is market-wide value-at-risk (VaR)-based risk management tracking systems, which enable firms and regulators to manage and oversee trading activities. Another example in the HFT ecosystem relates to online social media. They are not neces-

[5] For example, computer programs and algorithms are standard components for many electronic trading technology services. Computing devices also consist of a set of component technologies, including hard disks, monitors, and connectivity with an exchange for transactions. This indicates the importance of identifying the context of use and defining the scope of the financial IS and technology ecosystem.

sary for algorithmic trading, but offer a new channel for real-time newsfeeds.

3.3. Paths of Influence

Paths of influence enable us to represent the impacts of technology-based financial innovation across different technology roles (Adomavicius et al. 2008a). Technology innovation that plays any of the three roles can cascade through the other roles, resulting in subsequent innovations. For example, consider the success of the adoption of ECNs. On April 20, 2005, the NYSE announced that it would become a publicly-owned company and merge with Archipelago, a successful ECN. This altered the operation of stock markets in the U.S., and led to the development of new e-trading technologies, decreased bid-ask spreads and transaction costs, and increased execution efficiency and annual turnover. This represents the introduction of a new infrastructure influencing the development of innovative technologies and services.

We use C, S, and I to represent the *present state* of technologies in the component, service, and business infrastructure roles. We use an asterisk for the *future state* of a technology role. With this notation, we can analyze interdependencies over time and address the complexity of the relationships among them, to identify trends in technology-based financial innovation. Consider an example: the emergence of market-wide financial risk management based on VaR and data analytics. These developments originated in the 1990s at Bankers Trust and J.P. Morgan, and eventually reached market-wide application in 1998 (Han et al. 2004). The paths of influence for these innovations is: $C \rightarrow C^* \rightarrow (C^*, S^*) \rightarrow (C^*, S^*, I^*)$.[6]

3.4. Stakeholder Actions

Modeling supply-side development-related paths of influence alone is insufficient to provide a full explanation for what we have observed. Interactions among organizations and individuals in the ecosystem influence the technological evolution paths too, as Van der Valk et al. (2011) and others have pointed out. We will extend the earlier approach to include a *stakeholder actions perspective*. Stakeholder actions may have a positive or negative influence on technology innovations, often resulting in changes in profit, losses or gains, beneficial network effects, goodwill and social welfare (Au and Kauffman 2008). Suc-

[6] The parentheses suggest that, after some component innovations with the computational aspects of financial economics for risk management were achieved with the support of advanced computing technologies and hardware, the firms migrated these capabilities to form new in-house technology services, and made them market-supported and industry-wide via telecom capabilities.

cessful paths of innovation need participation and cooperation of many stakeholders in alliances to establish a set of common operational, process and technology standards. Considering stakeholder actions related to technological innovations is critical for mapping the paths of influence and patterns of evolution. In view of the influence of different stakeholders' strategies related to technological change, it is useful to define four different stakeholder actions: push-forward, pull-back, and strategic alliances to speed and to stall innovations.

Push-forward. This occurs when a stakeholder plays an active role in adopting a technology innovation, setting up a standard, or investing in business infrastructure construction. The London Stock Exchange's (LSE) Big Bang on October 27, 1986, is an example in which an influential stakeholder – a government regulator – pushed forward and accelerated the evolution of an innovation (Clemons and Weber 1990). Extensive regulatory reform was accomplished with the LSE's screen-based dealing system implementation. The application of the technological innovation driven by regulatory pressures has caused the LSE to continue to operate smoothly and appropriate a number of benefits. The arrival of sweeping and long-awaited technology-support deregulation pushed the evolution of technological innovation in the United Kingdom's financial market forward and benefited multiple stakeholders.

Pull-back. This action occurs when a stakeholder decides against adopting a specific technological innovation or setting up a new or competing technology standard. This typically has the effect of slowing down or even blocking the paths of influence for technology evolution. An example is field-programmable gate-array chips, and high-speed telecom protocols, such as InfiniBand and 10/40 gigabit Ethernet (10 billion bits per second). These offer the capability to trade at high speeds with low-latency direct market access. They create out-of-software hardware acceleration. Advances in IT support orders, data transfers and confirmations in 10 milliseconds (Mellanox Technologies 2013), faster than before and at a lower price (Durden 2009). The downside is that risk controls are less stringent due to the competitive pressures for trade execution (Chakraborty 2012). U.S. Senate (2009) hearings in October 2009 on dark pools, flash orders and HFT assessed the performance of computerized trading venues and algorithmic trading. Market practices for HFT began to change, which caused HFT's share in the U.S. to fall from 61% in mid-

2009 to 51% by late-2009 (Popper 2012).[7] A stakeholder, the regulator, slowed innovation.

Strategic alliances. When the action of an individual stakeholder is insufficient to push forward or pull back an innovation, firms seek partners for *strategic alliances to speed or stall it.* Difficulties with alliances arise though: stakeholders have different capabilities, business models, and interests. Alliances promote collaborative, not individual advantage. Different stakeholders cooperate to form *partnerships for perfection* of operational capabilities and *alliances for joint advantage* (Dai and Kauffman 2004).

