Analysis of Economic Systems Using Complex Systems Simulation Models

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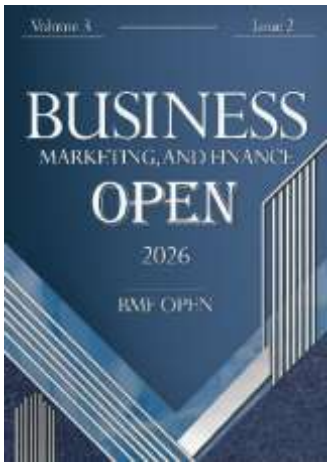

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Abstract: This study analyzes economic systems through complex systems simulation models. The impact of interest rate changes on three key economic variables, including the inflation rate, economic growth, and the unemployment rate, has been examined. Interest rate fluctuations, as one of the primary instruments of monetary policy, have extensive effects on economic variables. After data collection, simulation models such as agent-based models or network models are designed and implemented to simulate the complex interactions among various economic variables. At this stage, the NetLogo software is used to implement the models with high accuracy and to effectively run multiple simulations. The simulation results indicate that in the short term, an increase in the interest rate leads to a reduction in inflation and economic growth, but in the long term, this increase may cause a decline in production and a rise in unemployment. Conversely, a decrease in the interest rate may, in the short term, stimulate economic growth and reduce unemployment, but in the long term, it could lead to high inflation and economic crises. Ultimately, this study recommends that economic policymakers adjust interest rates carefully and with consideration of economic conditions and long-term forecasts in order to prevent adverse effects.

Keywords: interest rate, inflation, economic growth, unemployment, monetary policy, economic simulation, key economic variables.

1. Introduction

The analysis of economic systems has increasingly shifted toward complexity-based approaches that capture heterogeneity, nonlinearity, and network interdependencies. Traditional macroeconomic models often assume equilibrium and representative agents, but such assumptions fail to account for emergent behaviors, systemic risk, and adaptive dynamics in real-world economies. Complexity economics emphasizes the study of interactions among heterogeneous agents and institutions, giving rise to patterns and dynamics not reducible to individual components [1]. This paradigm has opened avenues for employing agent-based modeling (ABM), network analysis, and evolutionary frameworks to understand innovation diffusion, policy impacts, and systemic vulnerabilities.

Agent-based modeling has become central in economics and finance research due to its ability to model agents with bounded rationality, adaptive expectations, and diverse strategies. This methodology departs from the representative agent framework by allowing heterogeneity and decentralized interactions, leading to emergent macro-level patterns [2]. ABM has been particularly effective in macroeconomic analysis, as it captures business cycle dynamics, credit market instability, and monetary policy transmission. Studies highlight that macroeconomic

modeling with heterogeneous agents promotes transparency, reproducibility, and more robust insights compared to traditional methods [3]. The development of agent-based macroeconomics has laid a foundation for analyzing growth, distribution, and systemic risk in ways not possible under conventional models [4].

The interplay between financial networks and policy transmission mechanisms further underscores the importance of complexity-based perspectives. Financial networks act as channels through which shocks propagate and amplify across institutions. The physics of financial networks provides insights into structural vulnerabilities, contagion risks, and systemic resilience [5]. Empirical and theoretical work demonstrates how monetary policy affects interbank markets, credit allocation, and systemic stability via network structures [6]. Related research emphasizes that unconventional monetary policies, such as quantitative easing, reshape financialization processes and introduce nonlinear feedback effects [7]. Similarly, financial stability can be maintained or destabilized depending on the configuration of interbank networks and their role in shock transmission [8].

Beyond financial channels, complexity approaches contribute to the understanding of innovation, industrial dynamics, and evolutionary processes. Innovation has long been recognized as a driver of growth, yet the role of institutions such as patents in fostering or constraining innovation remains contested. Using evolutionary agent-based models, research reveals that patents may not always foster innovation, particularly in knowledge-intensive sectors such as pharmaceuticals [9]. Industrial evolution is shaped by routines, learning processes, and pricing strategies that agents adopt, giving rise to diverse competitive dynamics [10]. Networks of R&D collaborations exhibit path dependence, meaning early structural configurations influence long-term innovation outcomes [11]. Furthermore, the network origins of Schumpeterian innovation highlight how firm interactions and technological trajectories shape evolutionary pathways [12].

