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Developing a System Dynamics Model for Analyzing Fluctuations in Major Cryptocurrency Markets

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ABSTRACT

The cryptocurrency market has attracted unprecedented investor attention in recent years. Bitcoin, the world's largest digital currency, has experienced a price increase of more than 1,500% since the beginning of 2017. Despite numerous studies on the future of cryptocurrencies and their volatility, few studies have provided a comprehensive analysis of the broader cryptocurrency market and how cryptocurrencies evolve and fluctuate. The aim of the present study is to develop a system dynamics model for analyzing and forecasting cryptocurrency market fluctuations by considering a comprehensive set of influential variables. While focusing on Bitcoin, this study also examines several other common cryptocurrencies, such as Ethereum, which have received less attention in previous studies. In this study, using a system dynamics approach and Vensim DSS software, a comprehensive model was designed to analyze cryptocurrency market fluctuations. First, through a systematic review of the research literature, 28 influential factors were identified in six main categories, including fundamental, demand-related, macroeconomic, psychological-behavioral, technical and on-chain, and institutional-regulatory factors. Then, through the analysis of causal relationships and feedback loops, four reinforcing loops—price self-reinforcement, network effect, investment and mining, and halving effect—and four balancing loops—affordability, profit-taking, mining difficulty, and regulatory interventions—were mapped. To validate the model, historical data from four major cryptocurrencies—Bitcoin, Ethereum, Litecoin, and Ripple—over the period from 2017 to 2024 were used. The mean absolute percentage error (MAPE) was calculated as 10.5%, and the coefficient of determination (R^2) was 0.88, indicating the acceptable accuracy of the model. The simulation results of five different scenarios, including halving, institutional adoption, strict regulation, global economic crisis, and a combined scenario, showed that the halving event alone leads to a 42% increase in price, institutional adoption leads to a 69% increase in price and a reduction in volatility to 32%, and the combined scenario leads to a 123% increase in price. Furthermore, dynamic correlation analysis showed that the correlation among cryptocurrencies changes under different market conditions, and stablecoins have a weak negative correlation with other cryptocurrencies, ranging from -0.15 to -0.35. Finally, operational composite indices, including the Market Pressure Index (MPI), Network Sentiment Index (NSI), Regulatory Risk Index (RRI), Fundamental Strength Index (FSI), and Composite Volatility Index (CVI), were proposed for monitoring and forecasting fluctuations. The proposed model can be used as a tool for scenario analysis and more informed decision-making by investors and policymakers.

Keywords: system dynamics, cryptocurrency, forecasting, modeling, market volatility, Bitcoin.

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Introduction

The rapid expansion of digital technologies and decentralized financial systems has fundamentally transformed the structure of global financial markets during the past decade. Among these transformations, cryptocurrencies have emerged as one of the most controversial and influential financial innovations. Initially introduced through Bitcoin in 2009, cryptocurrencies gradually evolved from a niche technological experiment into a global financial phenomenon attracting investors, institutions, governments, and regulators worldwide. The cryptocurrency market has experienced substantial growth in market capitalization, transaction volume, and public acceptance, while simultaneously exhibiting extraordinary levels of volatility and uncertainty. The decentralized nature of cryptocurrencies, their dependence on blockchain technology, and the absence of central regulatory authorities have created new opportunities for investment diversification, financial innovation, and digital asset management (1-3). However, these same characteristics have also generated concerns regarding price instability, speculative bubbles, systemic risk, cybercrime, regulatory uncertainty, and market manipulation (4-6).

Cryptocurrency markets are characterized by severe price fluctuations compared with traditional financial assets. Unlike conventional currencies or equity markets, cryptocurrency prices can experience dramatic increases or declines within short periods of time. Bitcoin, Ethereum, and other major cryptocurrencies have repeatedly demonstrated extreme volatility patterns driven by investor sentiment, speculative behavior, macroeconomic conditions, technological developments, and institutional interventions. Such fluctuations have attracted significant academic attention because they challenge traditional financial theories related to market efficiency, asset valuation, and risk management (7-9). The growing importance of cryptocurrencies in international financial systems has therefore increased the necessity for comprehensive models capable of analyzing the dynamic interactions underlying market volatility.

Several studies have emphasized that cryptocurrency volatility cannot be explained through a single factor or isolated economic variable. Instead, cryptocurrency markets operate as complex adaptive systems in which technological, behavioral, macroeconomic, institutional, and regulatory dimensions interact dynamically over time. Traditional econometric approaches, although useful in identifying statistical relationships, often fail to capture nonlinear feedback structures, delayed effects, and endogenous interactions among variables. Consequently, researchers increasingly argue that cryptocurrency markets should be studied using holistic and dynamic analytical frameworks capable of integrating multiple interdependent components simultaneously (10-12).

One of the key dimensions influencing cryptocurrency markets is speculative investor behavior. Cryptocurrency prices are strongly affected by fear, greed, herd behavior, and speculative expectations. The absence of intrinsic valuation benchmarks similar to those existing in traditional equity or commodity markets intensifies the role of investor psychology. Studies have shown that social media trends, online searches, media coverage, and investor sentiment indices significantly affect cryptocurrency demand and price movements. During bullish periods, speculative enthusiasm often generates rapid price acceleration and bubble formation, while negative news and panic selling can produce abrupt market crashes (8, 12, 13). Such behavioral dynamics indicate the existence of reinforcing feedback loops in cryptocurrency systems, where rising prices attract new investors and additional investment demand, thereby amplifying further price increases.

The relationship between cryptocurrency markets and traditional financial markets has also become an important area of investigation. Some researchers argue that cryptocurrencies function as alternative investment assets capable of enhancing portfolio diversification, whereas others contend that cryptocurrencies increasingly exhibit interconnectedness with equity, commodity, and foreign exchange markets. Empirical findings suggest that cryptocurrency markets demonstrate varying degrees of correlation with stock indices, gold prices, and macroeconomic indicators depending on market conditions and global crises (14-16). During periods of financial uncertainty such as the COVID-19 pandemic and banking crises, cryptocurrencies have shown both safe-haven and speculative characteristics. For example, some studies indicate that Bitcoin may serve as a partial hedge against inflation or banking instability, whereas others emphasize its vulnerability to macroeconomic shocks and market contagion (17-19).

