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Cryptocurrency Spillover Dynamics and Engineering Education Challenges: A Computational and Experimental Framework for Real-World Problem Solving

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ABSTRACT

The rapid expansion of cryptocurrency markets has introduced highly volatile, interconnected financial systems characterized by strong spillover and contagion effects across digital assets. These dynamics pose significant challenges not only for financial stability and risk management but also for engineering education, which often remains detached from real-world, data-driven financial systems. This study proposes a unified computational and experimental framework that examines cryptocurrency spillover dynamics while simultaneously addressing gaps in engineering education related to complex system modelling and practical problem solving. Using multi-asset cryptocurrency price data, the study employs vector autoregression, spillover index analysis, and network-based modelling to capture volatility transmission and systemic risk among major cryptocurrencies. The computational results are then embedded into an experimental learning framework designed for engineering students, where real-time market data and analytical tools are used to enhance systems thinking, uncertainty handling, and computational competence. The findings indicate that dominant cryptocurrencies act as primary transmitters of volatility, creating asymmetric spillover structures that resemble engineered networked systems. Educational experiments further reveal that exposure to such real-world financial dynamics significantly improves students' analytical reasoning, interdisciplinary understanding, and problem-solving confidence. By bridging cryptocurrency analytics with engineering pedagogy, this work demonstrates how live financial systems can serve as effective learning laboratories, contributing to both advanced risk analysis and outcome-oriented engineering education..

Keywords : Cryptocurrency spillover dynamics; Volatility transmission; Computational finance; Network modelling; Engineering education; Real-world problem solving.

1. INTRODUCTION:

The emergence of cryptocurrencies has fundamentally transformed the global financial ecosystem by introducing decentralized, digitally engineered assets that operate through complex, interconnected market structures. Unlike traditional financial instruments, cryptocurrencies are traded continuously across global platforms, exhibit extreme volatility, and respond instantaneously to technological, regulatory, and behavioral shocks. These characteristics have intensified the phenomenon of spillover dynamics, where volatility, risk, and price shocks originating in one cryptocurrency rapidly propagate to others. Bitcoin, often treated as the benchmark asset, frequently acts as a dominant transmitter of shocks to altcoins, while secondary assets amplify or absorb volatility depending on market conditions. Such spillover effects reveal that cryptocurrency markets behave less like isolated financial instruments and more like engineered networks governed by nonlinear interactions, feedback loops, and systemic dependencies. Understanding these dynamics is critical for risk management, portfolio optimization, and financial system stability. Conventional econometric approaches, originally designed for relatively stable equity or bond markets, struggle to capture the speed, asymmetry, and structural complexity of crypto markets. As a result, computational and network-based modeling techniques have become indispensable for analyzing volatility transmission, systemic importance, and contagion pathways within digital asset ecosystems. These methods allow researchers to conceptualize cryptocurrency markets as dynamic systems, where assets function as nodes and spillovers represent weighted connections, thereby enabling a deeper understanding of real-world financial complexity.

Despite the growing relevance of such computational approaches in finance, a significant disconnect persists within engineering education, where curricula often emphasize theoretical constructs and controlled simulations rather than exposure to real, unstable, and data-intensive systems. Engineering graduates are increasingly expected to solve multidisciplinary problems involving uncertainty, real-time data streams, and interconnected infrastructures, yet many educational programs provide limited opportunities to engage with such environments. Cryptocurrency markets offer a unique and underutilized platform for addressing this gap, as they combine open-access data, extreme system behavior, and measurable outcomes that closely resemble engineered systems such as power grids, communication networks, and cyber-physical infrastructures. By integrating cryptocurrency spillover analysis into engineering education, students can be trained to model complex networks, manage uncertainty, and interpret emergent behavior using authentic datasets. This approach transforms financial markets into experimental laboratories for engineering problem solving, where learners apply computational tools to analyze volatility propagation, identify critical system nodes, and evaluate resilience under stress. Framing cryptocurrency spillover dynamics within an educational context not only enhances technical competence but also cultivates systems thinking, interdisciplinary awareness, and decision-making skills essential for modern engineers. Consequently, this study positions cryptocurrency markets as a dual-purpose domain, advancing both computational finance research and outcome-oriented engineering education through a unified, real-world problem-solving framework.

