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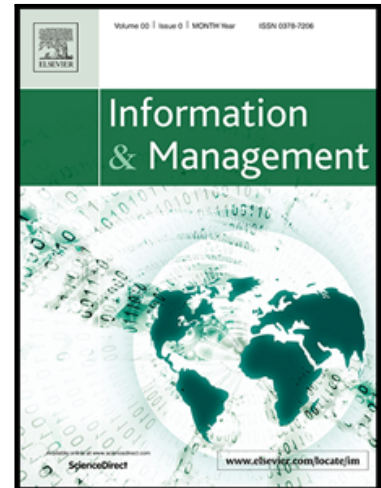


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1. Introduction

Regulation of the US financial system is complex and fragmented. Jurisdictions overlap, with firms reporting to federal and state agencies and numerous industry-sponsored self-governing associations. Gaps exist in oversight and supervisory structures with diverse intermediaries implicated in financial misconduct [1]. Rapidly changing financial technology increases heterogeneity and, by extension, the variables for regulatory oversight [2]. Prior research has focused on the relationship between regulation and innovation, notably on how regulation influences the process through which products and services enter markets, with less emphasis on how innovation shapes regulation [3]. Developments in financial innovation have led to unprecedented growth in new types of instruments and trading strategies [4, 5]. Studies describe how issuers deliberately obfuscate risk in complex securitized products [6]. Others discuss the link between the innovation of derivative instruments and regulatory ambiguity [3]. Building on this work, we examine how government agencies develop policies and practices to regulate technology in financial markets, specifically, regulatory mandates for automated trading.

The motivation for the study was an interest in how information technology transforms financial markets, and more specifically, regulatory decision-making on robotic trading. The focus is on algorithmic software embedded in systems that facilitate algorithmic trading and not on the financial outcomes of trading strategies. High-profile, often disruptive, financial market events generate questions about whether automated trading is a *causal* or *contributory* factor [7]. Other studies, mainly from the management and financial literature, look at how information technology performs the financial markets [8, 9]. Following our literature review, which included government and legal regulatory reports, our research questions seek to answer how information technology (since the early 1960s) impacts financial regulation:

- *How are regulatory decisions on algorithmic trading, especially high-frequency trading (HFT), evolving to keep pace with technological changes?*

- *How can regulators optimize decision outcomes from oversight mandates in collaboration with financial market participants?*

Our empirical focus is on the intersection between financial regulation and information technology, specifically regulatory mandates for automated trading. This is central to social research on contemporary financial markets, as the requirement to police the markets becomes more important and necessary [10]. We use the theory of bounded rationality, which asserts that decision-makers are intendedly rational. It proposes that individuals seek optimal decision outcomes but face limited rationality due to cognitive limitations, incomplete or imperfect data, and information, time, and resource constraints [11, 12]. Our findings show that this activity begins with the regulator seeking information to identify decision criteria and evaluate alternative options. They search for information to optimize decision choices and outcomes; but as they engage in the procedure, a series of constraints inhibit decision-making. The process model that is developed describes how such constraints, ultimately, lead to suboptimal decisions. This paper contributes to the literature on regulation and technology by showing that regulatory decision-making in algorithmic trading eschews optimal outcomes as decision choices are bounded by past and present regulatory regimes, each of which impacts the market, institutional, and technological environments.

We organize the paper as follows. Section 2 literature review identifies interrelated concepts that impact decision-making. Section 3 presents the theoretical context, where bounded rationality is used as a conceptual lens for regulatory decision-making in automated financial trading. Section 4 introduces the research methods, followed by Section 5 providing the data and analysis of the technological impact on financial regulation. In the discussion, we present our conceptual model, and the conclusion summarizes our main findings.

2. Literature Review

Although the impact of market fragmentation, technological complexity, and information asymmetry is discussed individually in the literature, their interrelated effects on regulatory decision making is not fully understood.

First, the global financial market is highly fragmented, receiving attention from policymakers, market participants, media, and academics [13]. How the market is conceptualized depends on how it is defined – globally and nationally. Financial market interaction occurs in cross-jurisdictional environments with diverse market participants [14, 15]. Over six decades, cross-jurisdictional institutional environments enabled by technology have shaped financial regulation. As financial markets evolved, trading venues invested in technology, further increasing fragmentation, but this failed to improve the competition of individual orders for securities. To change this, the Securities and Exchange Commission (SEC) introduced the Regulation National Market System (Reg NMS) in 2005. These laws supported HFT, further exacerbated latency arbitrage, and increased the opportunity for dislocation across trading venues [16]. By 2017, only 50% of equity trading was done at the New York stock exchange (NYSE) and Nasdaq, with the rest across 10 other equity exchanges, 50 alternative trading systems, dozens of large bank trading desks, 13 equity derivative trading options exchanges, and many equity-linked futures markets [17]. Together they offered entry into a virtual fragmented market [18] impacting cost and execution speeds, efficiency, and the stability of financial services.

Second, technological complexity, the consequence of differing market solutions, has revolutionized global financial markets and trading [19]. Over several decades, trading morphed from open outcry pits to fully automated algorithmic trading. Technology transformed the efficiency, speed, and complexity of financial instruments and transactions [20]. Automated large-volume block trading replaced humans. Trading strategies now require complex calculations executed at speeds beyond those of traditional manual processes. In parallel with technology as an enabler of financial markets, technology offers powerful risk oversight tools for regulatory bodies [21]. Regulators require financial firms to deploy technology to calculate and mitigate risk and to show compliance with regulatory mandates. Technology offers the potential to increase the market surveillance of trading activities but obscures accountability through the distinct logic of computer code and analytics. This “automation bias” undermines regulatory oversight and accountability [22]. Innovations in financial technology (FinTech) have further disrupted financial services in fundamental ways [23], with regulators now facing the “*perennial struggle to keep up, or rather, to not fall too far behind*” relentless technological change [10, p. 555].

Modern financial systems viewed as “*dynamically complex*” consist of interconnected components that work together and form a dynamic, which is made more complex by information technology [24]. Banks and financial institutions are the largest corporations by asset size making the complexity of the financial system “*greater than what is knowable*” [24, p. 736].