The COVID-19 pandemic represented a critical turning point in cryptocurrency market dynamics. Global lockdowns, expansionary monetary policies, rising inflationary pressures, and increased digitalization accelerated public interest in cryptocurrencies and decentralized finance. Simultaneously, the pandemic intensified uncertainty in global financial systems, causing substantial volatility spillovers between cryptocurrency markets and traditional assets. Research conducted during and after the pandemic demonstrated that cryptocurrencies experienced increased sensitivity to macroeconomic uncertainty, investor sentiment, and policy interventions (19-21). Moreover, volatility transmission among cryptocurrencies became more pronounced during periods of crisis, suggesting that dynamic correlations and systemic interdependencies play significant roles in market behavior (7, 14).

Another major factor influencing cryptocurrency markets is technological development and blockchain infrastructure. The utility, scalability, security, and adoption of blockchain networks directly affect investor confidence and long-term market valuation. Cryptocurrencies such as Ethereum have expanded the functionality of blockchain systems beyond simple financial transactions by enabling decentralized applications, smart contracts, decentralized finance, and metaverse-related economic activities (3, 22). The increasing integration of cryptocurrencies into digital ecosystems has strengthened network effects, whereby growth in the number of users and transactions enhances the overall value and attractiveness of the network. This process aligns with Metcalfe's law, which suggests that network value increases exponentially with user participation. Consequently, user adoption and technological innovation constitute critical drivers of cryptocurrency demand and long-term sustainability (1, 2).

Mining mechanisms and blockchain security also contribute significantly to cryptocurrency market dynamics. In proof-of-work cryptocurrencies such as Bitcoin, mining profitability, hashrate fluctuations, and halving events influence supply growth and market scarcity. Halving mechanisms reduce mining rewards over time, thereby restricting new coin supply and potentially increasing price under stable demand conditions. Previous market cycles indicate that Bitcoin halving events often precede substantial bullish periods, although their precise effects vary according to macroeconomic and behavioral conditions (8, 9). Furthermore, changes in network security and mining difficulty affect investor trust and long-term expectations regarding blockchain sustainability.

Institutional adoption has emerged as another transformative force in cryptocurrency markets. In recent years, major corporations, hedge funds, banks, and exchange-traded funds have entered cryptocurrency markets, increasing market legitimacy and attracting large-scale capital inflows. Institutional participation has contributed to greater liquidity, improved market infrastructure, and broader public acceptance. However, it has also intensified connections between cryptocurrency markets and traditional financial systems, increasing the possibility of cross-market contagion during economic crises (18, 23, 24). The approval of Bitcoin exchange-traded funds in several jurisdictions further accelerated institutional integration and significantly influenced market expectations.

Despite the growing institutionalization of cryptocurrencies, regulatory uncertainty remains one of the most influential determinants of market volatility. Governments and central banks worldwide have adopted divergent approaches toward cryptocurrencies, ranging from legal acceptance and regulatory frameworks to outright bans and transaction restrictions. Regulatory announcements frequently trigger substantial price fluctuations because investors interpret such interventions as signals regarding the future legitimacy and accessibility of digital assets (4, 25, 26). In some countries, concerns regarding capital flight, monetary sovereignty, financial crime, and tax evasion have motivated restrictive policies toward cryptocurrency trading and mining activities. Conversely, supportive regulatory environments and institutional frameworks can increase investor confidence and stimulate market growth.

The emergence of decentralized finance and digital monetary systems has also intensified debates concerning the future role of cryptocurrencies in global financial architecture. Some scholars argue that cryptocurrencies represent a challenge to traditional monetary systems and centralized banking structures, whereas others emphasize their speculative and unstable nature (11, 27). Islamic finance scholars have additionally explored the compatibility of cryptocurrencies with ethical and jurisprudential principles, highlighting both opportunities and concerns associated with decentralized digital assets (6, 28). These discussions demonstrate that cryptocurrency markets extend beyond purely financial dimensions and involve broader institutional, political, technological, and social implications.

Although previous studies have provided valuable insights into cryptocurrency behavior, several important research gaps remain. First, many existing studies focus primarily on isolated statistical relationships rather than comprehensive system-wide interactions. Second, a substantial proportion of prior research concentrates exclusively on Bitcoin, despite the growing importance of other major cryptocurrencies such as Ethereum. Third, most traditional econometric models are unable to capture feedback loops, delayed responses, nonlinear relationships, and endogenous interactions among variables. Fourth, limited attention has been devoted to integrating behavioral, macroeconomic, technical, and institutional factors into a unified analytical framework capable of explaining dynamic market evolution (2, 10, 12).

System dynamics methodology provides a suitable analytical approach for addressing these limitations. System dynamics enables researchers to model complex systems characterized by feedback loops, nonlinear relationships, accumulations, and time delays. By integrating causal loop diagrams, stock-and-flow structures, and simulation analysis, system dynamics models can provide deeper understanding of how cryptocurrency market volatility emerges and evolves over time. Such an approach is particularly valuable in cryptocurrency markets because these markets exhibit strong interactions between investor behavior, technological development, institutional interventions, supply-demand mechanisms, and macroeconomic conditions.

Furthermore, scenario analysis within a system dynamics framework allows researchers to evaluate the effects of events such as halving mechanisms, institutional adoption, regulatory shocks, and economic crises on cryptocurrency prices and volatility. This capability is especially important for policymakers, investors, and financial institutions seeking to understand potential future market trajectories and associated risks. The integration of dynamic correlations, behavioral variables, and network effects into a unified model can therefore provide more realistic and practical insights compared with static forecasting approaches.

Given the increasing economic significance of cryptocurrencies, the complexity of their volatility mechanisms, and the limitations of existing analytical approaches, there is a strong need for comprehensive dynamic models capable of explaining and forecasting cryptocurrency market behavior. Therefore, the present study aims to develop a system dynamics model for analyzing and forecasting volatility in major cryptocurrency markets by integrating fundamental, macroeconomic, behavioral, technical, institutional, and regulatory factors within a comprehensive feedback-based framework.