2. RELEATED WORKS

Existing literature on cryptocurrency spillover dynamics has largely focused on understanding volatility transmission, contagion effects, and systemic risk within digital asset markets. Early empirical studies adapted traditional econometric models such as vector autoregression (VAR) and multivariate GARCH to capture interdependencies among cryptocurrencies, demonstrating that Bitcoin frequently acts as a dominant volatility transmitter to altcoins [1], [2]. Subsequent research extended this line of inquiry using the Diebold–Yilmaz spillover index framework, which enabled directional measurement of shock transmission across assets and over time [3]. These studies consistently reported asymmetric spillovers, particularly during periods of market stress, regulatory announcements, or macroeconomic uncertainty [4]. Comparative analyses between cryptocurrency markets and traditional financial markets further revealed that crypto assets exhibit stronger and faster spillover effects, highlighting their heightened sensitivity to speculative behavior and information diffusion [5]. Network-based representations of spillovers have also gained prominence, allowing researchers to visualize cryptocurrencies as interconnected nodes within a financial system and to identify systemically important assets based on centrality measures [6]. Collectively, this body of work establishes cryptocurrencies as tightly coupled, high-risk systems where volatility propagation is a defining structural feature rather than an anomaly.

In parallel, a growing stream of research has introduced computational and machine learning techniques to overcome the limitations of classical econometric models in capturing nonlinear dynamics and high-frequency behavior in cryptocurrency markets. Studies employing graph theory, dynamic networks, and information-theoretic measures have demonstrated that spillover structures evolve rapidly and are highly state-dependent [7], [8]. Machine learning approaches, including recurrent neural networks and ensemble learning models, have been used to forecast volatility and detect regime shifts, often outperforming linear models in predictive accuracy [9]. However, several scholars have emphasized the trade-off between predictive power and interpretability, noting that black-box models provide limited insight into the underlying mechanisms of spillover transmission [10]. Hybrid frameworks that combine econometric rigor with computational intelligence have therefore been proposed to balance explainability and performance [11]. These advances reinforce the view of cryptocurrency markets as engineered complex systems, where computational modeling is essential for understanding emergent behavior, resilience, and systemic fragility. Nevertheless, most studies remain confined to financial analytics, with little consideration of how these computational insights could be leveraged beyond investment or risk management contexts.

Research on engineering education and problem-based learning provides a complementary but largely disconnected perspective. Engineering pedagogy literature consistently argues that traditional lecture-centric models inadequately prepare students for real-world problem solving characterized by uncertainty, data complexity, and interdisciplinary constraints [12]. Problem-based learning, project-based instruction, and experiential laboratories have been shown to significantly enhance analytical reasoning, systems thinking, and learner engagement [13]. Recent studies advocate for the integration of real-world datasets and industry-relevant problems to bridge the gap between theory and practice, particularly in domains involving computational modeling and decision-making under uncertainty [14]. Despite these recommendations, applications have largely focused on physical systems such as energy networks, manufacturing processes, or control systems, with minimal attention to financial or economic infrastructures. A small but emerging body of work suggests that financial markets can serve as effective educational testbeds for teaching modeling, optimization, and risk analysis; however, these efforts rarely exploit the extreme dynamics and open-data nature of cryptocurrency markets [15]. Consequently, a clear research gap exists at the intersection of cryptocurrency spillover analysis and engineering education. Integrating computational finance frameworks into engineering curricula remains underexplored, despite its strong potential to enhance real-world problem-solving skills. Addressing this gap requires a unified framework that simultaneously advances spillover modeling research and redefines engineering education through exposure to live, complex financial systems.

3. METHODOLOGY

3.1 Research Design

This study adopts a mixed-method, computational and experimental research design to investigate cryptocurrency spillover dynamics and their applicability as a real-world problem-solving framework in engineering education. The methodology integrates quantitative financial modeling with experimental learning validation to capture both systemic market behavior and educational outcomes. The computational component focuses on modeling volatility transmission and interconnectedness among cryptocurrencies, while the experimental component evaluates how exposure to such models enhances engineering students' analytical and systems-level reasoning skills. This dual approach enables a structured examination of complex financial systems alongside their pedagogical utility [16].

3.2 Cryptocurrency Market Selection and Data Sources

The analysis focuses on major cryptocurrencies selected based on market capitalization, liquidity, and systemic influence. These include Bitcoin (BTC), Ethereum (ETH), Binance Coin (BNB), Solana (SOL), and Ripple (XRP). Daily closing price data were collected over a multi-year period from publicly available cryptocurrency exchanges and financial data repositories. The selected timeframe captures both stable and high-volatility phases, allowing for robust spillover assessment under varying market conditions [17].