Third, because of fragmentation and technical complexity, information asymmetry can only increase as automated trading replaces humans. In the 1960s, delays or errors between trading activity and publication via a ticker tape were common. The solution to this problem – the computerized market data system (MDS) – had two different outcomes. For the regulator, reducing information asymmetry benefited the investor. For the NYSE, it increased the surveillance on staff efficacy. Kennedy [25, p. 890] commented, “*computerized finance and electronic telecommunications reproduce material politics of access and social asymmetries of information.*” In today’s market, information asymmetry occurs at firm-specific and systemic levels. Algorithmic traders, notably, HFT firms, develop sophisticated computer systems to gain advantage over competitors. HFTs fiercely protect their intellectual property. Exchange-located equipment, solid-state technology, and artificial intelligence capture and process data faster to generate profit advantages on economically identical assets. Here, asymmetry represents systemic features of market configuration on stock liquidity across locations with different latencies, costs, and transparencies [13]. Dark trading venues are another example of information asymmetry. They emerged in the 1980s’s and offer privacy on large blocks of shares. Unlike a lit exchange where all orders are visible, dark exchanges hide order details, thereby creating systemic information asymmetries between the pool and other exchanges [26]. They are mostly run by investment banks, and by 2014, over a third of all US trading occurred at them [27]. This generated high levels of interest from regulators, with many receiving large fines for illegal trading practices due to lack of transparency and asymmetry. In sum, firm- and systemic-level asymmetries present regulators with difficult decision challenges. Even if the regulator gains access to the HFT algorithmic code and other digital assets, dynamically complex and interconnected financial systems [24] make it difficult to evaluate how code interacts with other systems.

From the literature review, a deeper, more nuanced understanding of regulatory decision-making in automated financial markets benefits from a multidisciplinary approach. Different academic disciplines produce insightful studies on core themes and issues but in isolation of how regulation and technology evolve across market systems, structures, and firms. The combined concepts of market fragmentation, technological complexity, and information asymmetry are imperative for understanding how information technology has revolutionized financial trading, thus creating new instruments for regulatory oversight. Academic disciplines each offer their own interpretation of these concepts, with law, for example, providing interesting analysis on legal and rules-based opportunities and shortcomings in regulatory enforcement, albeit with a tendency to “black-box” technology. Similarly, the information systems literature on the IT artifact of algorithmic trading is relatively silent on the historical, policy, and market changes that have revolutionized financial markets. In particular, how information technology, combined with deregulation, impacts market fragmentation and information asymmetry. In this study, the three concepts guide the research inquiry on how financial regulators, over several decades, have developed regulatory mandates in a dynamically complex and evolving technology-enabled financial market.

3. Theoretical Context

The economic fallout from the global financial crisis of 2007–2008 implicated technology as a causal factor, obscuring regulatory oversight and masking how complex financial products increased risk for customers and investors [28, 29]. The financial crisis fueled by a massive growth in derivative innovation and traded volume, generated products whose risks were opaque [30]. Their excessive use led to the collapse of the US housing market and plummeting real estate security values. Damage to financial institutions culminated in an international banking crisis and an economic recession affecting the lives of billions of citizens. The financial system had become vulnerable and interconnected in ways not understood by “*the captains of finance or the system’s public stewards*” [25, p6]. Responding to the crisis, financial regulators were forced to impose revised mandates on financial companies that once again adapted their technologies [31]. How could regulation, designed to protect the investor, have failed in such a disastrous way?

To understand decision-making in the regulation of information technology in financial trading, Simon's theoretical position on a human agency is relevant. Behavioral accounts view human decision-making as bounded by cognitive limitations. Individuals compensate for these limitations by exploiting known structural environmental regularities [11, 12]. Bounded rationality asserts that decision-makers lack the ability and resources to reach an optimal solution; therefore, they apply their rationality to a limited set of decision choices. Cognitive limitations include the following: (1) the human capacity to process information is limited and (2) humans economize on the cognitive effort by relying on shortcuts. Other factors, including the influence of emotions on cognition and judgment, also contribute to a wide range of biases and errors in decision-making. The concept of *satisficing* illustrates how decision-makers seek solutions that satisfy some aspiration level, rather than an optimal outcome [11, 32, 33]. The theory offers an alternative to the mathematical modeling of decision-making in classical economics (and decision and management sciences) as actors are satisfied with good enough rather than optimal solutions.

Bounded rationality and satisficing applied to financial regulation of algorithmic trading depart from rational choice models that focus on optimal outcomes. Complex decision choices also arise from human judgment, gut feeling, heuristics, panic, and greed. Bounded rationality makes assumptions about the intellectual capacity of individuals, how they attach values to preferences, and access to resources, which facilitate or constrain decision-making. How regulators engage in decision-making despite limited cognitive and informational capability is a relevant question for algorithmic trading [34, 35]. The replacement of humans by automated trading in trade execution and fulfillment re-focuses regulatory attention on how information technology instantiates systemic and firm-specific financial markets. Lacking adequate information to pursue optimal outcomes, decision choices in algorithmic trading rely on satisficing criteria [36].

We observe that bounded rationality has acquired a reputation as a catch-all category that can explain observed deviations from maximizing rationality [37, 38]. The notion that humans are intendedly rational but face limitations is not in itself sufficient to explain decision outcomes. Responding to this criticism, our study uses bounded rationality as a conceptual lens for regulatory decision-making in algorithmic trading, not simply to

reinforce cognitive and informational limitations, but to develop a nuanced understanding of the development and application of regulatory mandates. Theories of bounded rationality are applied in financial market research [39], but no studies are found specifically on regulatory decision-making in algorithmic trading. In using the theory of bounded rationality, our primary aim is to identify the various constraints facing regulatory decision-makers, rather than to evaluate the success or otherwise of regulatory mandates.