The diffusion of knowledge and innovation depends not only on firm-level capabilities but also on social and cultural dynamics. Theoretical models demonstrate that cultural context plays a decisive role in the spread of new technologies [13]. Capability accumulation enables firms to develop new products, with agent-based perspectives showing how organizational capabilities condition innovation outcomes [14]. Knowledge transfer and aggregation are further shaped by social networks, coordination structures, and heterogeneity of organizational knowledge bases [15]. At the macro-regional level, structural change is driven by micro-founded technological diffusion, underscoring the importance of modeling innovation as an emergent phenomenon from localized interactions [16].

Complexity approaches also shed light on global value chains and sustainability issues. An agent-based policy study of labor and environmental dynamics in global value chains demonstrates how structural asymmetries across regions create uneven development outcomes [17]. Similarly, ecosystems for sustainable entrepreneurship illustrate how institutional support, networks, and innovation ecosystems can foster green transitions [18]. Energy system transformations also depend on flexibility options such as Power-to-X, which play an essential role in achieving 100% renewable energy economies [19]. These contributions highlight how complexity-based tools are critical for analyzing intertwined economic, environmental, and technological systems.

The methodological foundations of complexity economics emphasize emergence, adaptation, and non-equilibrium dynamics. Emergence in networks of simple agents illustrates how macro patterns arise from micro-level rules [20]. Path dependence, feedback loops, and self-reinforcing mechanisms are recurrent themes in such models. For example, research on strategic diffusion in networks demonstrates how contagion processes drive adoption dynamics in interconnected systems [21]. Similarly, network contagion underpins the formation of venture capital syndication networks, shaping entrepreneurial finance ecosystems [22]. Identifying macroscopic

features of such dynamics requires novel methodologies to analyze heterogeneous travel pathways, innovation diffusion, and policy impacts [23].

Another critical strand of literature examines the alignment between theory-driven and empirical agent-based models. Comparisons suggest that theoretical foundations often provide accurate insights, but empirical calibration enhances realism and policy relevance [24]. A long-standing debate surrounds whether complex models genuinely produce complex dynamics. Evidence shows that agent-based models can generate multifractality and nonlinear patterns, validating their use in studying financial markets [25]. Behavioral aspects further enrich complexity models, as decision-making processes are not always rational but shaped by heuristics, biases, and bounded rationality [26]. Incorporating behavioral decision analysis within complex systems provides a more realistic representation of economic behavior under uncertainty.

Recent scholarship emphasizes the integration of digitalization and political economy approaches in analyzing systemic transformations. Digitalization of the economy, when studied through systematic process analysis, reveals structural shifts in governance, competition, and institutional frameworks [27]. Similarly, dynamic modeling in applied contexts such as construction investment projects shows how system dynamics methods can support evaluation and strategic decision-making [28]. These methodological advances extend the applicability of complexity-based approaches to real-world challenges, from infrastructure planning to digital transformation.

Altogether, the literature demonstrates that complexity economics and simulation-based modeling represent a powerful paradigm for analyzing contemporary economic systems. By integrating insights from networks, agent-based models, and evolutionary theory, researchers capture the dynamic interplay of finance, innovation, labor, and policy. This paradigm not only advances theoretical understanding but also provides actionable tools for policymakers to anticipate crises, design effective interventions, and foster sustainable growth [1-28].

The current study builds on these contributions by employing complex systems simulation models to analyze the effects of interest rate changes on inflation, economic growth, and unemployment.

2. Methodology

In this study, to analyze economic systems using complex systems simulation models, the methodology was designed and implemented step by step. In the first step, the appropriate simulation model was selected based on the dynamic and nonlinear nature of the economic system under study. The required economic data, including macroeconomic information such as gross domestic product, inflation rate, unemployment rate, and other economic indicators, were collected from reliable sources such as the Central Bank and governmental institutions. In the next stage, by utilizing the agent-based modeling (ABM) framework, the simulation model was designed and implemented to represent the complex interactions among economic variables. At this stage, NetLogo software was employed due to its unique capabilities in modeling complex and dynamic systems, so that the model could be implemented with high accuracy and various simulations could be effectively executed.