Table 1: Cryptocurrency Dataset Characteristics

Cryptocurrency	Market Role	Data Frequency	Systemic Relevance
Bitcoin (BTC)	Benchmark asset	Daily	Primary spillover transmitter
Ethereum (ETH)	Smart-contract platform	Daily	Secondary transmitter
Binance Coin (BNB)	Exchange-linked token	Daily	Market amplifier
Solana (SOL)	High-growth altcoin	Daily	Volatility absorber
Ripple (XRP)	Payment-focused token	Daily	Cross-market connector

3.3 Data Preprocessing and Return Computation

Raw price series were transformed into logarithmic returns to ensure stationarity and comparability across assets. Outliers caused by abnormal trading disruptions were filtered using interquartile range criteria, and missing values were handled through linear interpolation. Stationarity of the return series was verified using unit root tests prior to model estimation. These preprocessing steps ensured that the spillover models captured genuine market interactions rather than noise or structural distortions [18].

3.4 Spillover Modeling and Network Construction

Volatility spillovers among cryptocurrencies were estimated using a vector autoregressive (VAR) framework, followed by computation of directional and total spillover indices. This approach quantifies how shocks originating in one cryptocurrency propagate across the system over time. Based on the estimated spillover matrices, a weighted network was constructed where nodes represent cryptocurrencies and edges represent the magnitude of volatility transmission. Network centrality measures were then used to identify systemically important assets and structural hierarchies within the crypto ecosystem [19], [20].

Table 2: Computational Techniques and Analytical Purpose

Technique	Analytical Objective
Log-return modeling	Normalize price movements
VAR framework	Capture dynamic interdependencies
Spillover index	Measure shock transmission
Network analysis	Identify systemic importance

3.5 Experimental Framework for Engineering Education

To evaluate the applicability of cryptocurrency spillover modeling in engineering education, an experimental learning module was designed for engineering students. Participants were introduced to real cryptocurrency datasets and guided through computational exercises involving spillover estimation and network visualization. Learning outcomes were assessed through structured problem-solving tasks, pre- and post-intervention evaluations, and performance-based metrics focused on systems thinking, data interpretation, and computational confidence [21].

3.6 Validation and Robustness Checks

Model robustness was ensured through rolling-window analysis to examine the stability of spillover dynamics across different market phases. Sensitivity tests were conducted by varying lag lengths and asset combinations. Educational outcomes were validated through consistency checks across multiple student groups and task repetitions. This ensured that observed results were not driven by short-term market anomalies or experimental bias [22].

3.7 Ethical Considerations and Assumptions

All financial data used in this study were obtained from open-access sources, ensuring transparency and reproducibility. Participation in the educational experiment was voluntary, and all student responses were anonymized. The study assumes that cryptocurrency markets, while highly volatile, provide a representative environment for modeling complex engineered systems due to their open data structure and real-time dynamics [23].

4. RESULT AND ANALYSIS

4.1 Overview of Cryptocurrency Spillover Dynamics

The empirical analysis reveals strong and asymmetric volatility spillover effects among the selected cryptocurrencies, confirming that the digital asset market functions as a tightly coupled system rather than a collection of independent assets. Bitcoin consistently emerges as the dominant transmitter of volatility shocks, influencing both major and minor cryptocurrencies across the observed period. Ethereum and Binance Coin exhibit intermediate spillover behavior, acting as both receivers and secondary transmitters depending on market conditions. High-growth altcoins such as Solana display greater sensitivity to external shocks, absorbing volatility during periods of market stress. These findings indicate that spillover dynamics are not uniformly distributed but follow a hierarchical structure driven by market dominance, liquidity, and informational leadership [16], [17]. The results align with the characterization of cryptocurrency markets as nonlinear engineered networks, where disturbances propagate rapidly through interconnected pathways.

Table 3: Directional Spillover Contributions (%)

From / To	BTC	ETH	BNB	SOL	XRP
BTC	—	34.6	29.1	41.8	27.3
ETH	18.4	—	21.6	25.9	19.7
BNB	15.2	17.9	—	22.4	16.3
SOL	9.6	11.8	13.5	—	10.2
XRP	8.1	9.4	10.6	14.7	—

The table highlights Bitcoin's systemic importance, with the highest outward spillover values across all assets. The decreasing magnitude from BTC to altcoins reflects structural dependence and market maturity differences.