4. Methods

Regulatory mandates derive from top-down (command and control) and bottom-up (self-regulation) policies. To gain an understanding of US regulatory decision-making in algorithmic trading, it was essential to examine policies and mandates emerging from the two bodies that had issued them: the SEC and the Commodity Futures and Trading Commission (CFTC). From the literature, it was apparent that, to understand decision-making outcomes, it was imperative to view decision-making as a process. Using a process-data-oriented approach where qualitative data were collected to “*understand how and why events play out over time*” [40, p. 691], we track the regulatory process over several decades, to demonstrate how mandates shape decision-making. The objective was to develop a qualitative case study [41, 42] focusing on current regulatory decrees and practices for algorithmic trading. The research began in 2016 by carrying out a literature review on the singular topics of financial regulation and algorithmic trading. The literature on regulation from law and policy studies [22] combined with studies from management, finance, and information systems directed the research inquiry. An inductive (theory-informed) open-ended approach [43, 44] was preferred over a hypothetico-deductive (theory testing) one [45].

4.1 Data Collection and Analysis

To answer the research questions, three types of organizations were selected to generate insights on how information technology instantiates financial trading. Thirty-five interviews were arranged with regulatory bodies, financial firms, and technology vendors [18 regulators, 12 HFTs, and 5 independent software vendors (ISV) (see Table 1)]. Each stakeholder occupies a different, albeit interconnected part of the regulatory-technology nexus. The regulator, who had the responsibility of designing and introducing regulatory mandates, is impacted by the technologies adopted by financial firms to fulfill their trading strategies. The degree to which technology shapes

regulation influences how firms engage in activities that either comply or detract from the intentions of regulatory rules, which in turn influence the type of technology used in future trading strategies. The researchers found that a revolving door exists between the regulated and regulator, with many financial experts joining government bodies to work in advisory roles.

Primary data collection from on-site interviews combined opportunities for follow-up telephone calls to clarify various data points. This method of data collection and analysis has elements of participant observation [46], as a member of the research team serves in an advisory capacity to the SEC and CFTC on defining regulatory policies for automated trading. The meetings attended covered the period 2016–2020. Further, primary data were collected from other participants, notably HFTs and ISVs. Initially, HFTs were reluctant to grant interviews due to their refusal to discuss business trading strategies. They only agreed to interviews to discuss regulatory policy and practice, excluding any discussion of business strategy. ISVs offered views and insights on compliance technology oversight in trading activities, mainly to discuss perceived or unforeseen risks from human error or deliberate financial malpractice.

The exploratory-inductive, theory-building approach guiding the study was initially designed to develop and contrast the findings from short case studies [42] on the instantiation of information technology in financial markets. However, the more interesting focus generated data on stakeholder views on the market and regulatory policy in automated trading practices. Descriptive studies provide insights into phenomena that is less well understood in the extant literature [43]. Comparative case study analysis was not selected as a research approach, since the singular point of interest was regulator, HFT, and ISV and participation in defining, interpreting, and monitoring regulatory policy in the context of rapidly changing, automated trading environments. Interviews with informants over time generate process data [40] that provide insights as to why, for example, regulators move from principles-based regulatory mandates to rules-based approaches.

In discussions with regulators, HFTs, and ISVs, only ISVs agreed to the recording of interviews. Regulators discussed the regulatory policy in general terms. They were not prepared to discuss individual cases, such as imposing financial sanctions and penalties on specific firms for noncompliance. HFTs were also reluctant to

discuss their business strategies and if they had been fined by the regulator for breaching compliance mandates. ISVs were more forthcoming but did not wish to discuss technical problems in their compliance products. Noting these restrictions on the questionnaire design, our focus was on how regulatory mandates were optimized (or otherwise) across the financial industry in an environment of almost constant technological change. To analyze our data, we developed generic themes [47] on different regulatory regimes and time spans covering regulatory models, technology capability, stakeholder involvement, and policy drivers for regulatory mandates.

Table 1. Primary and Secondary Data Sources (2016–2020)

Primary Data					
Informants	Regulators	HFTs	ISVs		
SEC Regulator	10				
CFTC Regulator	8				
Traders				7	
Quants				4	
Compliance Officers				1	4
Business Development					1
Secondary Data					
Regulator reports (SEC, CFTC) and public responses to proposed changes. Legal reports on regulation and IT	Academic sources (journals and working papers)	General industry publications on financial Trading/HFT	Businessanalysis and consultancy reports (e.g. Gartner, PWC, Accenture).		

To supplement primary data, secondary source data were collected from various sources including government reports, legal and regulatory mandates, public responses to planned regulatory change, academic papers, industry and practitioner articles/commentaries, stock market publications/data (i.e. NYSE, Nasdaq), and media content. The secondary source material is invaluable to research on regulatory policy since it includes high-level detail on significant financial market events and how regulators have responded. For this study, we analyzed policy documents and statements from regulatory agencies. The data were an invaluable source, which reflects how information technology has impacted policy decisions over several decades, often leaving regulators few options but to impose ex-post (as opposed to ex-ante) regulatory mandates on financial markets.

5. Impact of Technology on Financial Regulation

Interviews with financial market regulators and firms in conjunction with historical data on the financial trading show four distinct phases of technological impact on the financial market landscape. Figure 1 presents those acts that were specifically written to show how automated technology would affect the market and the two government agencies that created them. Further details on each of these acts are given in Appendix 1.

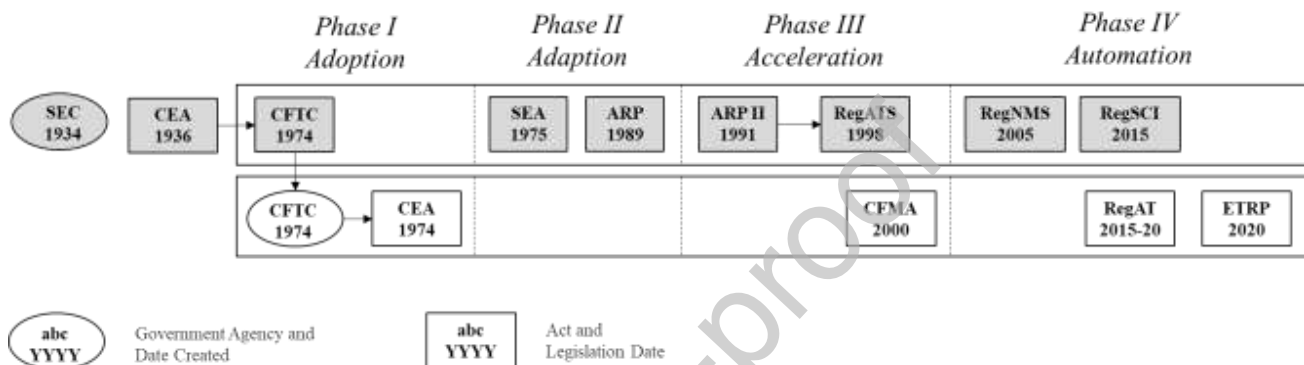


Figure 1. Four phases of financial and regulatory change in automated trading systems