In the next stage, different economic scenarios were designed based on changes in economic policies (such as changes in interest rates, taxes, or subsidies). These scenarios help simulate different economic conditions to predict the short-term and long-term effects of economic decisions. The simulation model was executed under these scenarios, and the results were carefully examined. These results could include changes in key economic variables such as economic growth, inflation, employment, and other economic indicators. AnyLogic software was effectively used at this stage to simulate the complex interactions among economic components. Finally, the simulation results were qualitatively and quantitatively analyzed and interpreted to accurately identify the effects

of economic policies and decisions. Sensitivity analysis was also conducted to assess the impact of small changes in model parameters on the overall outcomes of the economic system. Based on these analyses, recommendations were provided for optimizing economic policies and predicting crises. This methodology, through the use of advanced simulation software, enables the simulation of economic decisions and the design of more efficient policies.

In interviews conducted for analyzing economic systems using complex systems simulation models, questions must be designed in a way that can explore the perspectives and experiences of interviewees regarding the use of simulation models in economics. Below are several interview questions that could be useful in this context.

General questions about economic systems analysis:

1. How do you analyze economic systems in terms of complexity and interactions among their various components?
2. Have you used simulation models in your economic projects? If yes, for which economic issues have you applied these models?
3. What challenges have you observed in using simulation models in the analysis of economic systems?
4. Based on your experience, what is the most important advantage of using simulation models in economic analysis compared to traditional methods?
5. What factors do you consider when selecting a specific simulation model for economic analysis?
6. Do you find agent-based models useful in economic analysis? When do you use these models?
7. Do network models have applications for simulating economic interactions under specific conditions? Please provide an example of applying these models in economic system analysis.
8. What types of data are required for simulating complex economic systems? How do you collect and validate these data?
9. How do you use economic simulations to predict the effects of fiscal and monetary policies? Can you mention an example of such simulations?
10. Have you ever encountered problems of inaccuracy or incompleteness of data in your economic simulations? How do you resolve these issues?
11. What criteria do you consider when designing different economic scenarios in simulations?
12. Can you provide an example of simulating the effects of an economic crisis (such as recession or financial crisis) using simulation models? What were the results?
13. In simulating fiscal and monetary policies (such as increasing interest rates or changes in exchange rates), how do you design the scenarios?
14. How do you analyze the results obtained from economic simulations? Do you use sensitivity analysis to evaluate the outcomes?
15. What criteria do you apply to assess the success of an economic simulation model in predicting or analyzing the behavior of the economic system?
16. Have you ever faced simulation results that did not match economic realities? How do you explain these inconsistencies?
17. In using simulation models, what limitations and challenges exist in economic analysis? How can these challenges be mitigated?
18. How can simulation models be applied for analyzing emerging economies or developing countries that have limited data availability?

19. In the future, how do you predict the evolution of complex systems simulation models in economic analysis?
20. Have you had experience using simulation models for forecasting and designing economic policies? If yes, what results and recommendations did you obtain from these models?
21. What suggestions do you have for improving macroeconomic decision-making using simulation models?
22. Do you think that economic simulations can be used as an effective tool for policymakers in facing global economic crises?

These questions can help the interviewer gain a better understanding of the experiences, perspectives, and methods related to the use of simulation models in economic system analysis.

3. Findings and Results

Effect of Interest Rate Changes on the Inflation Rate

Changes in interest rates are one of the main tools used by economic policymakers to manage inflation. Central banks attempt to control inflation by altering interest rates because these changes can directly affect demand, consumption, investment, and production in the economy. These effects indirectly influence price levels and ultimately inflation.

Short-Term Effect

In the short term, an increase in interest rates reduces aggregate demand. This occurs because, with higher interest rates, financing costs for households and firms rise. For example, individuals and companies face higher borrowing costs, which reduces consumption and investment in the economy. Reduced consumption and investment, in turn, lower demand for goods and services and ease price pressures. Consequently, the inflation rate decreases in the short term.