Strategic alliances offer opportunities for stakeholders to produce value-creating services capabilities at scale to save development costs too. An example is ECNs to facilitate off-exchange trading.[8] The merger of NYSE and Archipelago in 2005, and between NASDAQ and Instinet increased market-wide e-trading (Stoll 2006). Competition from ECNs and regional exchanges, and regulatory pressures forced them to consider *co-opetition* (Brandenberger and Nalebuff 1996, Teece 1992). Strategic alliances by market leaders helped them to discover ways to accelerate and appropriate value from innovations.

Stakeholders do not always reach a consensus about the value of technological innovations though. This can result in a strategic alliance causing an innovation to stall. Due to the risks and uncertain market responses that may accompany new technology innovations, key stakeholders may collude to slow down or block adoption of a technology as a form of *collective resistance*. This will not hold back a valuable technological innovation for long in the market though. It may permit the stakeholders to quickly regroup, adjust their strategies and technology investment plans, and consider how to experiment with the new technology or find ways to partner with the technology innovator.

An example is the OptiMark Trading System, created in the mid-1990s.[9] OptiMark offered a new "three-dimensional" trading environment for institutional traders, allowing the typical quotes for price

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[7] For alternate estimates of the high and low percentages of HFT of all equity trades, please refer to Iati (2009), who estimated HFT trading at 73% of the total on the NASDAQ exchange. Another source is Stebbins (2013), who estimated that HFT activity accounted for 60% of all futures trading at exchanges in the U.S.

[8] ECNs were widely adopted after the SEC (1998) authorized their existence with its Regulation of Alternative Trading Systems (ATS) rules.

[9] In the late 1990s, OptiMark Technology Inc., together with its major stakeholders General Atlantic Partners, Softbank, Dow Jones, American Century, Goldman Sachs, Merrill Lynch, Credit Suisse First Boston and Paine Webber, built OptiMark Trading Systems. It was intended to support the trading of large block orders by applying advanced IT in NASDAQ for U.S. over-the-counter (OTC) equities and at the Pacific Exchange for U.S.-listed equities (OptiMark Technology 1999).

and quantity to be supplemented with the strength of the trader's preference to buy or sell. The market's response was disappointing though. Twenty months after its initial launch in 1999, OptiMark was unable to attract sufficient order flow from institutional traders; they criticized the interface and matching algorithm for their complexity (Clemons and Weber 1998). Its closure in 2000 illustrates the difficulty of aligning the interests of innovators, investors, traders and regulators to push forward the adoption and diffusion of financial market IT innovations.

4. PATHS OF INFLUENCE ANALYSIS FOR THE HFT ECOSYSTEM

We now analyze the paths of influence for the evolution of electronic trading technologies.

4.1. The HFT Technology Ecosystem

We extend the four-step technology ecosystem analysis of Adomavicius et al. (2007) by adding stakeholder analysis, and applying it to the HFT technology ecosystem. Our purpose is to understand the influence of different groups of stakeholders on the technology innovations within the HFT ecosystem, and the relationship among technologies with different roles relative to the provision of electronic trading solutions. This will serve as a basis for interpreting how the market has developed and will evolve further:

- **Step 1 (Identification of stakeholders).** *All stakeholders that are relevant to a specific technology-based financial innovation must be identified for this analysis.* The HFT technology ecosystem has various stakeholders, including investors and issuers, traders, infomediaries,[10] brokers, financial intermediaries, market-makers, exchanges, financial IS and technology services providers, as well as government regulators.

- **Step 2 (Identification of focal technology and context).** *Identification of a focal technology is the starting point for mapping out the ecosystem, and a specific context of use*. HFT technologies represent the focal technology in the ecosystem and they support the electronic trading context of use, as well as the creation and provision of services for issuers, investors, and intermediaries.

- **Step 3 (Identification of competing technologies).** *Identification of other types of technologies that may compete directly with the focal technology, or provide similar services or functionality within the context of interest is important too.* Program trading (index arbitrage, large-volume trades, etc.) and manual trading solutions with automated monitoring of data and consolidating information are the competing technologies in the HFT context.

[10] An *infomediary* generates revenues "from helping consumers both protect and enrich themselves by capturing their own customer information and then selling it to the many companies that are now getting that information for free" (Hagel and Singer 1999a). For a fuller discussion, the interested reader should see Hagel and Singer (1999b).

- **Step 4 (Identification of component technologies).** *Identification of technologies that are used as components related to the focal and competing service technologies is the next step*. In the HFT ecosystem, the component technologies include microchips, telecom networks, data collection and storage, program code and algorithms, high-performance computing, and data analytics.
- **Step 5 (Identification of business infrastructure technologies).** *Finally, we must identify technologies that work in concert with services role technologies to increase the value available to investors and other stakeholders in the overall services platform.* This set of technologies may include ECNs, online social media support, and financial risk management systems, among other things.

We next develop this perspective further related to two aspects: stakeholders and the technologies.

Stakeholder analysis. We first characterize how stakeholders' actions can affect the paths of influence in the ecosystem.[11] Recognizing the range of stakeholders' impacts is helpful to understand how an HFT ecosystem will develop, and how it ties in with our paths of influence thinking. Figure 1 depicts stakeholders in the HFT ecosystem and classifies the potential impacts of their actions.

Different stakeholders are arrayed around the points of the compass (Au and Kauffman 2008). To the north are financial IS and technology services providers, which often are technology companies, but may also be high-frequency traders themselves, and even financial intermediaries or exchanges. Good examples are microchip technology vendors and semiconductor manufacturers. Fixnetix developed a microchip that can execute trades in *nanoseconds – one billionth of a second* (Stafford 2011).