Methods and Materials

The present study is descriptive in nature, as it is based on library studies, prominent websites in this field such as the historical database of CoinMarketCap and similar sources, articles, and journals. In this study, an attempt has been made to examine cryptocurrency market fluctuations by developing a system dynamics model. The statistical population of the present study includes major cryptocurrencies, namely Bitcoin and Ethereum, which are analyzed and examined across different time periods.

The data collection method in this study is field-based. By studying different price movement patterns in the cryptocurrency market and examining available documents, records, and reports on the factors affecting fluctuations, the study seeks to identify a predictable pattern in the cryptocurrency market.

Considering the research topic, theoretical foundations, and research objectives, the system dynamics model was designed and analyzed using Vensim DSS software.

System dynamics analysis is usually conducted using specialized software, because the analytical power of this approach is maximized through computer simulations. One of the most common software packages used in system dynamics simulation is Vensim. The stages of system dynamics simulation include the following:

1. Defining the problem boundaries
2. Determining the most important stocks and the flows that change them
3. Identifying the sources of information affecting the flows
4. Determining the main feedback loops
5. Drawing the causal loop diagram connecting stocks, flows, and information sources
6. Writing the equation that determines the flow
7. Determining the parameters and initial conditions based on statistical methods, expert opinions, and data obtained from market research
8. Simulating the model and analyzing the results

Findings and Results

Based on the systematic review of the literature and prior studies, the factors affecting cryptocurrency market volatility were identified and classified into six main categories and 28 subfactors. The frequency of each factor across 31 credible sources was used as an indicator of its relative importance. The results show that psychological-behavioral variables, demand-related variables, regulatory factors, and core technical network variables have the highest recurrence in the reviewed sources and therefore constitute the most influential dimensions of cryptocurrency volatility.

Table 1. Factors Affecting Cryptocurrency Market Volatility

Category	Key Factor	Operational Variables	Frequency in Sources	Relative Importance
Fundamental factors	Circulating supply	Number of mined coins, cryptocurrency inflation rate	28	Very high

Fundamental factors	Mining mechanism	Mining difficulty, mining reward, electricity cost	24	High
Fundamental factors	Maximum supply	Total supply cap, halving date	26	High
Fundamental factors	Token burn rate	Supply-reduction mechanism, deflationary policies	18	Medium
Demand-related factors	Trading volume	Daily trading volume, liquidity	29	Very high
Demand-related factors	Number of active addresses	Active wallets, growth of new users	27	High
Demand-related factors	Number of transactions	Daily transactions, transaction speed	25	High
Demand-related factors	Transaction fees	Average fee, cost of network use	19	Medium
Macroeconomic factors	U.S. dollar exchange rate	U.S. Dollar Index (DXY)	22	High
Macroeconomic factors	Interest rate	Federal Reserve interest rate, Treasury yields	20	Medium
Macroeconomic factors	Stock indices	S&P 500, Nasdaq, global indices	21	Medium
Macroeconomic factors	Gold price	Global gold price, safe-haven assets	17	Medium-low
Macroeconomic factors	Global inflation	Inflation rates in major economies	16	Medium-low
Psychological-behavioral factors	Fear and Greed Index	Market sentiment measure	30	Very high
Psychological-behavioral factors	Internet search activity	Google Trends, keyword searches	28	Very high
Psychological-behavioral factors	Social media activity	Related tweets, number of posts, likes, and shares	26	High
Psychological-behavioral factors	Investor sentiment	Surveys, sentiment indices	24	High
Psychological-behavioral factors	Herding behavior	FOMO, panic selling	23	High
Technical and on-chain factors	Network difficulty and hashrate	Network processing power, network security	27	High
Technical and on-chain factors	Mining reward	Block reward, halving events	25	High
Technical and on-chain factors	Number of whales	High-balance addresses, ownership concentration	22	Medium
Technical and on-chain factors	Developer activity	Number of GitHub commits, updates	21	Medium
Technical and on-chain factors	Network upgrades	Hard forks, protocol updates	19	Medium
Institutional and regulatory factors	Government regulation	New laws, regulatory positions	28	Very high
Institutional and regulatory factors	Institutional adoption	Entry of large companies, ETFs	26	High
Institutional and regulatory factors	Sanctions and restrictions	Country-level bans, exchange restrictions	24	High
Institutional and regulatory factors	Central bank support	CBDCs, central bank positions	20	Medium
Institutional and regulatory factors	Taxes	Tax laws, capital gains tax rate	18	Medium

Based on the identified factors, a causal loop diagram was designed for the cryptocurrency volatility system. The model includes four reinforcing loops and four balancing loops. The reinforcing loops are responsible for growth acceleration, speculative escalation, and price bubbles, whereas the balancing loops act as corrective mechanisms that limit unlimited price growth.

The first reinforcing loop, R1, represents price self-reinforcement. In this loop, an increase in cryptocurrency price increases media and investor attention, which increases demand and produces further price growth. The second reinforcing loop, R2, represents the network effect: an increase in the number of users increases transactions and usability, which increases network value according to Metcalfe’s law, strengthens demand, raises price, and attracts more users. The third reinforcing loop, R3, represents investment and mining: a price increase raises mining profitability, increases hashrate, improves network security, strengthens investor confidence, and further increases demand. The fourth reinforcing loop, R4, represents the halving mechanism: a reduction in mining reward decreases new supply, increases scarcity, raises price under stable demand conditions, and increases attention to the next halving event.

The model also includes four balancing loops. B1, the affordability loop, shows that price increases reduce purchasing power and access for retail investors, thereby reducing demand and moderating price. B2, the profit-taking loop, indicates that rapid price increases increase the motivation of early investors to realize profits, increasing selling pressure and reducing price. B3, the mining difficulty loop, shows that an increase in hashrate raises network difficulty, increases mining cost, reduces profitability for marginal miners, and stabilizes hashrate. B4, the regulatory intervention loop, indicates that sharp price increases and price bubbles increase regulatory concerns, leading to stricter regulation, reduced accessibility, lower demand, and price decline.