The four phases reveal changing regulatory policies and practices. Each phase marks an inflection point at which distinctive technological change impacts regulatory decision-making and mandatory outcomes. The regulatory mix incorporates *ex-ante* and *ex-post* responses to complex market structural changes and fragmentation, the impact of financial technologies in the form of software products and services that shape trading practices, and how information is created, accessed, and manipulated by financial intermediaries. Table 2 presents further information on these four phases, interwoven with our three interrelated concepts that influence regulatory decision-making.

Table 2. Regulation of Automated Trading: 1960–2020

Phase of Technology	Influences on regulatory decision-making		
	Market Fragmentation	Technical Complexity	Information Asymmetry
Phase I - Adoption 1960–1974 Changes to operations in response to government and SEC pressure	1966, the manual writing of trade details on ticker tape was digitized by the market data system (MDS). The NYSE viewed the tool as a way of monitoring what trading information was recorded, rather than how trading was conducted by brokers and dealers. Most financial activity occurred on the NYSE, with open outcry trading integral to the process [48]. Toward the end of the 60s, increasing cost, due to market fragmentation, became a major concern to large institutions. By 1970, fragmentation caused stock prices to diverge. SEC first discusses the central market system.	In 1963, the SEC released the first in-depth review, the Special Study of the Securities Markets [49]. Technical changes soon made its 15-year projections obsolete. The volume of daily trades increased [50], which were enabled by low-level computerization [51]. Competition to the NYSE came from privately owned electronic communication networks (ECNs) such as Institutional Networks (now Instinet). Their computer services and networks automated the trading process. In 1971, technological advances enabled competition from NASDAQ [52].	Amendments to the securities act of 1964 [53] strengthened the SEC's ability to remove structural asymmetries on price between investors and the trading floor [25], although specialist activity seen by the NYSE as too complex to automate. The MDS was used in different ways – seen by the NYSE as a management tool to check on agents but by the SEC to remove informational asymmetry between the public and the exchange trading floor.
Phase II - Adaption 1975–1989 Modification of changes imposed on exchanges	The NYSE proposed its Intermarket Trading System (ITS) connected to other exchanges via the communication network provided by SIAC (then 2/3 opened by the NYSE). Suggestions for a separate nationwide trading facility to replace exchange floor activities was further proposed [54].	Studies, reports, and congress hearings culminated in the Securities Exchange Act Amendments 1975 authorizing the SEC to electronically harmonize trading venues [55]. Exchanges resisted automation because of the perceived complexity of some orders. Recognizing the growing impact of technology to change financial markets, the SEC issued its first Automated Review Policy (ARP) statement in 1989 [56].	A national market system (NMS) was created by the SEC, but the necessary architecture was managed by industry. This created a different timeline on adaption leading to both an asymmetry of information flow and intermarket arbitrage. Investors do not know what was occurring in the market because different technologies at exchanges maintain asymmetric data and confusion.
Phase III - Acceleration 1990–2004 Increasing rate of technological change	In 1998, the SEC introduced Regulation Alternative Trading Systems (Reg ATS) [57]. Here, some of the guidelines presented in ARP and ARP II became rules, again with the goal of allowing ATS to compete with the traditional exchanges. Rescinding of rule 390 meant that trading a stock listed at the NYSE no longer had to occur at just that exchange [58]. The SEC encourages different systems to connect to each other, rather than consolidating the NMS with more comprehensive regulation.	Significant technological developments occurred with the commercialization of the Internet in the mid-1990s. Rapidly advancing technological change spawned further risk mitigation guidance, with the SEC issuing ARP II [59] in 1991, again based on voluntary compliance. Automated trading created new types of instruments in a high-speed interconnected market. A 2002 report by the US General Accounting Office [60] raised fears that the SEC was no longer able to fulfil its mission [61]. It claimed that the SEC had not kept pace with the growth, complexity, and international operation of the market.	In 1984, NASDAQ created the automated small order execution system (SOES). With the development of “Watcher” software, which was released in 1990, trade opportunities enabled fast reaction to information ahead of dealers and market makers [62]. The ability to execute trading decisions hundreds of times each day redefined financial trading and was the forerunner of HFT. Execution decisions quickly shifted from trade floor to the brokers server. In 2000, Regulation Fair Disclosure [63] was issued to try and stop companies from releasing selective information, which gave unfair advantages.
Phase IV - Automation 2005–2020 Global markets performed by algorithms	Regulation National Market System (Reg NMS), introduced in 2005 [64] had an underlying philosophy of open competition between private agents to produce a stronger and more resilient market than one using dictatorial mandates and aggressive enforcement [65]. In 1990, 17% of the shares listed on the NYSE traded at other venues. By 2015, it was 66% [66, p. 125].	Limited regulatory oversight, a consequence of financial innovation and technology, characterizes the period leading up to the Global Recession of 2008, with the burgeoning derivative market implicated in this seismic market [67]. Between October 2007 and 2008, over \$8 trillion was lost on the US stock market [68].	Although trade details are sent to a central consolidator before publication to the market, those whose technology was co-located were able to access before other firms [69]. Dark pools are private exchanges, which do not provide any transparency [70]. Initially, these were created to avoid dealing with the HFT firms, at many, this is no longer possible.

5.1. Adoption Phase I: 1960–1974

The first phase saw the first adoption of technology, which would fundamentally change the way the market operated. Trade executions had existed in the realm of ideas, with financial firms hiring on past performance. Early adoption of this new form of technology changed trading strategies. For example, block trading managed thousands of shares in batches to lessen the impact on price. Basket trading bought and sold ratios of large numbers of different securities. In 1965, 5 million shares were traded; 3 years later, it was 12 million by when the NYSE was unable to keep up-to-date paper records.