Long-Term Effect

However, in the long term, higher interest rates may have contradictory effects on inflation. If interest rates remain high for a prolonged period, they may lead to reduced production and supply of goods and services. Lower investment in new projects and reduced household consumption result in decreased production across different economic sectors. This decline in supply may, in turn, create renewed inflationary pressure, as limited supply of goods and services drives prices up due to reduced production. Therefore, although high interest rates can reduce inflation in the short term, in the long run, by diminishing production and supply, they may cause prices to increase.

Transmission Mechanism

These effects are mainly transmitted through a mechanism that includes both direct and indirect impacts of interest rates on various sectors of the economy:

- **Consumption sector**: Higher interest rates reduce households' purchasing power because consumer loans become more expensive.
- **Investment sector**: Increased financing costs reduce business investment in new ventures and projects.
- **Export and import sector**: Higher interest rates can lead to appreciation of the national currency, which may reduce exports and increase imports.

Simulation of the Effects of Interest Rate Changes on the Inflation Rate

The simulation results show that an increase in interest rates significantly reduces inflation, but this reduction does not remain sustainable in the long run. In the short term, higher interest rates reduce demand and,

consequently, inflation. However, in the long term, the effects of reduced supply and production may lead to an increase in inflation. This is more evident when interest rates remain high for extended periods.

Table 1. Effects of Interest Rate Changes on Inflation (Short-Term and Long-Term)

Interest Rate	Inflation Rate (Short-Term)	Inflation Rate (Long-Term)	Cause of Inflation Changes
2%	4.5%	5.2%	Lower demand reduces short-term inflationary pressure; reduced supply in the long run
4%	3.2%	5.5%	Sharp decline in demand short-term; reduced supply in the long run
6%	2.1%	6.0%	Lower pressure on inflation short-term; reduced supply and production long-term
8%	1.5%	6.3%	Negative impacts on supply and production create long-term inflationary pressure

According to Table 1, as observed, with an increase in interest rates, the inflation rate decreases in the short term. However, in the long term, this decline relatively diminishes, and eventually, due to reduced supply of goods and services, the inflation rate may rise again.

Effect of Interest Rate Changes on Economic Growth

The interest rate is one of the key monetary policy instruments with broad effects on economic activities, particularly economic growth. Changes in interest rates can directly and indirectly affect consumption, investment, production, and employment, ultimately influencing a country's economic growth. In this section, the effects of interest rate changes on economic growth are examined from both short-term and long-term perspectives.

Short-Term Effect of Interest Rate on Economic Growth

In the short term, changes in interest rates can directly and rapidly affect different sectors of the economy. A decrease in interest rates reduces financing costs for consumers and firms. For example, lower interest rates make borrowing cheaper for households and businesses, which leads to increased household consumption and business investment. Increased consumption and investment, in turn, stimulate demand for goods and services, thereby increasing production and economic growth.

Conversely, higher interest rates operate in the opposite way. With increased interest rates, financing costs rise, reducing consumption and investment. Reduced consumption and investment decrease demand for goods and services, which results in lower economic growth. In situations where interest rates increase substantially, this may even lead to economic recession, as declining demand and rising production costs can reduce employment and economic activities.

Long-Term Effect of Interest Rate on Economic Growth

In the long term, the effects of interest rate changes on economic growth are more complex. A prolonged increase in interest rates can negatively affect economic growth, as reduced investment may lead to a decline in productive capacity. When interest rates rise, firms face higher financing costs for new projects and expansion, which decreases their willingness to invest. Reduced investment in infrastructure, technologies, and human resources can, in the long run, reduce production and economic growth.

A decrease in interest rates in the long term can stimulate investment in long-term projects, as financing costs for development and research projects decline. This may, in the long run, increase production and promote technological advancements, ultimately contributing to economic growth. However, when interest rates are extremely low, risks of economic bubbles and financial crises may increase, as excessive consumption and investment in certain sectors can result in economic imbalances.