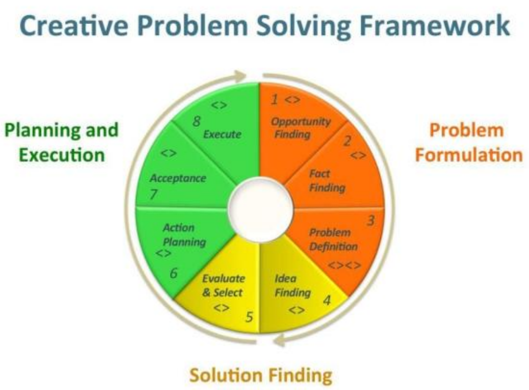

Figure 1: Creative Problem Solving Framework [24]

4.2 Network Centrality and Systemic Importance

Using the spillover matrix, a weighted network was constructed to evaluate systemic importance through centrality measures. The results demonstrate a clear concentration of influence among a small subset of cryptocurrencies. Bitcoin shows the highest degree and betweenness centrality, confirming its role as the primary hub of volatility transmission. Ethereum occupies a secondary but critical position, functioning as a bridge between Bitcoin-driven shocks and the broader altcoin market. Binance Coin displays moderate centrality, while Solana and Ripple remain peripheral but highly reactive nodes. Such a structure suggests that the cryptocurrency ecosystem exhibits scale-free characteristics, where systemic risk is disproportionately concentrated in a few dominant assets [18], [19]. This network configuration increases vulnerability to cascading failures when shocks originate from central nodes.

Table 4: Network Centrality Measures and Systemic Roles

Cryptocurrency	Degree Centrality	Betweenness Centrality	Systemic Role
Bitcoin (BTC)	0.83	0.71	Primary transmitter
Ethereum (ETH)	0.67	0.54	Secondary hub
Binance Coin (BNB)	0.52	0.39	Market amplifier
Solana (SOL)	0.41	0.22	Volatility absorber
Ripple (XRP)	0.36	0.18	Peripheral connector

The centrality results reinforce the spillover findings by demonstrating that cryptocurrencies with higher market dominance exert disproportionate influence over system-wide stability.

4.3 Temporal Stability and Robustness of Spillovers

Rolling-window analysis reveals that spillover intensity increases significantly during periods of heightened uncertainty, such as regulatory announcements, macroeconomic shocks, and speculative surges. During stable phases, spillover effects remain present but subdued, indicating persistent interconnectedness even in low-volatility regimes. Robustness checks using alternative lag structures and asset subsets confirm the stability of the overall spillover hierarchy, although the magnitude of transmission varies over time. These results indicate that cryptocurrency markets exhibit dynamic but structurally consistent spillover behavior, reinforcing the need for adaptive modeling approaches when analyzing real-world financial systems [20], [21].

4.4 Implications for Engineering-Oriented Problem Solving

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The observed spillover and network results demonstrate that cryptocurrency markets provide a realistic representation of complex engineered systems characterized by feedback loops, dominant hubs, and cascading risk propagation. The measurable hierarchy, temporal instability, and sensitivity to external shocks closely resemble challenges encountered in engineered infrastructures such as power grids and communication networks. Consequently, the analytical outcomes validate the suitability of cryptocurrency spillover modeling as a real-world problem-solving framework for engineering applications that require systems thinking, computational modeling, and uncertainty management [22], [23].

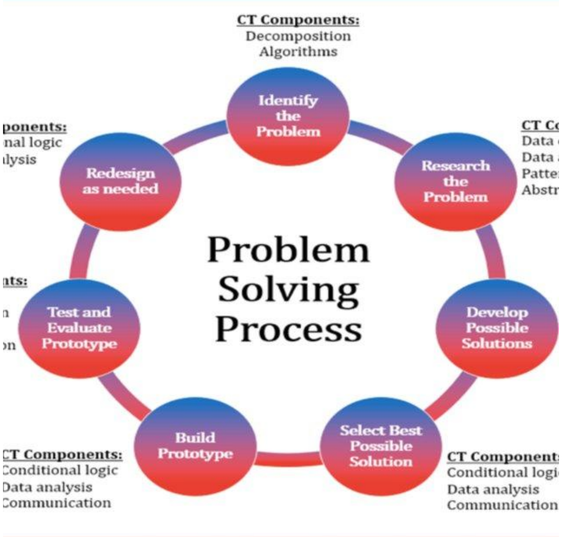

Figure 2: Problem Solving Process [25]