With the creation of the CFTC in 1974, two separate bodies regulated the US financial market. This adoption phase marks a transition period with financial markets using limited technological resources. Here, the lack of transparency in trading decisions was human centered. The shift came as information technology, which was deployed to make trades more transparent, also created opacity and obfuscation as automation could conceal decision choices through computer code.

5.2. Adaption Phase II: 1975–1989

In 1975, amendments to the Securities Exchange Act of 1934 had the objective of establishing a national market system (NMS). Congress, however, neither defined what an NMS was, nor how it would be structured [71]. Automation increased the speed and volume at which transactions occurred. By 1987, just 2 days' trading on the NYSE was equivalent to the annual volumes for the year of 1964. Throughout the 1980s, automating manually intensive processes improved the efficiency and timeliness of executions, yet required adaptation of interconnected business processes.

During this phase, information technology became more prevalent in stock exchanges, each of which adapted its computer networks and applications to meet specific business requirements. The emphasis on principles-based, self-regulation afforded financial firms more freedom to interpret regulatory policy according to their interests. Deregulation and technological change loosened the regulatory grip on financial firms and redefined the risk profile.

5.3. Acceleration Phase III: 1990–2005

A wholesale change in financial trading occurred during this period, with the acceleration of information technology influencing the financial market structure and reshaping how regulators engage with financial firms and intermediaries. As financial trading exploded, the impact on the regulators' ability to ring-fence risk criteria and formulate rules-based compliance mandates was significant. However simply imposing further laws, rules, and sanctions was not sufficient to mitigate firm and systemic risks. By 2000, regulation contained in the Commodity Futures Modernization Act [72] represented the most significant reform to the Commodity Exchange Act since the creation of the CFTC. Although it eliminated overlapping jurisdiction between the SEC and the CFTC, excluded from regulatory oversight were over-the-counter (OTC) derivatives executed on electronic platforms. One SEC regulator commented, *"The importance of the OTC market to the US financial system was totally skewed. No longer legally tied to an underlying [asset] these products grew exponentially, and so did the risk"* #Reg1.

The defining characteristic of this phase is the proliferation of technological infrastructure, applications, and networks, not only increasing market fragmentation but also financial innovation with new products and services traded on exchanges. Regulators, who recognized the increased threat of systemic vulnerability and risk, shifted their position by imposing tighter controls and obligations on financial market participants. An ISV comment shows how technology became cheaper and more capable *"The biggest limitation was what [compliance] checks could be done given the inflexibility of software running on a mainframe. This all changed in the 90's when PC's drove system development"* #ISV1. That said, the rush to create additional ex-ante rules and regulations failed to increase the resilience of the market, thereby leaving regulators on the back foot of relentless and unpredictable technological change.

5.4. Automation Phase IV: 2005–2020

One of the most significant changes to US financial markets architecture occurred in 2005 with Regulation National Market System (Reg NMS). With increased market fragmentation, these rules were intended to give optimal trading prices to the investor [73]. This necessitated an increase in automation

for a market structure dominated by HFTs, thus leading to claims of unfair trading practices [16]. One HFT trader commented *“Trading is driven by technology and whoever has the best will win [the trade]”* #HFT2, while another said *“The only way you can compete is to buy the fastest tool”* #HFT4. Speed was important but so too was the strategy being run. A compliance officer said *“We spend over \$3 million on data from Reuters and all of our analysis and research is on this, giving us an edge on smaller competitors”* #HFT5. The SEC did not anticipate how technology would fundamentally change market activities, responding by re-evaluating the substantive content and efficacy of Reg NMS rules [74].

Automation not only fragmented financial markets, giving rise to increased diversity of intermediaries, but also transitioned trading from the domain of brokers and dealers to one dominated by quants and programmers. One HFT analyst discussed system complexity, *“The most important part of our execution research team was the market impact team. Having figured the model out, it needed almost 900 inputs.”* #HFT2. Further, it changed how for some finance operated and behaved, as another quants analyst said *“This is an investment-intensive enterprise and once you are in, you can drive out your competitors”* #HFT3. Technology created new strategies, as commented by another trader *“HFT has become an information processing and data analytics business. Some people fail because the size of the data overwhelms them. There is no room in HFT for people who can't think in terms of large-scale data”* #HFT8. It was not just farming big data, such firms had to increase their trading activities, as commented by another trader, *“The only way that you could now compete and cover the costs of business [e.g., colocation, microwave towers] was by really increasing the amount of trading that you did”* #HFT6.

As order volumes increased, so too did system risk. One trader commented *“Quality is measured in standard deviations [of returns]. The firms that survive are gonna be the ones that don't blow themselves up”* #HFT1. Another said *“Knowing you have a problem in 5 minutes might be 4 minutes and 59 seconds too late. Every day we spend a great deal of time on real time quality control”* #HFT7. The most widely cited event by the SEC and CFTC of “out of control” automated markets was the Flash Crash on 6 May 2010 [7]. In 30 minutes, almost \$1 trillion dollars was wiped off the value of stocks as trading became

extremely turbulent. A report published by the SEC claimed that a mutual fund trader had launched a program to sell 75,000 contracts (valued at \$4.1 billion) in 20 minutes [75]. The interaction between automated execution programs and algorithmic trading strategies created a “hot-potato” effect with HFT systems quickly buying and selling contracts. A quants analyst said *“You don’t derive these strategies. They’re based on logic about what other market participants will do. If we do this, then they’ll do that.”* #HFT5. The feedback loops embedded in the software dynamically changed the execution patterns, which according to the SEC led to unpredictable outcomes [76]. A Chicago-based data provider, Nanex, presented a different reason. They claimed that it was the high volumes of trades and sale price information, sent to and from other exchanges, which flooded the NYSE message queue [77]. The technology used at the NYSE was old and simply could not cope, which was why trading was halted and the message queues cleared. Prior to this date, the speed of technology and trading volumes transmitted had not overloaded the exchange and exceeded its capacity.