To the south are investors and issuers, which are at the opposite end from clients and services. They act as value-takers in the presence of the innovation-creating value-makers (Kauffman and Walden 2001). Issuers create capital by issuing stocks or bonds. Retail and institutional investors contribute their capital. It is important to bear in mind, related to the Fixnetics example, the lengths that technology providers have gone to support the "arms race" we described earlier. The reader should keep in mind that there is a *zero-sum game* aspect to developments such as this though, and some investors and issuers may not be beneficiaries, but instead may be harmed. If such technology innovations help to empower certain inves-

[11] In prior research, we defined a *robust framework* as providing "*a basis for effective analysis of some related technological innovations, based on a set of dimensions that maintain their validity over time and across different settings and applications, and that also permit the analyst to assess relevant theories, organizational strategies, industry transformations, technology impacts, and so on, through the framework's lens*" (Au and Kauffman 2008, p. 146). This is our purpose: a framework creates the capacity to make observations about the HFT ecosystem with respect to the components, services, infrastructures and stakeholders.

tors and trader, the profits that they achieve will come as a direct result of losses by others in the market.

An important aspect of the financial services industry is the use of intermediaries. To the east are intermediaries, including high-frequency traders, financial infomediaries, brokers, market-makers, and exchanges. They facilitate services such as routing, matching and settling trades. They are also major sponsors of HFT technology innovations; they smooth the adoption and diffusion of disruptive trading technology innovations in this ecosystem. There is no clear demarcation among intermediaries, issuers and investors, since some intermediaries act as investment banks that trade for themselves. In the western economies, we see government regulators that track HFT practices, monitor market quality, regulate market participants, make market rules, and improve market efficiency and liquidity through a variety of market and public policies. Intermediaries and regulators appear on the opposite sides of the framework, since actions from one may lead to impacts identified and strategic actions taken by the other.

The framework depicts two different levels of stakeholder impacts on innovations using a set of concentric circles. The inner circle contains the micro-level impacts. The intermediaries' efforts to use HFT narrows the bid-ask spreads, increases trading speed and volume, and reduces transaction costs. HFT supports market liquidity and execution efficiency in terms of five microstructure properties of the financial market: tightness, immediacy, depth, breadth, and resiliency (Ibikunle 2012, Sarr and Lybek 2002). In addition, price efficiency on the exchange also increases: a liquid market enhances the efficiency of the price discovery process (O'Hara 2003, Chordia et al. 2008). Financial IS and technology service providers' participation in the new round of competition of technology innovations may generate limited or significant competitive advantage for the adopters of these innovations, if only for a time (Josefek and Kauffman 1997). Investors and issuers are able to achieve a higher level of informedness in their market operations, while bearing lower investment risk and generating higher returns from their HFT activities.[12]

[12] Some observers have commented that this may be a destructive force, however, when the adoption of technological innovations leads to the loss of control by firms that are operating in the market (Patterson and Strasburg 2012). For example, in September 2012, Dataminr (www.dataminr.com) launched a new technology-based market signal detection service that can turn social media data streams into actionable trading signals, with US$30 million of funding to build its systems capabilities (Brokaw 2012). It helps report the latest business news up to 54 minutes faster than conventional news coverage. In November 2012, however, the U.S. Federal Bureau of Investigation (FBI) began to look into the use of social media as a form of security fraud, due to the instant impact of stock market-related sentiments on asset prices (Goldstein and Ablan 2012).

The outer concentric circle represents macro-level impacts of government regulators. They supervise the use of new technological innovations and set up regulatory interventions and tax policy revisions that influence other stakeholders' market activities. For example, after adoption of social media streams as a source of news coverage, in April 2012 the SEC and the Commodities and Futures Trading Commission (CFTC) issued a commentary on social media use for public firm announcements (CFTC 2012).

In general, when disruptive technology innovations have come into the capital markets, greater value typically is generated for most of the stakeholders. Nevertheless, when issues such as fraud or sudden market crashes arise, regulators have to make new regulations and policies to re-stabilize the market and guide stakeholders' activities in order to engender investor market trust.

Technology ecosystem analysis. We next consider the other part of the HFT technology ecosystem: technologies that play the components, services, and business infrastructure roles. See Table 1. The potential interactions among these technologies roles are depicted in Figure 2.

Figure 2 considers the focal technology, HFT, and competing technologies, manual and program trading, as the middle level indicated as service role of technologies. There are two additional levels: the business infrastructure-related technologies present in the ecosystem and the component technologies that support them. Although this depiction of the structure of the HFT technology ecosystem is limited in its richness, it is nevertheless relatively complete in its coverage. It also is possible to reflect that, at a specific point in time, the components, services and infrastructures played different roles than they do today.

4.2. A Paths of Influence Analysis for the HFT Technology Ecosystem

To substantiate our approach, we next provide an empirical validation of the paths of influence for innovations in the HFT technology ecosystem. Electronic trading technologies have been around since the 1980s. During the ensuing years, there have been many technological changes in this ecosystem. They span the capital and commodities markets in financial services and other area that generate capital through equity issuance and trading (investment management, hedge funds, algorithm traders). Our empirical validation seeks to identify the patterns of technology evolution by coding trading-related technologies into three different roles, and representing the technology changes using a *state transition diagram*.