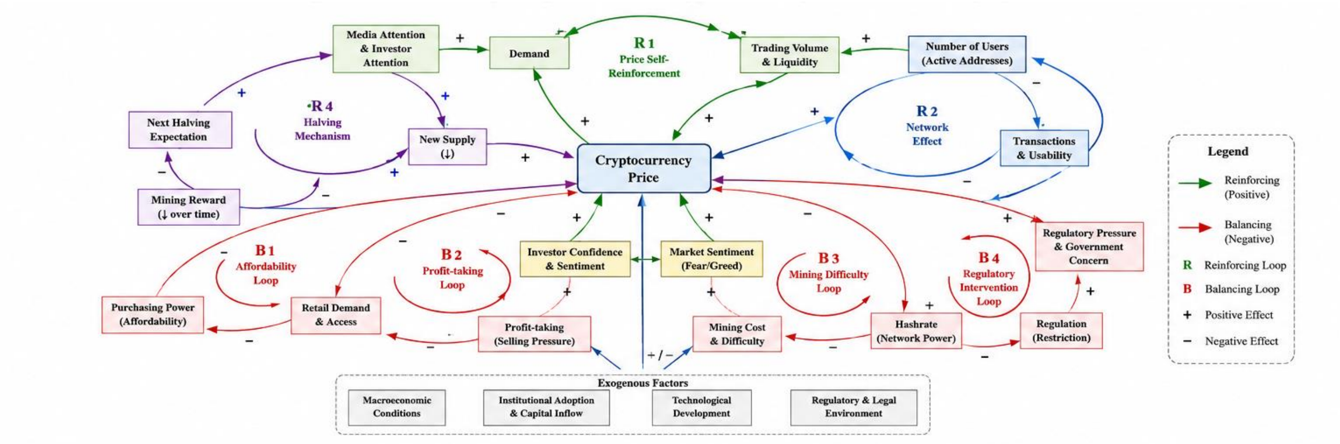

Figure 1. Causal Loop Diagram of the Cryptocurrency Market Volatility System

The stock and flow structure of the model was then developed. The main stocks included cryptocurrency price, number of active users, circulating supply, network hashrate, market capitalization, and investor confidence. Cryptocurrency price was measured in U.S. dollars; active users were represented by the number of wallets with transactions; circulating supply was measured by the number of coins available in the market; network hashrate was measured in hashes per second; market capitalization was calculated as the product of price and circulating supply; and investor confidence was represented as a composite index ranging from 0 to 100.

The main flows of the model included the price change rate, user acquisition rate, user exit rate, mining rate, and hashrate change rate. The price change rate was affected by supply-demand imbalance and market sentiment. The user acquisition rate was influenced by price, media attention, and usability. The user exit rate was affected by high transaction fees and scalability problems. The mining rate depended on hashrate, mining reward, and network difficulty. The hashrate change rate was influenced by mining profitability and equipment prices.

The following equations were used as the core mathematical structure of the model:

$$MC_t = P_t \times CS_t$$

where $MC_t$is market capitalization at time t, $P_t$is cryptocurrency price, and $CS_t$is circulating supply.

$$V_{network,t} = k \times U_t^2$$

where $V_{network,t}$ is network value, U_t is the number of active users, and k is the network-effect coefficient. This formulation reflects Metcalfe's law.

$$\Delta P_t = f(D_t - S_t, Sent_t, Liq_t, RegRisk_t, Macro_t)$$

where ΔP_t is the price change rate, $D_t - S_t$ is the demand-supply imbalance, $Sent_t$ is market sentiment, Liq_t is liquidity, $RegRisk_t$ is regulatory risk, and $Macro_t$ represents macroeconomic conditions.

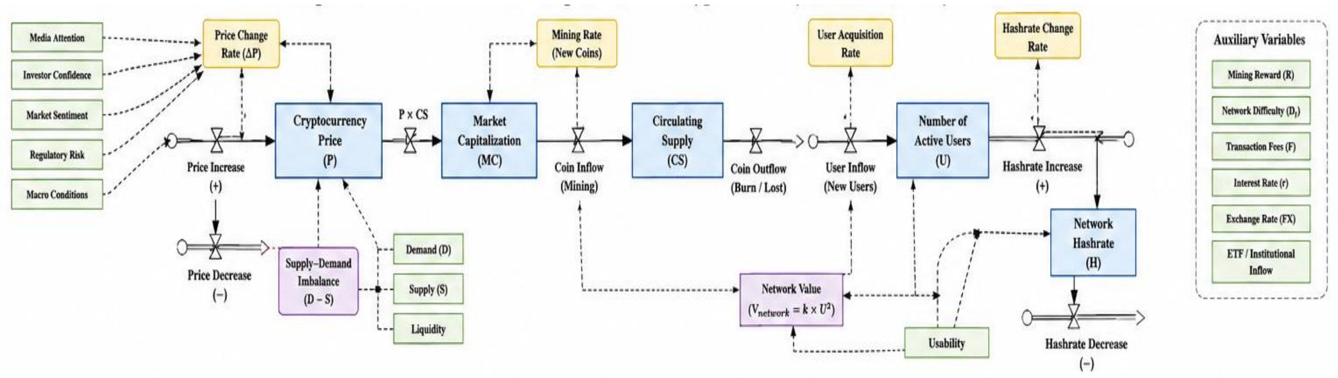

Figure 2. Stock and Flow Diagram of the Cryptocurrency Market Volatility Model

The designed model was validated using historical data from four major cryptocurrencies, namely Bitcoin, Ethereum, Litecoin, and Ripple/XRP, over the period from 2017 to 2024. The behavior reproduction test showed that the model had acceptable predictive accuracy. The average mean absolute percentage error was 10.5%, and the average coefficient of determination was 0.88.