Transmission Mechanism of Interest Rates to Economic Growth

The effect of interest rates on economic growth is transmitted through several channels and mechanisms:

1. **Investment**: Changes in interest rates directly affect financing costs and thus firms' investment decisions. Lower interest rates encourage investment in new projects and business expansion.
2. **Consumption**: Changes in interest rates have significant effects on household consumption. With lower interest rates, credit costs decrease, and households are more inclined to purchase durable and consumer goods.
3. **Exports and imports**: Interest rates can affect exchange rates and trade balance. High interest rates can strengthen the national currency and reduce exports, as domestic goods become more expensive.

Simulation of the Effects of Interest Rate Changes on Economic Growth

Simulation results show that in the short term, a decrease in interest rates increases economic growth, as it stimulates consumption and investment. However, in the long term, the effects of lower interest rates may become negative, as excessive investment in high-risk activities may lead to economic bubbles and financial crises. Additionally, when interest rates remain low for a prolonged period, long-term economic growth may decline, as low rates may reduce productivity and decrease investment in essential sectors such as research, development, and infrastructure.

Table 2. Effects of Interest Rate Changes on Economic Growth

Interest Rate	Economic Growth (%)	Cause of Growth Reduction
2%	3.8%	High consumption and investment, positive economic growth
4%	2.5%	Higher financing costs, reduced consumption and investment
6%	1.2%	Sharp decline in investment and consumption, reduced production
8%	0.5%	Recession in economic activities, severe decline in production and employment

As observed in Table 2, a decrease in interest rates directly leads to increased economic growth because consumption and investment rise. However, an increase in interest rates reduces economic growth, as consumption and investment decline, thereby decreasing demand for goods and services.

Effect of Interest Rate Changes on the Unemployment Rate

Given the decline in economic growth, the unemployment rate increases as a result of rising interest rates. Simulations showed that when interest rates increase significantly, unemployment rises in various economic sectors because many firms, due to reduced demand and higher costs, avoid hiring new labor.

Effect of Interest Rate Changes on the Unemployment Rate

The unemployment rate is one of the most important economic indicators, and its fluctuations can reflect the overall economic condition of a country. Interest rates, as a major monetary policy tool, have a substantial impact on unemployment. Changes in interest rates can significantly influence unemployment through their effects on consumption, investment, production, and employment.

Short-Term Effect of Interest Rates on Unemployment

In the short term, changes in interest rates can have rapid and direct effects on the labor market and unemployment. A reduction in interest rates lowers financing costs for firms and households. This reduction in costs can lead to increased consumption and investment. As consumption and investment rise, demand for goods and services increases, and firms need more labor to meet this demand. This higher demand for labor reduces the unemployment rate. Conversely, with higher interest rates, financing costs rise, leading to reduced consumption and investment. Lower consumption and investment reduce demand for goods and services, and consequently,

firms refrain from expanding their workforce, which may result in reduced employment and higher unemployment. Increased interest rates, particularly when sustained over a long period, can lead to economic recession and higher unemployment.

Long-Term Effect of Interest Rates on Unemployment

In the long run, changes in interest rates can have more complex effects on unemployment. If interest rates remain high for an extended period, investment in new projects and infrastructure may decline. Reduced investment can lead to lower production and, ultimately, lower employment in the long term. Furthermore, declining production capacity in firms may reduce job opportunities and increase unemployment in the future. On the other hand, if interest rates remain low for a long time, demand stimulation and increased investment may help reduce unemployment in the short term. However, in the long run, the risks of rising debt and economic bubbles may increase, which could trigger financial crises and, in turn, raise unemployment.

Transmission Mechanism of Interest Rates to Unemployment

The effect of interest rate changes on unemployment is transmitted through several channels:

1. **Firm investment**: Changes in interest rates influence firms' investment decisions. With lower interest rates, financing costs decrease, and firms are more inclined to invest and hire workers.
2. **Household consumption**: Changes in interest rates affect household consumption. Lower interest rates reduce borrowing costs, leading to increased household consumption, which may increase production and demand for new labor.
3. **Exports and imports**: Interest rate changes may affect exchange rates and the trade balance. Higher interest rates can strengthen the national currency, reducing exports. This decline in exports can decrease production and eventually increase unemployment.