Data collection and description. We gathered relevant data between the 1980s and 2010s on industry announcements, news for multiple sectors, government reports and surveys, and publicly-available historical records related to electronic trading technologies. We also conducted interviews with industry practitioners, executives and analysts to get relevant information.

We obtained announcements on about twenty technology innovations in HFT. We coded them into three roles: the component, service, and business infrastructure roles. We explained technology trends using information on the timing of related technology releases and their application, development and deployment. An example is the introduction of the designated order turnaround (DOT) system in 1976 and later SuperDOT in 1984 at the NYSE (Hasbrouck et al. 1993). SuperDOT enabled the direct routing of orders for listed securities to specialists on the trading floor, increasing market efficiency.

We also collected information about stakeholders' actions and related technology innovations. We characterized them as different forces that drive innovation. For example, in 1983 Bloomberg built its first computerized system to provide real-time market data with a US$30 million investment from Merrill Lynch. Since then, financial consultants and Wall Street analysts have stressed the capabilities of computerized systems to acquire, monitor and consolidate information on orders for various financial instruments. In the 1990s, the introduction of ECNs and a Regulation on Alternative Trading Systems (ATS) supported development of off-exchange electronic trading venues that match buyers and sellers for transactions. This pushed forward HFT innovations and practices. After 2005, the release of Regulation NMS and continuing advances in computing technology began to drive market demand for more sophisticated algorithms and execution efficiency, transforming some stakeholders' prospects for creating new revenues and profits in equity market trading. HFT constituted 35% of equity trades in the U.S. in 2005, and this number increased to approximately 70% by 2012, though this share diminished later. Table 2 shows our data collection, listing years and events in the HFT technology evolution process.

Categorizing paths of influence in HFT. The evolution of electronic trading technologies has been driven by a combination of supply-side and demand-side forces. Both paths of influence and stakeholder actions may trigger the introduction of a new technology or the improvements to an existing technology in the markets. For example, since 2005, the emergence of low-latency arbitrage and trading based on news releases, order flows and other trading signals has been influenced by the technologies in all three roles, as well as the push-forward actions of the regulators and other stakeholders.

To interpret the interactions between stakeholder actions and technological innovations, we classified their impacts on each other in a systematic way. For example, the capability to trade with low-latency, direct market access encouraged innovation in speed-of-light, microwave data transmission technology. This *component integration and evolution innovation* is represented by a C → C* path. Regulation NMS set the stage for development of HFT since 2005, and market participants began to refine their trading programs and algorithms. This can be represented by a *service-driven component development innovation* path, S → C*. And the integration of social media streams into trading signals influenced the development of new algorithms for stream data analytics with social media data, represented by an *infrastructure-driven component creation innovation* path, I → C*. These are all *component-oriented paths of influence*.

Similarly, *service-oriented paths of influence* include: advances in microchips for nanosecond trade execution became possible through the development of new trading technologies, represented by this *design and compliance innovation* path, C → S*. The decimalization of stock quotes in 2001 further pushed forward the practice of algorithmic trading, as represented by a *service integration and evolution innovation* path, S → S*. And use of risk-adjusted return on the capital (RAROC) in financial risk management resulted in trading strategies as an *infrastructure-leveraging service creation innovation* path, I → S*.

Finally, we identified *business infrastructure-oriented paths of influence*. The automation of trading processes led to the introduction of Regulation ATS in 1998, and then the emergence of ECNs, which is represented by a *standards and infrastructure development innovation* path, C → I*. New infrastructure co-location services were developed when higher-speed trade execution was sought after, to minimize the latency of communication to the computerized system of the exchanges, as represented by a *diffusion and adoption innovation* path, S → I*. The emergence of new business infrastructure, especially the launch of social media such as Facebook and Twitter, has provided a new impetus for additional ways to support electronic trading via an *support integration and evolution innovation* path, I → I*. (See Table 3.)

Identifying evolutionary patterns for HFT. The events that occurred in the HFT technology ecosystem also represent the patterns of innovation evolution, based on technology roles and paths of influence thinking. We next provide a visual mapping of these changes using *a state transition diagram* to depict the innovations that emerged in this ecosystem and to map HFT evolution over time. (See Figure 3.)

The figure shows thirteen periods in the timeline. The arrows represent the paths of influence identified after coding the related technologies into roles. The arrows in each period represent empirical observations of HFT's evolutionary patterns. Hollow and solid arrowheads differentiate the drivers on the technology and stakeholder sides that form them. As in Figure 3, we identified five patterns (#1 to #5).

Service development. The first is the *service development pattern*, which occurs when the innovations are clustered in the component and service technologies areas (Adomavicius et al. 2008a). The component and service technologies were being refined and gained greater attention over time. The evolution of HFT started with the automation of the security trading process in the 1980s. The emergence of program trading, the decimalization of price quotes at the stock exchanges, and the evolution of computer chips and trading algorithms all populate the *service development pattern* of technology evolution.

Service and infrastructure alignment. The second is the *service and infrastructure alignment pattern*. The push forward actions associated with Regulations ATS and NMS represent a service and infrastructure alignment pattern. The observed empirical developments occurred due to key service and business infrastructure technologies that were present, but not component technologies. They presaged the move to decimal bid-ask quotes, and stimulated development of component and service technologies.