Table 2. Model Validation, Extreme-Condition Tests, and Parameter Sensitivity Results

Validation Component	Item	Test Period, Condition, or Change	Model Result	Interpretation
Behavior reproduction	Bitcoin	2017–2024	MAPE = 8.3%; R^2 = 0.94	Strong historical behavior reproduction
Behavior reproduction	Ethereum	2017–2024	MAPE = 10.1%; R^2 = 0.89	Acceptable historical behavior reproduction
Behavior reproduction	Litecoin	2017–2024	MAPE = 11.5%; R^2 = 0.86	Acceptable historical behavior reproduction
Behavior reproduction	Ripple/XRP	2017–2024	MAPE = 12.2%; R^2 = 0.83	Acceptable historical behavior reproduction
Behavior reproduction	Average	2017–2024	MAPE = 10.5%; R^2 = 0.88	Overall acceptable model accuracy
Extreme-condition test	Hashrate = 0	Price expected to approach zero	Confirmed	Acceptable
Extreme-condition test	Supply = maximum	Downward pressure on price expected	Confirmed	Acceptable
Extreme-condition test	Demand = 0	Price expected to approach intrinsic value	Confirmed	Acceptable
Extreme-condition test	Media attention = 0	Volatility expected to decrease	Confirmed	Acceptable
Sensitivity test	Price elasticity of demand	±20% change	±14% effect on price after 12 months	Moderate sensitivity
Sensitivity test	Network-effect coefficient	±20% change	±18% effect on price after 12 months	Relatively strong sensitivity
Sensitivity test	News sensitivity	±20% change	±22% effect on price after 12 months	Strong sensitivity
Sensitivity test	Mining reward rate	50% reduction due to halving	+25% effect on price after 12 months	Strong positive supply-side effect

The main validation equations were as follows:

$$MAPE = \frac{100}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right|$$

where A_t is the actual value and F_t is the forecast value.

$$R^2 = 1 - \frac{\sum_{t=1}^{n} (A_t - F_t)^2}{\sum_{t=1}^{n} (A_t - \bar{A})^2}$$

where A_t is the actual value, F_t is the forecast value, and $\bar{A}$ is the mean of actual values.

$$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^{n} (A_t - F_t)^2}$$

The RMSE criterion was also used during the calibration process in Vensim DSS to minimize the distance between model outputs and actual market data for the 2020–2024 period.

The validated model was used to analyze the effects of five scenarios on Bitcoin price and volatility. The scenarios included the continuation of current trends, halving, institutional adoption, strict regulation, global economic crisis, and a combined scenario consisting of halving and institutional adoption.

Table 3. Simulation Results of Different Scenarios for Bitcoin

Scenario	Description	Price After 24 Months (USD)	Change Compared with Baseline	Annual Volatility (Standard Deviation)
S0: Baseline	Continuation of current trends	65,000	—	45%
S1: Halving	Occurrence of halving event with 50% reward reduction	92,000	+42%	58%
S2: Institutional adoption	Entry of ETFs and institutional investors	110,000	+69%	32%
S3: Strict regulation	Implementation of broad legal restrictions	38,000	-42%	62%
S4: Global economic crisis	Economic recession and capital flight to safe-haven assets	85,000	+31%	55%
S5: Combined scenario	Joint effect of halving and institutional adoption	145,000	+123%	48%

The results show that the institutional adoption scenario produced the most favorable balance between price growth and volatility reduction. Under this scenario, the Bitcoin price increased by 69%, while annual volatility decreased to 32%, compared with 45% in the baseline scenario. This finding indicates that institutional investors may contribute not only to price growth but also to market stabilization by increasing liquidity depth and professionalizing market behavior.

The combined scenario produced the strongest price effect. The simultaneous occurrence of halving and institutional adoption increased price by 123%, which was greater than the simple additive effect of the two separate scenarios. This indicates a synergistic interaction between a fundamental supply-side shock and a structural demand-side expansion.

The strict regulation scenario produced a 42% decline in price and increased volatility to 62%. Therefore, regulatory shocks were identified as one of the most destabilizing forces in the cryptocurrency market. The global economic crisis scenario increased price by 31%, suggesting that under certain macroeconomic conditions, Bitcoin may partially function as a perceived alternative or safe-haven asset, although with relatively high volatility.

The time-sensitivity analysis showed that the model can reproduce the direction and approximate magnitude of major historical market events. For Bitcoin halving in May 2020, the model estimated a 50% price increase over the following 12 months, while the actual effect was approximately +46%, resulting in a model error of +4%. For the China ban in September 2021, the model estimated a 35% decline, compared with an actual decline of approximately 32%, resulting in an error of -3%. For Bitcoin ETF approval in January 2024, the model estimated a 30% increase, while the actual effect was approximately +35%, resulting in an error of -5%. For the FTX collapse in November 2022, the model estimated a 45% decline, while the actual effect was approximately -40%, resulting in an error of -5%.

The model also showed that different feedback loops dominate under different market conditions. In bull markets, R1, price self-reinforcement, and R2, the network effect, dominate the system and accelerate growth. In bear markets, B2, profit-taking, and B4, regulatory intervention, become dominant and intensify decline. After halving events, R4, the halving loop, and R3, the investment and mining loop, dominate and create upward pressure on price. During regulatory shocks, B4 dominates and produces price decline. During periods of sustainable growth, R2 and R3 jointly support more balanced expansion through network growth and security improvement.

Table 4. Event Effects, Dominant Feedback Loops, and Dynamic Correlations

Analytical Dimension	Market Condition, Event, or Pair	Model Result	Observed or Systemic Pattern	Interpretation
Event effect	Bitcoin halving, May 2020	+50% over 12 months	Actual effect: +46%; model error: +4%	Model closely reproduced the post-halving price effect
Event effect	China ban, September 2021	-35%	Actual effect: -32%; model error: -3%	Model reproduced the negative regulatory shock
Event effect	Bitcoin ETF approval, January 2024	+30%	Actual effect: +35%; model error: -5%	Model slightly underestimated the positive institutional effect
Event effect	FTX collapse, November 2022	-45%	Actual effect: -40%; model error: -5%	Model reproduced the direction and magnitude of crisis shock
Dominant loop	Bull market	R1 and R2	Reinforcing loops	Acceleration of growth
Dominant loop	Bear market	B2 and B4	Balancing loops	Intensification of decline
Dominant loop	Post-halving period	R4 and R3	Reinforcing loops	Price increase
Dominant loop	Regulatory shock	B4	Balancing loop	Price decrease
Dominant loop	Sustainable growth	R2 and R3	Reinforcing loops	Balanced growth
Dynamic correlation	Bitcoin–Ethereum	Normal: 0.78; bull: 0.85; bear: 0.82; regulatory shock: 0.65	Correlation increases in bull and bear markets but declines under regulatory shock	High co-movement with regime sensitivity
Dynamic correlation	Bitcoin–Litecoin	Normal: 0.65; bull: 0.72; bear: 0.70; regulatory shock: 0.52	Correlation remains positive across all regimes	Moderate-to-high co-movement
Dynamic correlation	Ethereum–Ripple/XRP	Normal: 0.52; bull: 0.60; bear: 0.58; regulatory shock: 0.40	Correlation weakens under regulatory shock	Medium regime-dependent correlation
Dynamic correlation	Bitcoin–stablecoins	Normal: -0.15; bull: -0.10; bear: -0.25; regulatory shock: -0.35	Weak negative correlation	Stablecoins partially function as defensive portfolio components