Between 2009 and 2014, technical events shocked the financial markets as software failed and technology struggled to operate as designed. Appendix 2 gives a summary of the most significant failures during this period. They all implicated financial software as a major contributory factor, presenting regulators with even greater risk oversight challenges. Mary Schapiro, Chairman of the SEC, said that these were *“basic technology 101 issues”* [78].

The frequency of system failure pressured the SEC to develop new mandates and Regulation Systems Compliance and Integrity (Reg SCI) [79], which became effective on 3 February 2015. After 20 years of regulating the use of technology in the US securities market via voluntary principles, the Commission now has a formal regulatory structure [80]. One HFT compliance officer said *“There were rules which were either ambiguous or at cross-purposes with other rules and so this presented opportunities. If they are open to interpretation, then you interpret them in the most profitable way possible. The interpretation just needs to be defensible”* #HFT3. Not only did these rules reduce system risk but technology offers new opportunities.

In 2020, the CFTC introduced Electronic Trading Risk Principles (ETRP) [81], having failed to legislate its earlier policy Regulation Automated Trading (Reg AT). Interestingly, this was based on the principles that they had *already* passed [82]. One vendor commented “*The post-crisis period has seen many attempts to regulate the markets and the technology...with either rules or principles-based approaches. Financial trading today, is run by predictive algorithms and computer code, and this alone makes it difficult for regulators to know what is going on.... Pushing more rules doesn’t really work because some companies, like HFTs, will be happy to pay fines because they can offset them against the profits they make...and self-regulation gives financial firms even more freedom to interpret regulatory laws and mandates from their own self-interest*” (ISV#2).

Regulators now use a mixture of principles- and rules-based legislation, reflecting the difficulty in getting this right. In December 2020, despite “*a relationship that has not been without tensions over the years*” [83, p. 1], the SEC and CFTC released their first-ever joint rule on security futures margins (SFM) [84]. For the first time in almost 50 years, the initiative was to evaluate consolidating rules in a fragmented market.

6. Discussion

From the analysis of financial regulation as an evolutionary process, regulatory bodies face difficult challenges, as each of the four phases marks an inflection point in digital technology transformation. The conflation of technology and regulation introduces normative inputs into governance and compliance regimes, with uncertain outcomes. Technology systems for managing risk mask uncertainty and malfeasance, thus creating different types or new forms of unforeseen risk. Algorithmic code impacts regulatory outcomes embedded in formal mandates. Private-firm exploitation of information technology shapes regulatory decision-making, which leads to suboptimal outcomes from oversight mandates. Technology offers powerful tools to enable financial firms to meet regulatory goals, but it influences decision-making in ways that depart from those ends (as witnessed by high-profile disruptive market events).

Human decision-making processes complicate regulatory challenges. We theorize that decision optimization views individuals as having perfect or sufficient information about their preferences and the alternatives available to them. Individuals do their best under prevailing and complex conditions. This presumes groups and individuals maximize utility by choosing the preferred alternative [11]. An important element of the choice process is the impact of constraints, which make choice necessary. Regulators, attempt to optimize decision outcomes, make trade-offs between alternative options, and make explicit in their policy mandates their choice of either rules-based or principles-based regulatory approaches. Findings show that constraints on decision choices are much more complex in context-specific, evolving regulatory, and technological environments. Ever-increasing decision choices implicated by evolving financial technology make it difficult to represent the preference option (alternative) to maximize utility.

Bounded rationality positions rational choice in the context of cognitive and informational limitations of decision-makers [85]. Individuals are intendedly rational yet constrained by these limitations [86]. Findings show that regulators enact decision-making under *constrained optimization*. A complex scenario plays out as primary and secondary data that reveal decision choices shaped by the interconnections among regulatory regimes, financial markets, and automated trading. We theorize four decision-making constraints on regulatory models, which emerge from primary and secondary data: incompatible and polarized regulatory models, comparative knowledge and expertise of regulator and regulated, technology's role in obscuring regulatory decision choices, and different stakeholder agendas. These are shown in Figure 2, with the process beginning with a regulatory action, which results in suboptimal outcomes.

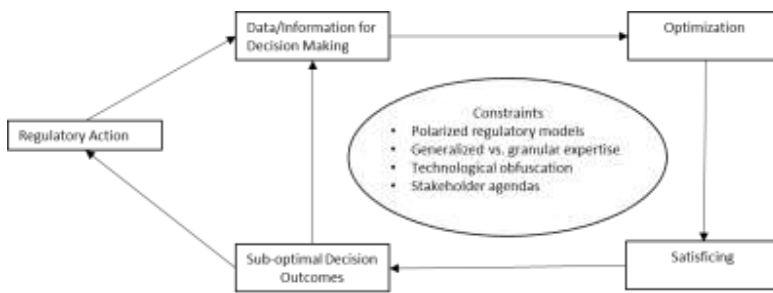


Figure 2. A process model of regulatory decision-making in financial market trading

We theorize that the first constraint, regulatory policy drift, occurs as the content and meaning of formal rules and laws that change over time [87]. Constantly changing information technology drives political action, which shapes the design of regulatory regimes, laws, and rules. Findings show that regulatory regimes alternate from top-down (institution-led) regulation to (firm-specific) self-regulation. In the 30 years up to the 2008 financial crisis, deregulation allowed financial firms more freedom to create new financial products with fewer administrative safeguards to prevent financial meltdown [20]. Deregulation drives new financial product innovation [88] specifically in derivatives [3]. As self-regulation replaced command-and-control regimes, financial firms were given discretionary powers to interpret and formulate regulatory mandates. A consequence was the dilution of regulatory oversight as regulated firms influenced the narrative of how mandates were developed and executed. Deregulation further reduced regulatory powers to uphold institutional and public norms at the risk of subversion by self-interested parties.