Feed-forward, feed-back. Our other empirical observations suggest the presence of *feed-forward* and *feed-back patterns*. The feed-forward pattern typically involves a new service that becomes feasible in the presence of a new component or a new infrastructure. The introduction of ECNs, social networks, nanosecond trading technology and infrastructure co-location services all represent a feed-forward pattern in the evolution of HFT technology. The feed-back pattern, in contrast, involves a new service motivated by the development of a new business infrastructure that enhances it. New components may be possible due to the development of business infrastructures and services. In the HFT development process, we observed the appearance of a feed-back pattern when new infrastructures and services, such as financial risk management and social media news streams, became available to aid trading algorithms and strategies.

Incremental evolution. The last one, the *incremental pattern* of technology evolution, occurs when new components make subsequent component innovations possible, or when new services beget subsequent service innovations, and so on for business infrastructures. The regulator may hold up application of the technologies to ensure stability and maintain market performance. The 2009 pull-back actions to slow widespread adoption of HFT and the 2013 social media developments are incremental patterns.

We conclude that there is evidence from demand-side and supply-side forces that affected the paths of influence. If the adoption of a key technology is blocked or slowed by stakeholder actions, the pattern that uses the component will be affected. Stakeholders' actions, on their own behalf or in coalitions, are able to slow down new services development, change the patterns of technology evolution, and cause their evolutionary paths to shift. Similarly, stakeholders may push a technological innovation forward, and partner for perfection or attempt to build advantage to accelerate services development.

The visual representation of evolutionary patterns, as in Figure 3, enabled us to understand and assess next-generation innovations in the HFT ecosystem. The future state of the HFT technology will be likely to continue to be characterized by new components and services technology innovations that support more advanced features and functionalities. For example, high-frequency traders are now competing to develop extraordinarily high-speed and sophisticated computer programs for generating and routing orders to execution. They also are trying to minimize network and other types of latencies by using co-location infrastructure services and data feeds offered by exchanges and other channels. Such advances allow high-frequency traders to submit many orders that can be canceled shortly after submission.

5. DISCUSSION AND MANAGERIAL IMPLICATIONS

Based on our historical analysis and observations about the paths of influence and technology evolution in the HFT ecosystem, we next discuss some factors that affected HFT innovations along with the evolutionary process of electronic trading technologies. We also offer managerial implications to support managerial decision.

Our paths of influence analysis suggests that HFT technology evolution of late has been faster compared to the 1980s and 1990s. The performance of new technologies has been improving, and this has created the impetus for even more innovations from the technology side. Also, incentives and positive responses from stakeholders, especially the regulatory agencies' guiding actions, have created a supportive environment to speed up new technology-based innovations in financial markets. Not everything we have observed – including the developments related to clearing and settlement, pre-netting and the hold-back of trade data – has been supportive of more rapid growth. Instead, the emphasis has been on safe growth in recent years, as a basis to support the future diffusion of HFT capabilities.

Our empirical observations suggest an important conclusion: that *initiatives and incentives from the technology and stakeholder sides have been aligned reasonably well, with the result that they generally were able to accelerate the historical pace of technology evolution in the HFT ecosystem*. An important reason for the recent acceleration in technology innovation in the HFT area is the relative *newness of the technology*. In the presence of continuous innovation, the related impacts can be incremental or achieve "breakthrough" levels of transformation (Zhou et al. 2005).

Some historical events from the innovation timeline in Figure 3 support this statement. The first ECN, Instinet, was established in 1969, but only after the 1996 NYSE-Archipelago merger was electronic trading widely adopted. Twitter was founded in 2006, and shortly after began to be adopted by high-frequency traders. They have incorporated live tweets into their trading algorithms since 2012, as a way to assess developing news in the market, representing accelerated diffusion.

The performance of new technologies also has improved in comparison to earlier technologies, and in many settings this created a profound impact on adoption, diffusion and follow-on innovation (Sood et al. 2012). First, after critical mass adoption or a period of rapid improvement in performance, development of existing technologies may be slowed by stakeholder actions; they may also have reached maturity, or been inappropriate for new investment (Brown 1992). Second, newer technologies engender greater market interest and investment, and firms value the greater *present value of growth opportunities* (PVGO) that new technologies can create. Third, similar benefits are likely to accrue to consumers when new levels of performance are demonstrated. Due to performance improvements stemming from new technology innovations, trade execution efficiency, transaction volume and market liquidity have all increased dramatically since 2006, and HFT now accounts for most of the equity trades in markets around the world.

The actions of stakeholders on the demand side to push innovations forward contributed to the faster pace of HFT evolution as well. They helped to establish a supportive environment for technology-based financial innovations to attract investments and diffuse at a faster speed. In recent years, the capital market has changed, creating an environment characterized by: increasingly higher technology and R&D investments; new stakeholders' involvement in various market activities across different industries; and continuing advances with existing technologies and the emergence of new technologies. As a result, the current market exhibits a Darwinian diversity of financial products and services, lower transaction costs and higher liquidity, and more effective market monitoring and regulatory processes than ever before.

Let's turn to another question now. How has competition among technology providers affected the evolution and performance of HFT technology? MacCormack et al. (2013) have suggested that supply-side technology competition often triggers breakthrough ideas and spurs new innovations. This has indeed happened in the financial IS and capital market area related to HFT.