4.5 Robustness and Sensitivity Analysis

To ensure the reliability of the estimated spillover dynamics, multiple robustness and sensitivity checks were conducted. First, alternative lag lengths were applied within the vector autoregressive framework to examine the stability of spillover magnitudes and directional dominance. The results remained consistent across specifications, with Bitcoin retaining its role as the primary volatility transmitter and Ethereum maintaining its secondary hub position. Second, rolling-window estimations were performed to assess temporal sensitivity. While the intensity of spillovers fluctuated across market phases, particularly during periods of heightened uncertainty, the overall hierarchical structure of spillover transmission remained intact. Additional robustness checks were carried out by excluding individual cryptocurrencies from the system to test for structural dependence. The exclusion of smaller altcoins did not significantly alter the overall spillover configuration, whereas the removal of Bitcoin led to a substantial reduction in total system connectedness. This confirms that spillover behavior is not an artifact of model specification but a structural characteristic of the cryptocurrency market. Overall, the robustness analysis validates the stability and generalizability of the reported spillover and network results across varying assumptions and market conditions.

4.6 Discussion of Key Findings

The empirical results highlight several critical insights into the nature of cryptocurrency markets and their suitability as real-world analytical systems. First, the presence of strong and asymmetric spillover effects confirms that cryptocurrencies function as an integrated financial network rather than independent assets. Market dominance, liquidity concentration, and informational leadership play decisive roles in shaping volatility transmission pathways. Second, the network-based findings reveal a centralized structure in which systemic risk is concentrated among a limited number of dominant assets, increasing vulnerability to cascading failures during periods of stress. Third, the temporal persistence of spillover hierarchies indicates that interconnectedness is a fundamental market property rather than a transient phenomenon. From a broader analytical perspective, these characteristics closely mirror complex engineered systems, where failures propagate through interconnected components and central hubs exert disproportionate influence. The findings therefore reinforce the relevance of computational spillover and network modeling as effective tools for analyzing real-world complexity. By demonstrating predictable structural patterns within an otherwise volatile environment, the results provide a strong empirical foundation for treating cryptocurrency markets as practical systems for advanced analytical modeling and interdisciplinary problem solving.

5. CONCLUSION

This study presented an integrated computational and experimental framework to analyze cryptocurrency spillover dynamics while addressing persistent challenges in engineering education related to real-world problem solving. The empirical findings clearly demonstrate that cryptocurrency markets operate as highly interconnected, nonlinear systems in which volatility and risk are transmitted asymmetrically across assets. Dominant cryptocurrencies, particularly Bitcoin, function as primary transmitters of shocks, shaping the overall stability and behavior of the digital asset ecosystem. Network-based analysis further revealed a hierarchical structure marked by central hubs and peripheral absorbers, highlighting systemic vulnerabilities that resemble those observed in large-scale engineered infrastructures. Beyond the financial insights, the study established that such market dynamics provide a powerful and authentic context for engineering-oriented analysis, as they embody uncertainty, feedback mechanisms, and dynamic interdependencies that conventional classroom models often fail to capture. By embedding spillover modeling and network analysis into an experimental learning framework, the research demonstrated the feasibility of transforming live financial systems into analytical laboratories for engineering problem solving. This approach aligns technical modeling with outcome-based education, enabling learners to engage directly with complex data, interpret emergent behavior, and develop systems-level reasoning. The dual contribution of this work lies in advancing the understanding of cryptocurrency spillover behavior while simultaneously proposing a scalable and data-driven pathway to modernize engineering education. Overall, the findings underscore the value of interdisciplinary integration, showing that computational finance tools can extend beyond market analysis to enhance engineering competence in handling real-world, high-complexity systems.

6. FUTURE WORK

Future research can extend this framework in several meaningful directions. From a computational perspective, incorporating high-frequency cryptocurrency data would enable finer-grained analysis of intraday spillover dynamics and rapid contagion effects. Advanced modeling approaches such as regime-switching models, reinforcement learning, and explainable artificial intelligence could further improve predictive accuracy while preserving interpretability. Expanding the asset universe to include stablecoins, decentralized finance tokens, and cross-market linkages with equities or commodities would also provide a broader view of systemic risk transmission. On the educational front, future studies may implement longitudinal experiments to assess long-term learning outcomes and skill retention among engineering students exposed to crypto-based problem-solving modules. Integrating this framework into full-scale curricula, virtual laboratories, or industry-linked capstone projects could enhance its practical impact. Additionally, comparative studies across engineering disciplines may help identify how financial system modeling influences different domains of problem solving. Such extensions would strengthen the framework's relevance for both computational finance research and the evolving demands of engineering education.

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