The dynamic correlation results indicate that cryptocurrency correlations are not constant over time. In bull markets, correlations increase, as shown by the Bitcoin–Ethereum correlation rising from 0.78 under normal conditions to 0.85 in bull markets. This pattern reflects the contagion of positive sentiment and herding behavior. In bear markets, correlations remain high, confirming the existence of risk contagion. Under regulatory shocks, correlations decline because different cryptocurrencies respond differently depending on their governance structure, legal exposure, and market use case. Stablecoins show weak negative correlations with major cryptocurrencies, ranging from -0.15 to -0.35, supporting their defensive role in cryptocurrency portfolios.

Based on the model, five composite indices were proposed for monitoring and forecasting market volatility: the Market Pressure Index, Network Sentiment Index, Regulatory Risk Index, Fundamental Strength Index, and Composite Volatility Index. These indices integrate on-chain data, market sentiment, regulatory news, and fundamental network variables to provide a broader view of market conditions.

Table 5. Proposed Monitoring Indices and Baseline Forecasts for 2025–2030

Component	Variable or Index	2025	2026	2027	2028	2029	2030	Application or Warning Range
Proposed index	Market Pressure Index (MPI)	—	—	—	—	—	—	Combines price change, trading volume, and order book data; warning range: >0.80 or <-0.20
Proposed index	Network Sentiment Index (NSI)	—	—	—	—	—	—	Combines Google Trends, tweets, and wallet searches; warning range: >0.70 indicates FOMO
Proposed index	Regulatory Risk Index (RRI)	—	—	—	—	—	—	Combines regulatory news, legal changes, and restrictions; warning range: >0.60
Proposed index	Fundamental Strength Index (FSI)	—	—	—	—	—	—	Combines hashrate, active addresses, and developer activity; warning range: <0.30 indicates weakness
Proposed index	Composite Volatility Index (CVI)	—	—	—	—	—	—	Weighted combination of MPI, NSI, RRI, and FSI; warning range: >0.70 indicates severe volatility
Baseline forecast	Average predicted Bitcoin price, USD	68,450	72,110	85,230	95,500	112,340	125,000	Annual average price under the business-as-usual scenario
Baseline forecast	Price standard deviation in the model, USD	12,340	14,560	18,990	22,450	28,780	32,100	Annual model-based price dispersion
Baseline forecast	Average predicted market capitalization, trillion USD	1.35	1.42	1.68	1.88	2.21	2.46	Annual average market capitalization
Baseline forecast	Maximum annual market capitalization, trillion USD	1.58	1.67	2.01	2.25	2.65	2.98	Maximum market capitalization within each year
Baseline forecast	Average confidence index	72	70	75	78	80	82	Average annual investor confidence
Baseline forecast	Average net capital inflow, billion USD/month	1.20	1.10	1.80	2.00	2.30	2.50	Mean monthly net capital inflow
Baseline forecast	Average volatility index, Crypto_VIX	58	62	60	58	55	52	Average annual cryptocurrency volatility index

The Composite Volatility Index was formulated as follows:

$$CVI_t = w_{MPI}MPI_t + w_{NSI}NSI_t + w_{RRI}RRI_t + w_{FSI}(1 - FSI_t)$$

$$w_{MPI} + w_{NSI} + w_{RRI} + w_{FSI} = 1$$

In this formulation, MPI_trepresents market pressure, NSI_trepresents network sentiment, RRI_trepresents regulatory risk, and FSI_trepresents fundamental strength. Because higher fundamental strength reduces volatility risk, the term $(1-FSI_t)$is used in the composite index.

The baseline simulation was implemented in Vensim DSS. First, the causal loop diagram was developed by entering the identified reinforcing and balancing loops and the core variables into the model environment. Second, the stock and flow diagram was designed by defining stocks, flows, and auxiliary variables. Third, the mathematical equations were entered into the Equation Editor. Lookup functions were used for variables such as the effect of interest rates on capital flow. Fourth, the initial values and parameters were entered. The initial conditions at $t = 0$, equivalent to December 2024, were defined as follows:

$$MC(0) = 1.44 \text{ trillion USD}$$

$$IC(0) = 75$$

$$CS(0) = 19.65 \text{ million BTC}$$

The parameters were determined through calibration using SyntheSim and optimization procedures to minimize RMSE between model outputs and actual data for the 2020–2024 period. The baseline simulation was then run over a six-year horizon from 2025 to 2030 using a monthly time step. The baseline scenario assumed continuity in macroeconomic trends, including interest rates and economic growth, and the absence of major unexpected shocks.

The baseline forecast indicates a gradual upward trend in Bitcoin price and total market capitalization from 2025 to 2030. The average predicted Bitcoin price increases from USD 68,450 in 2025 to USD 125,000 in 2030. Average predicted market capitalization rises from USD 1.35 trillion to USD 2.46 trillion over the same period, while the maximum annual market capitalization reaches USD 2.98 trillion in 2030. The model also predicts that investor confidence will improve from 72 in 2025 to 82 in 2030, while average monthly net capital inflow will rise from USD 1.20 billion to USD 2.50 billion. At the same time, the Crypto_VIX decreases from 58 in 2025 to 52 in 2030, suggesting that under the baseline scenario, the market may gradually become deeper, more liquid, and relatively less volatile.

Overall, the findings show that cryptocurrency price volatility is a complex and multidimensional phenomenon arising from the dynamic interaction of fundamental, demand-related, macroeconomic, psychological-behavioral, technical and on-chain, and institutional-regulatory factors. The proposed system dynamics model identified 28 influential factors and mapped the feedback loops among them, thereby providing a comprehensive representation of the dynamics governing this market.