In our view though, an even stronger assertion is possible though: that *supply-side competition and demand-side support have created more frequent improvements in the performance of technologies, leading to transformational innovations for the HFT marketplace.* First, historically, competition among technology providers has encouraged cooperation among a diverse pool of stakeholders with different strengths and capabilities. Second, a large number of different stakeholders have been willing to invest in HFT innovation and R&D. Third, as the number of competing technologies increases, their supporters have to push harder to promote them and demonstrate higher performance potential. Innovation comes faster as a result. Fourth, innovations based on new technologies also may deliver opportunities in dimensions for improvement that were not available via earlier technologies. Finally, the returns from investing in innovation are larger at the margin in an oligopolistic than in a monopolistic market, which favors new technology firms that have come in, challenging market incumbents (Fellner 1961). As a result, more intense competition and perceptions of higher future opportunities have resulted in more capital becoming available for the provision of technology innovation and services improvement, leading to a faster pace of evolution.

On the stakeholders' side, the regulators have largely relied on and encouraged technological competition to address abuses that occurred during the earlier era of floor-based trading. For example, the competition among various trading venues encouraged by Regulation NMS has enabled alternative venues to take away trading volume from the NYSE and NASDAQ. This also facilitated the entry of HFT-capable market-makers and the related technologies they have used (Menkveld 2013). As new electronic trading technologies have become available, markets have lower transaction costs, higher market liquidity, and narrower bid-ask spreads. This suggests that the performance of the related technologies has improved.

Technology changes in the HFT content have been relatively smoother lately, while in earlier years the evolution was discontinuous. Faster and higher-impact innovations have opened the way for even more beneficial technology changes. The performance of existing technologies frequently improves when there is a possibility of an extraordinary payoff looming ahead. There is fierce technology competition and the participation of stakeholders who believe they have the right kinds of technology solutions to make an impact and cash in.

Though there are risks and uncertainties associated with irreversible investments in technology, firms still will have the flexibility to decide whether and when to adopt a new technology (Dixit and Pindyck 1994). Sometimes they may have an incentive to postpone adoption to a later time, when the technological risks are resolved and the future payoffs of adoption come into clearer focus. HFT technology has a winner-take-all nature to it though. This creates strong *first-mover advantage*: when a new technology is able to support faster trade order submission and execution, there is a huge profit opportunity for the adopter to benefit from. This makes it more likely that a firm will make a commitment to invest in an immature technology, decreasing its flexibility to make other investments (Mason and Weeds 2010).

We have observed that many new technological issues associated with HFT arose in the market, leading to failures, error, fraud and financial losses in the historical timeline of the HFT ecosystem that we have studied. Recall for this context the example that we briefly noted earlier. On August 1, 2012, Knight Capital, one of the largest market-makers in U.S. equities, introduced a new trading algorithm in its automated order routing system without sufficiently testing it. It accumulated large positions in 148 NYSE-listed stocks over about 45 minutes as a result of a glitch in the software, and incurred estimated losses of between US$440 and US$460 million, leading to Knight Capital's acquisition by another firm (SEC 2013a). Again, consider the zero-sum game at work here: Knight Capital's losses were profits for others.

Another example occurred with the initial public offering (IPO) of Facebook stock on May 18, 2012. NASDAQ encountered serious computer problems: its software was not able to handle the pace of order submissions and cancellations by human traders and computer algorithms until 2:00 pm the following day (Popper 2013). This caused millions of dollars of losses to investors and their broker-dealers. These problems created a need for regulatory oversight to ensure adoption of technology innovations did not damage the overall quality of the markets. Regulators in the HFT area were needed to provide guidance to stakeholders so they could identify and obtain the benefits of truly valuable innovations. Thus, for the HFT context, it appears that *technological risks and uncertainties created freedom for a greater variety of innovations, as well as the concomitant necessity for regulatory oversight to guide them.* These observations further underscore the important role of regulators as stakeholders that have a high vested interest in maintaining fair, orderly and social welfare-producing financial markets.

Industry practitioners need to understand the patterns of technological change, the evolution of electronic trading technology, and the innovations that are likely to emerge in the future. Recent advances in online social networks, data analytics, and nanosecond trading technology and the likelihood of continuing regulatory changes have created questions about future capital markets. The conclusions reported in this section are based on our empirical observations. We recognize that more structured data beyond key historical events in the market will enable fuller empirical validation. Our work is nevertheless an important step forward for the creation of useful tools for managerial prediction and technology ecosystem change forecasting, even if the present analysis has not delivered this additional capability yet.

6. CONCLUSION

Analyzing and assessing technological innovations in financial services sector has been a difficult but important problem. In this article, we proposed a *financial IS and technology ecosystem perspective* that is useful for this purpose, by incorporating technology roles and proposing the new application of stakeholder actions. By considering the role that stakeholders play, as well as their potential impacts, we have been able to characterize some of the factors that affect the paths of influence in the HFT technology ecosystem. We used a graphical coding approach representing technology components, services and infrastructures, and the roles they play in technological innovation, as a basis for our analysis. We supplemented this with the inclusion of different kinds of stakeholders and their respective push and pull actions within the ecosystem. We have been able to identify evolutionary patterns within which complex relationships can be observed between technology and the transformation of financial market. This approach also builds a theoretical and procedural basis for the assessment of the future state of the electronic trading technology ecosystem, and analyzes the effects of different stakeholders' actions.