The second constraint, differing capability, exacerbates the effective monitoring of regulated firms by administrative agencies. The generalized expertise of the regulator against the granular expertise of the financial firm proliferates information asymmetry, which further drives deregulation. Regulated entities possess superior knowledge about the strategic and technical capability of their operations, which prevents regulators from scrutinizing decision pathways intentionally or unconsciously concealed by firms. Delegation of decision criteria to firm participants to optimize regulatory outcomes increases information asymmetry. Mathematicians, or “quants,” who program algorithmic trading systems embed

decision preferences of senior managers and traders, not communicated to regulatory agencies. Substantive details about firm strategies are of interest to regulators. Reporting practices, however, privilege only the transmission of codified and transparent information that reveals only partial aspects of firm strategy, thereby leaving regulators in a weaker position to surveil firm activities.

The third constraint is technological obfuscation. Financial technology proliferated as regulators replaced rule-based mandates with context-specific judgment by regulated entities. Regulatory categories encoded in written rules and informal cognitive and informational categories employed by market participants create an incomplete regulatory landscape with some activities falling between the cracks. Greater freedom to choose technology deployment enables firms to circumvent regulatory rules and even engage in unlawful or unethical activities, such as front running and spoofing. Executing code developed by algorithmic trading firms is not made available to the regulator without a subpoena. It represents their strategies and competitive advantage over other vendors. Failure to readily share is based on two arguments: low confidence that it will be securely stored and a belief that the regulator does not have the skills to understand how the code operates. The reintroduction of human judgment in regulatory oversight is no longer possible as automated trading contributes to problems of cognitive limitations and incomplete information. With the removal of humans from financial trading, technology has undermined the traditional methods of coordinating and controlling behavior [89]. Algorithmic trading strategies thus give rise to distorted outcomes as “decision pathologies” mask the risks and threats targeted by regulation [22]. Such pathologies increase as regulatory agents fail to comprehend how nontransparent automated trading practices perform in the markets.

The fourth constraint, the stakeholder behavior of financial firms, creates the technical attributes that distort or remove the accountability of the decisions they execute. Programming preferences concealed by layers of embedded stakeholder assumptions in algorithmic trading strategies make it difficult for internal compliance teams to evaluate the efficacy of regulatory mandates. This problem increases as external regulators, without the resources to unravel complex formal code that executes trading strategies, must

also ensure code is tested by the exchanges. In this scenario, regulators instead rely on the discretion and judgment of compliance managers to show safeguards are in place for mitigating systemic and firm risks. Findings suggest the solution to this ambiguity is unclear, as heterogeneous stakeholders follow different institutional and individual agendas and rules. Stakeholders also face limits to their own cognitive frames, motivated by business, financial, legal, and personal goals that shape their decision choices. Pursuing optimal outcomes from rational choices, decision-makers intentionally (and even unintentionally) limit the information provided to regulators based on their strategic priorities. For example, HFTs motivated by high end-of-day profits conceal decision choices from the regulator that would reveal trading practices. Even if the regulator uncovers unethical or even rule-breaking behavior, the HFT may conclude the risk is worth taking as the financial penalty weighed against profit maximization is not sufficient to act as a deterrent.

Since the early 1960s when technology was first introduced to automate specific areas of the trading process, regulation has had to change to accommodate the very trading methods it had legislated. Always directing increased use of technology, often the consequences were unintended. Findings reveal regulatory decision-making is constrained by complex interactions between the regulator and regulated. The combined set of constraints forces regulators to acknowledge that optimal regulatory outcomes are unachievable. Our findings show that with limited options to scrutinize the impact of technology-enabled financial trading (at systemic and firm-specific levels), the regulator opts for a work-around solution. In this scenario, regulators re-evaluate their decision choices and priorities and enact a “satisficing” response [86].

7. Conclusion

This paper contributes to the literature on regulation and technology by showing regulatory decision-making is a process that inevitably leads to suboptimal decision outcomes. Revisiting the seminal work of Herbert Simon [38, 39, 49] provides a useful theoretical lens to analyze our primary and secondary source data on the regulation of information technology in financial markets. Using a process-data-oriented

approach [40], we track regulatory actions over several decades, to demonstrate how regulatory mandates shape decision-making. The findings from our data supports Simon's observations that satisficing underpins the behavior of decision-makers in circumstances in which an optimal solution is not possible [33]. In our study, we theorize decision-making on two regulatory models applied to financial firms based on bottom-up self-regulation or top-down regimes. Both models treat financial firms as unitary decision makers, operating in isolation of the wider regulatory and market landscape. Each model also shapes the decision choices of atomistic, self-interested firms, with regulators aiming to optimize decision outcomes, albeit confronted by a complex set of constraints on their decision choices. Findings support prior research that institutional and corporate decision-making does not conform to monolithic templates of rationality [90]. Rather, relationships among diverse stakeholders, internal and external to firms, increase the scope and complexity of decision choices. The combined choices of groups and individuals thus shape behavior in ways that are neither inherently rational nor conducive to producing optimal outcomes [12, 91].

Further, algorithmic trading that competes on speed rests on the code's rule-based ability to execute trading decisions without situation-specific human discretion [92]. Since regulators have largely refrained from more active involvement in shaping financial trading practices, information technology has developed from the bottom up (firm-level) leaving regulators relatively powerless to impose ex-ante (as opposed to ex-post) mandates. The design of regulatory mandates thus relies on ex-post judgment by administrative bodies that refine or redefine the criteria and lessons learned from previous mandates. Externally imposed obligations (regulatory and public norms) however contrast with firm-specific strategies (i.e., HFT profit maximization). In the context of regulatory norms, these constraints produce decision outcomes that are noncompliant with private (low-frequency traders) and public (investors) interests. In sum, as these constraints stem from decision priorities privileged by only a few, they are hidden from scrutiny by external bodies. As such, they obscure the very values and norms about which

regulatory agencies are most concerned, thus enabling algorithmic traders to pursue profits by executing strategies that, in some cases, circumvent the rules.