The validation results, with an average MAPE of 10.5% and an average R^2 of 0.88 for four major cryptocurrencies, indicate that the model has acceptable accuracy in reproducing historical market behavior. This result supports the view that although cryptocurrency markets are highly volatile, their price movements are not entirely random and contain systematic patterns that can be identified and modeled.

A central finding of the study is that reinforcing loops such as price self-reinforcement, network effects, investment and mining, and halving mechanisms explain rapid growth, exponential movements, and bubble formation in cryptocurrency markets. Conversely, balancing loops such as affordability constraints, profit-taking, mining difficulty, and regulatory intervention act as corrective mechanisms that prevent unlimited growth.

The scenario results show that institutional adoption has a strong stabilizing role by increasing price and reducing volatility at the same time. Halving creates strong upward pressure on price, but with higher volatility. Strict regulation produces the strongest negative shock, reducing price and increasing volatility. The combined scenario shows a synergistic effect between supply reduction and institutional demand expansion.

The dynamic correlation analysis shows that correlations among major cryptocurrencies increase during bull and bear markets but decrease under regulatory shocks. This finding has direct implications for portfolio management, because diversification benefits vary across market regimes. Stablecoins display weak negative correlations with major cryptocurrencies and may therefore serve as partial defensive assets during turbulent periods.

Finally, the proposed indices, especially the Composite Volatility Index, provide operational tools for market monitoring, early warning, and risk management. These indices combine market pressure, network sentiment, regulatory risk, and fundamental strength, making them useful for investors, analysts, and policymakers seeking to monitor cryptocurrency volatility more systematically.

Discussion and Conclusion

The present study aimed to develop a system dynamics model for analyzing and forecasting volatility in major cryptocurrency markets by integrating fundamental, macroeconomic, behavioral, technical, institutional, and regulatory variables within a comprehensive dynamic framework. The findings demonstrated that cryptocurrency market volatility is a multidimensional and nonlinear phenomenon emerging from the interaction of multiple interconnected factors operating through reinforcing and balancing feedback loops. The proposed model identified 28 influential variables categorized into six principal dimensions and successfully reproduced the historical behavior of major cryptocurrencies with acceptable predictive accuracy. The average forecasting error of 10.5% and coefficient of determination of 0.88 indicate that despite the highly volatile nature of cryptocurrency markets, systematic patterns and dynamic structures governing price fluctuations can be identified and modeled. These findings support previous studies emphasizing that cryptocurrency volatility is not entirely random and is strongly influenced by structural, behavioral, and macroeconomic drivers (7-9).

One of the most important findings of the present study concerns the dominant role of reinforcing feedback loops in generating rapid price growth and speculative bubbles. The model showed that the price self-reinforcement loop significantly contributes to the acceleration of bullish trends. In this loop, rising prices increase media attention and investor interest, which stimulate additional demand and create further price appreciation. This mechanism explains why cryptocurrency markets often display exaggerated and nonlinear reactions to news and investor sentiment. These findings align with studies demonstrating the importance of speculative behavior, herding effects, and emotional reactions in cryptocurrency markets (12, 13). Previous research has similarly shown that speculative dynamics and investor psychology amplify volatility and increase the likelihood of bubble formation in digital asset markets (4, 28).

The network-effect reinforcing loop also emerged as a major determinant of long-term cryptocurrency growth. According to the findings, increases in active users, transaction activity, and usability strengthen network value and consequently increase demand and market valuation. This finding is consistent with blockchain-based economic theories emphasizing the importance of user adoption and technological scalability in determining cryptocurrency value (1, 2). The role of Ethereum and decentralized applications in expanding the utility of blockchain systems further supports this argument (3, 22). The present study demonstrated that network growth operates as a reinforcing mechanism capable of generating sustained expansion in cryptocurrency ecosystems, particularly when technological innovation and institutional participation occur simultaneously.

Another significant finding relates to the mining and halving mechanisms embedded within cryptocurrency systems. The simulation results indicated that halving events produce substantial upward pressure on prices due to the reduction in new supply. The model predicted an average post-halving price increase of approximately 42%, which is broadly consistent with historical Bitcoin market cycles. This finding confirms the importance of scarcity mechanisms in cryptocurrency valuation and supports studies suggesting that supply-side constraints significantly influence market expectations and investor behavior (8, 9). The mining-security loop identified in the model also highlights the relationship between mining profitability, network hashrate, security, and investor confidence. As prices increase, mining activity becomes more profitable, strengthening network security and further enhancing investor trust. This dynamic demonstrates the endogenous nature of cryptocurrency market evolution and the importance of technical infrastructure in sustaining long-term growth.

In contrast to reinforcing mechanisms, the balancing loops identified in the study acted as stabilizing forces limiting excessive market expansion. Among these balancing loops, regulatory intervention emerged as one of the most influential determinants of market correction and volatility reduction. The simulation results showed that strict regulatory scenarios could reduce cryptocurrency prices by approximately 42% while simultaneously increasing volatility. These findings are consistent with previous studies emphasizing the vulnerability of cryptocurrency markets to legal restrictions, monetary policies, and government interventions (6, 25, 26). Regulatory uncertainty remains one of the primary sources of instability in cryptocurrency markets because investors interpret policy actions as indicators of future market accessibility and legitimacy. The findings also correspond with evidence from real-world events such as the Chinese cryptocurrency restrictions and the associated market decline.

The present study further demonstrated that institutional adoption plays a critical role in shaping cryptocurrency market behavior. The institutional adoption scenario produced the highest combination of price growth and volatility reduction. Specifically, the model predicted that the entry of exchange-traded funds and institutional investors would increase prices while reducing annual volatility from 45% to 32%. This finding suggests that institutional participation contributes to deeper liquidity, more professional trading behavior, and greater market efficiency. These results align with prior studies arguing that institutional integration enhances the maturity and legitimacy of cryptocurrency markets (23, 24). The findings are also consistent with recent empirical evidence showing that institutional acceptance of Bitcoin through ETFs and regulated investment products has increased investor confidence and expanded capital inflows into digital asset markets (18).