This study contributes new knowledge in two ways. First, we proposed a new theoretical perspective. It emphasizes supply-side and demand-side forces as key drivers of technology changes and innovations in financial services markets. We especially emphasized the forces that different stakeholders create and may affect the observed outcomes. We constructed an approach that combines demand and supply dynamics to complement the technology ecosystem approach. By integrating the effects of innovations from these two sides, our research bridges the gap between the studies on innovation at the organizational and technology levels. Second, this work demonstrates the empirical applicability of our proposed historical analysis approach in the HFT ecosystem setting. We have used the word *ecosystem* throughout this work to emphasize that our view is a composite one: it's not just about IT, but about the organizational, institutional, relational and regulatory environments too, as well as how they have changed over time.

Our visual mapping strategy to code complex historical events that occurred in the HFT technology evolution process enabled us to validate the existence of several different patterns in the paths of influence. We considered the pace of technology evolution, the competition around it, and the risks and uncertainties too – all based on empirical observations arising from the HFT paths of influence analysis.

The proposed approach also is useful for analyzing other financial innovations that are not technology-focused. Applying the concepts and modeling approach associated with the paths of influence perspective in a financial services product ecosystem is a promising extension to the present work. Nevertheless, note that the observed paths of influence for technological innovation can be affected by many different factors in different business and industry contexts. The approach that we have demonstrated may not be able to capture all of them. Thus, there are ample opportunities for extending our proposed method, applying it to other contexts, and deepening the rigor of the empirical analysis.

Analyzing stakeholder actions, together with historical changes in the evolutionary trajectories that can be observed, supports the assessment of future technology-based financial innovations. Although this is a promising view, and this research has produced a variety of kinds of new knowledge, we nevertheless caution the reader. Our proposed approach – for now at least – will not be able to achieve strong power for future-oriented forecasting. The reality is that there are complex relationships among various dynamic factors, such as technology, competition, public policy, financial institutions, and market regulation. Excluding relevant factors and forces may result in a loss of contextual fidelity and analytical richness, diminishing the capability for the approach to render useful predictions for future technological innovations.

Moreover, limiting the number of predictive constructs that are considered involves a trade-off between complexity and tractability. Thinking about this issues serves a useful purpose though: it encourages a clearer focus on aspects of the stakeholders, the business setting and the observed technological changes that are most likely to drive next-stage technology innovation and ecosystem transformation. Our approach also may benefit from taking into account the role of external forces, such as market dynamics, the demand environment, regulatory forces, and society and culture.

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Figure 1. Stakeholders in the HFT Technology Ecosystem

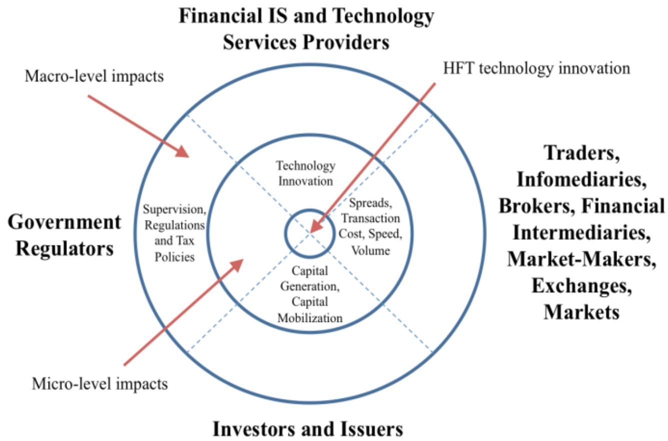

Figure 2. Interactions among the Three Technology Roles in the HFT Ecosystem

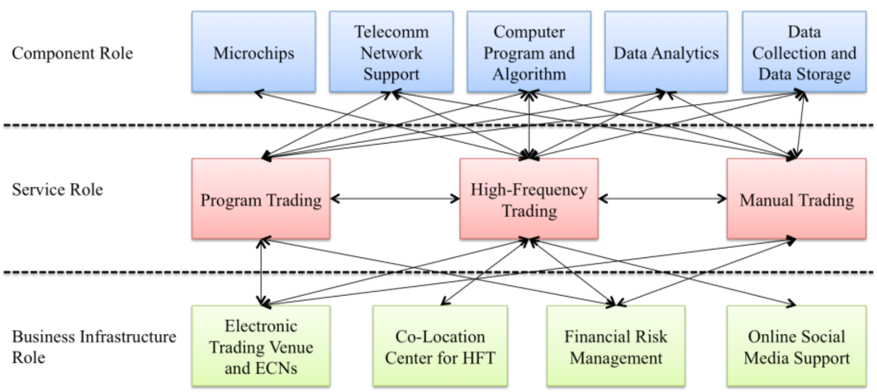

Figure 3. Graph-Based State Transition Diagram for HFT Technology (1983-2013)