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APPENDIX 1

The regulation of US financial markets developed from the statutes introduced by Congress, following the disruptive 1929 Wall Street Crash. The first two major acts introduced were the Securities Act of 1933 (concerned with the distribution of new securities) and the Securities Exchange Act of 1934 (SEA) (which paid attention to trading securities, brokers, and exchanges). Later in 1934, the major governing body, the Securities and Exchange Commission (SEC), was formed. Its mission was to protect investors by maintaining a fair, orderly, and efficient security market. Civil charges would be used, if necessary, on companies or individuals who broke security laws. Additional acts were passed by congress, but the growth of the market was slow due to the Great Depression and then the World War II. Created several decades later in 1974, the Commodity Futures Trading Commission (CFTC) served as an independent federal regulatory agency, whose mission was to regulate futures, agricultural and other commodities traded on exchanges. Table A1 shows all the acts that have been issued and updated to influence the use of technology on market operations.

Event	Description
CFTC Act 1974	The Commodity Futures Trading Commission Act proposed sweeping changes to the CEA of 1936. The SEC's Chairman declined jurisdiction over the commodity futures industry, which led to the creation of the CFTC.
CEA 1974	Changes to the Commodity Exchange Act of 1974 were "...to strengthen the regulation of futures trading, to bring all agricultural and other commodities traded on exchanges under regulation" [93, p.1389].
SEA 1975	The Securities Exchange Act of 1934, updated in 1975, had the goal of "...linking of all markets for qualified securities through communication and data processing facilities will foster efficiency, enhance competition, increase the information available to brokers, dealers, and investors, facilitate the offsetting of investors' orders, and contribute to the best execution of such orders [94, p.112].
ARP 1989	The Automated Review Policy in 1989 offered voluntary guidelines on the best practices to mitigate system risks by assessing vulnerabilities
ARP II 1991	The SEC issued ARP II, again based on voluntary compliance. Key to this was the need to ensure the automation of regulated systems.
Reg ATS 1998	Regulation of Automated Trading Systems changed some of the guidelines presented in ARP and ARP II into rules, with the goal of allowing automated trading systems to compete with traditional exchanges.
CFMA 2000	The regulation contained in the Commodity Futures Modernization Act represented the most significant reform to the CEA since the creation of the CFTC. However, excluded from regulatory oversight were OTC derivatives executed on electronic platforms.

Reg NMS 2005	The underlying philosophy of the Regulation National Market System was open competition between private agents to produce a stronger and more resilient market than one using dictatorial mandates and aggressive enforcement.
Reg SCI 2015	Regulation Systems Compliance and Integrity was introduced to counter the limitations of voluntary inspection programs in a highly automated market.
Reg AT 2015-20	Regulation Automated Trading was a collection of rules designed to ensure that regulations kept pace with the evolving technological changes in the market. An inability to adequately define risk led to its withdrawal.
ETRP 2020	The Electronic Trading Risk Principles replaced Reg AT. It was focused on trading platform experiencing a market disruption or system anomaly due to electronic trading.

Table A1 Regulatory acts designed to influence the use of technology

APPENDIX 2

The events between 2009 and 2014 had catastrophic effects on investor confidence. The software was seemingly untested, inadequately installed, or the hardware itself was simply not able to cope as data volumes went beyond capacity thresholds. Before Reg NMS was introduced in 2005 (becoming law in 2007), there had not been any issues associated with the volume of traffic transmitted to the exchanges. This regulation changed how the market operated. Automated trading companies (HFT) worked on different networks using the fastest equipment because they now competed on latency. To do so, they invested heavily in technological capability, surpassing anything used elsewhere. It took many years for the exchanges to catch up. Table A2 shows the most significant technological failures across this period.

Date	Market Event
8 Oct 2009	Malfunctioning of Infinium Capital Management's ATS. Later fined because the behavior of their system caused issues on <i>other</i> automated trading systems \$500k.
30 Oct 2009	Flash crash on NYSE, although not as large as the crash on 6 May 2010, a similar price collapse was witnessed.
3 Feb 2010	Software issues because of Infinium Capital Management's failure to adequately supervise, test, and control their ATS led to \$350k fine.
28 April 2010	Flash crash on the NYSE, although not as large as the crash on 6 May 2010, a similar price collapse was witnessed.
6 May 2010	Flash crash on the NYSE during an automated \$4.1 billion sale triggered a 6% plunge in the value of the stock market (about \$1 trillion).
8 Nov 2010	EDGA and EDGX exchanges ran untested code, which generated trades totaling about \$773 million. Resolving this cost the exchanges \$2.1 million.
5 Feb 2011	NASDAQ OMX Group revealed that hackers had penetrated certain of its computer networks during the past year.

13 April 2011	EDGX Exchange inadvertently disconnected its database, which disrupted trading. Resolving this cost the exchange \$668k.
11 Oct 2011	EDGX and EDGA violations due to all their trading rules not being publicly available.
23 March 2012	BATS Global Markets suffered a software bug, which prevented orders from their own initial public offering (IPO) from being filled.
18 May 2012	NASDAQ OMX Group's US exchange suffered technical problems which delayed the IPO of Facebook.
1 Aug 2012	Knight Capital Group failed to copy new software to all their servers. This caused a trading error, leading to a loss of \$440 million.
25 April 2013	Chicago Board Options Exchange delayed trading for three hours due to a software bug. This was identified as a design flaw in the messaging infrastructure.
15 Aug 2013	NASDAQ OMX Group suffered a 3-hour delay because of a software bug, which prevented the dissemination of stock quotes.
20 Aug 2013	Goldman Sachs ATS flooded the market with erroneous orders because of a programming error. Later fined \$7 million.
22 Aug 2013	NASDAQ Stock Market LLC halted trading for 3 hours because unusually high volumes exposed a bug in the system, which prevented a successful failover.
4 Sept 2013	NASDAQ Stock Market LLC halted trading for a few minutes, its cause was similar to the outage on 22 August.
1 Nov 2013	NASDAQ Options Market suffered a 5-hour delay due to the system's inability to handle the volume of orders.
29 April 2014	NYSE Arca and NYSE Amex Options systems were unable to correctly price complex orders, which in some cases were erroneously filled.

Table A2 Significant technological failures between 2009 and 2014

Bios

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Author Statement

Wendy Currie: Conceptualization, Methodology, Writing - Review and Editing. **Jonathan Seddon:** Conceptualization, Methodology, Writing - Review and Editing. **Ben Van Vliet:** Conceptualization, Methodology, Writing - Review and Editing.