The results regarding macroeconomic uncertainty and financial crises provide additional insight into the evolving role of cryptocurrencies within global financial systems. The simulation results indicated that global economic crises may increase demand for cryptocurrencies under certain conditions, particularly when investors perceive digital assets as alternatives to unstable traditional financial systems. This finding partially supports previous research suggesting that Bitcoin can function as a hedge or safe-haven asset during periods of financial instability (17). However, the model also showed that cryptocurrencies remain highly volatile during such periods, indicating that their safe-haven properties are limited and context dependent. These findings align with studies emphasizing that cryptocurrencies simultaneously exhibit speculative and defensive characteristics depending on prevailing market conditions (14, 16).

Another important contribution of the present study involves the analysis of dynamic correlations among cryptocurrencies. The findings showed that correlations among major cryptocurrencies are not stable over time and vary according to market conditions. During bullish and bearish periods, correlations increased substantially, indicating strong contagion effects and collective investor behavior. However, under regulatory shocks, correlations weakened because different cryptocurrencies responded differently according to their institutional structures, technological characteristics, and regulatory exposure. These findings support previous studies demonstrating volatility spillovers and dynamic interconnectedness among cryptocurrency markets (7, 20). The results further suggest that diversification benefits in cryptocurrency portfolios are highly conditional and may diminish during periods of systemic market stress.

The negative correlations identified between stablecoins and major cryptocurrencies also carry important implications for portfolio management and risk mitigation. Stablecoins demonstrated weak but consistent negative relationships with volatile cryptocurrencies, indicating their potential role as defensive instruments during periods of market turbulence. This finding is particularly important for investors seeking short-term risk reduction strategies within digital asset portfolios. Previous studies discussing cryptocurrency diversification and portfolio optimization similarly emphasize the importance of incorporating low-volatility assets to reduce exposure to market shocks (23, 24).

The proposed composite monitoring indices represent another major contribution of the study. The Market Pressure Index, Network Sentiment Index, Regulatory Risk Index, Fundamental Strength Index, and Composite Volatility Index collectively provide practical tools for monitoring real-time market conditions and forecasting short-term volatility. Among these indices, the Composite Volatility Index demonstrated particularly strong predictive capability for identifying periods of severe market turbulence. By integrating on-chain metrics, market sentiment, macroeconomic conditions, and regulatory variables, these indices provide a multidimensional assessment of cryptocurrency market risk. This finding supports arguments that cryptocurrency analysis requires integrated frameworks rather than isolated financial indicators (4, 10).

Compared with previous studies, the present research offers several methodological and conceptual innovations. First, unlike many earlier studies that focused on a limited number of variables, the present model integrated 28 influential factors across six major dimensions. Second, whereas many prior investigations concentrated primarily on Bitcoin, this study incorporated multiple major cryptocurrencies and examined their dynamic interactions. Third, the use of system dynamics methodology enabled the modeling of nonlinear feedback loops, accumulations, delays, and endogenous interactions that are difficult to capture using conventional econometric approaches. Fourth, the simulation of multiple scenarios provided deeper insight into possible future market trajectories and the interaction effects of institutional, regulatory, and macroeconomic events. Finally, the operational composite indices proposed in the study provide practical tools for investors, analysts, and policymakers involved in cryptocurrency risk management and market monitoring.

The findings also carry important theoretical implications. The study demonstrates that cryptocurrency markets should be understood as adaptive and evolving systems rather than isolated speculative assets. Market volatility emerges through continuous interaction between technological development, investor behavior, macroeconomic conditions, institutional adoption, and regulatory responses. This perspective aligns with heterodox and institutional approaches emphasizing the complexity and evolutionary nature of digital financial systems (11, 27). The integration of behavioral finance, network economics, and system dynamics within a unified analytical framework therefore contributes to a more comprehensive understanding of cryptocurrency market behavior.

At the practical level, the findings suggest that investors and policymakers should pay close attention not only to price trends but also to broader structural indicators such as network activity, institutional participation, regulatory developments, and investor sentiment. The results indicate that sustainable cryptocurrency growth depends on balanced interactions among technological innovation, regulatory clarity, market confidence, and institutional infrastructure. Excessive speculation without corresponding network development or institutional support may increase the likelihood of bubbles and market instability. Conversely, balanced growth supported by institutional adoption and technological progress may reduce volatility and improve long-term market sustainability.

The present study therefore provides evidence that cryptocurrency market fluctuations are generated through interconnected dynamic mechanisms rather than isolated events. By identifying the reinforcing and balancing loops governing market behavior, the study offers a comprehensive explanation for the emergence of speculative cycles, contagion effects, regulatory shocks, and long-term market evolution in cryptocurrency systems.

One limitation of the present study is that the model focused primarily on major cryptocurrencies such as Bitcoin, Ethereum, Litecoin, and Ripple, while many emerging digital assets and decentralized finance platforms were not included. In addition, although the model integrated a broad range of variables, certain qualitative dimensions such as political uncertainty, geopolitical conflict, and informal investor networks were difficult to quantify precisely. The forecasting results are also dependent on the assumptions embedded within the simulation scenarios and may vary under unexpected technological or macroeconomic disruptions.

Future studies are recommended to expand the model by incorporating decentralized finance protocols, non-fungible token ecosystems, artificial intelligence-based trading systems, and cross-border digital payment infrastructures. Researchers may also examine the effects of geopolitical tensions, central bank digital currencies, and environmental sustainability concerns on cryptocurrency market dynamics. Furthermore, integrating machine learning techniques with system dynamics models could improve forecasting precision and adaptive scenario analysis in rapidly changing financial environments.

From a practical perspective, the findings of the present study suggest that investors, policymakers, and financial institutions should adopt multidimensional monitoring systems for cryptocurrency markets rather than relying solely on price-based indicators. Policymakers should design balanced regulatory frameworks capable of reducing systemic risk without suppressing technological innovation. Investors should continuously evaluate market sentiment, institutional participation, network activity, and regulatory developments when making portfolio decisions. Financial institutions and exchanges may also utilize the proposed composite indices as early-warning mechanisms for identifying periods of excessive volatility and potential market instability.

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Authors' Contributions

All authors equally contributed to this study.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

All ethical principles were adheried in conducting and writing this article.

Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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