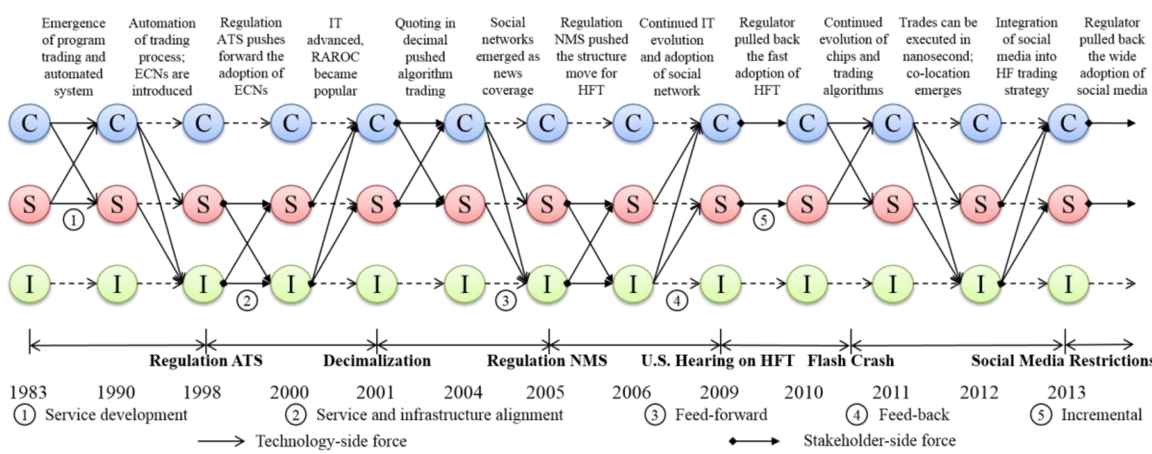

Table 1. Technology Roles in the HFT Ecosystem

ROLE	E-TRADING-RELATED TECHNOLOGIES	COMMENTS
Component	Microchips Telecom network support Data collection and data storage Computer programs and algorithms High-performance computing, data analytics	Different combinations or a synthesis of component technologies support different trading practices. HFT-related innovations involve development of cutting-edge computing, hardware, and telecomm network technologies.
Service	High-frequency and program trading Manual trading with automated data monitoring	HFT and other technologies co-exist with services to issuers and investors, who adopt e-trading strategies to support profits.
Business Infrastructure	Co-location center for HFT firms to provide appropriate infrastructure Electronic trading venues and ECNs Online social media support Financial risk management	Business infrastructure technologies are widely used in trading. They supply data feeds with news and information for traders, minimize trading risks and execution latency, and assist in creating competitive advantage.

Table 2. Key Events in the Development of the HFT Technology Ecosystem

YEAR	EVENT
1980s	The replacement of floor trading with automation of the trading process; and the emergence of program trading
1983	Bloomberg built the first computerized system for Wall Street firms
1990s	Emergence of ECNs
1998	SEC introduced Regulation Alternative Trading Systems
2000	Fast trades had an execution time of several seconds, accounting for only 10% of all trading
2001	Stock exchanges started quoting prices in decimals, encouraging algorithmic trades by ECNs
2004	Facebook was launched and online social media emerged
2005	Regulation National Market System established; HFT made up 35% of equity trades in the U.S.
2006	Twitter was launched and wide adoption of online social media occurred, affecting securities info sharing
2009	U.S. Senate held a regulatory hearing on dark pools, flash orders, HFT and other e-trading issues
2010	HFT execution time decreased to microseconds; HFT made up 56% of equity trading On May 6th, the "Flash Crash" occurred: Dow Jones Industrial Average down by 1,000 points
2011	Fixnetix launched nanosecond trading technology for super-fast trade execution
2012	In May, a glitch associated with HFT struck Facebook's initial public offering, creating chaos for valuation In June, the SEC approved a "limit up-limit down" mechanism in Release 34-67091 In August, Knight Capital incurred losses of US$440-460 million due to software errors in algorithmic trading In September, Dataminr used software to turn social media streams into trading signals HFT was responsible for about 70% of all U.S. equity trades, the year its share in the market peaked In November, FBI began to look into social media as a form of securities fraud
2013	In April, Bloomberg incorporated live tweets into its economics data service SEC and CFTC announced restrictions on public company announcements through social media Data were transmitted at the speed of light via superfast microwave transmission services In September, Italy became the first country to launch a trading levy on HFT trading, discouraging usage

Table 3. Examples of Paths of Influence for HFT Technology Evolution

	COMPONENT-ORIENTED PATHS	SERVICE-ORIENTED PATHS	INFRASTRUCTURE-ORIENTED PATHS
	C*	**S***	**I***
C	*Component integration and evolution* Data transmitted at speed of light via microwave transmission	*Design and compliance* Development of microchips to support new nanosecond trade execution	*Standards and infrastructure development* Automation of trading processes encouraged the emergence of ECNs [(a)]
S	*Service-driven component development* Increase in HFT led traders to refine their trading programs and algorithms [(a)]	*Service integration and evolution* Decimalization of price quotes pushed forward algorithmic trading [(a)]	*Diffusion and adoption* Super-fast trade execution supported emergence of co-location services
I	*Infrastructure-driven component creation* Integration of social media streams as new data feeds for HFT [(a)]	*Infrastructure-leveraging services creation* Widespread use of RAROC assessment in equity trading services [(a)]	*Support integration and evolution* Emergence of social media-led news to support equity trading

Note: [(a)] The examples have paths of influence driven more by the demand-side forces or stakeholder actions.