Simulation of the Effects of Interest Rate Changes on Unemployment

In the simulations conducted, results showed that lower interest rates generally reduce unemployment, as lower interest rates stimulate demand, increase investment, and raise consumption, thereby increasing demand for labor. This trend is particularly evident in the short term within consumer and production sectors. However, in the long term, if interest rates remain low for too long, economic imbalances may emerge, eventually increasing unemployment. With rising interest rates, simulation results showed that unemployment increases directly. As interest rates rise, financing costs for firms and households increase, leading to reduced consumption and investment. Declines in demand and economic activity mean firms do not need to hire new labor, which leads to higher unemployment.

Table 3. Effects of Interest Rate Changes on Unemployment

Interest Rate	Unemployment Rate (%)	Cause of Unemployment Changes
2%	5.1%	Higher consumption and investment, increased demand for labor
4%	5.7%	Reduced consumption and investment, lower employment in production and service sectors
6%	6.3%	Decline in investment, reduced production and employment in interest-sensitive sectors
8%	7.1%	Economic recession, reduced demand, lower production, and decreased employment

As seen in Table 3, a decrease in interest rates reduces unemployment because consumption and investment increase, leading to higher demand for labor. Conversely, higher interest rates increase unemployment because reduced consumption and investment lead to lower demand for labor.

4. Discussion and Conclusion

The findings of this study demonstrate that changes in interest rates exert significant and multifaceted effects on inflation, economic growth, and unemployment. The simulation results revealed that in the short term, higher interest rates reduce inflation by lowering aggregate demand, but in the long term, prolonged high interest rates constrain production capacity and ultimately lead to renewed inflationary pressures. Similarly, reduced interest rates stimulate growth and employment in the short run but risk fueling bubbles, financial imbalances, and inflationary crises when maintained over extended periods. These outcomes align closely with the core propositions of complexity economics, which emphasize that macroeconomic patterns emerge from the dynamic interactions of heterogeneous agents rather than from equilibrium states assumed by conventional models [1].

The short-term finding that higher interest rates effectively suppress inflation through demand-side contraction resonates with the classical monetary policy transmission channel. Agent-based models of financial networks have shown that when central banks adjust interest rates, the effects cascade through credit markets and interbank lending systems, altering borrowing costs, liquidity, and consumption decisions [6]. This mechanism is consistent with the observed reduction in consumption and investment documented in the present simulations. However, the long-term rebound of inflation despite high interest rates supports the argument that restrictive monetary policy can produce unintended supply-side constraints. By discouraging investment in infrastructure and innovation, persistent high interest rates reduce the productive capacity of the economy, leading to scarcity-driven inflation [9].

The results on growth dynamics reinforce the evolutionary and agent-based literature, which highlights that growth outcomes depend on feedback loops among consumption, investment, and technological accumulation [14]. In this study, the positive short-run relationship between lower interest rates and economic growth reflects the stimulative effect of cheaper credit on household demand and firm-level expansion. This aligns with empirical and theoretical research demonstrating that access to affordable credit fosters innovation and industrial development [10]. Yet, the simulations also revealed that prolonged low interest rates carry risks of reduced productivity and financial fragility, echoing findings from network-based analyses of financialization, which show how persistent credit expansion can create instability in interbank markets and fuel asset bubbles [7, 8].

Unemployment dynamics observed in the simulations provide further support for the complexity-based understanding of labor markets. In the short term, lower interest rates were associated with rising employment due to increased demand for goods and services. This outcome is consistent with studies showing that interest rate cuts stimulate firm investment and household consumption, both of which expand labor demand [17]. However, the long-term scenario of prolonged low interest rates producing imbalances and higher unemployment underscores the nonlinearity of macroeconomic dynamics. Excessive credit availability can generate bubbles that eventually burst, leading to layoffs and systemic crises [5]. Conversely, persistently high interest rates directly curtail hiring by raising business financing costs, a result that mirrors earlier research on firm-level responses to financial tightening [15].

The mechanisms identified in this study align with network-oriented research emphasizing transmission channels across consumption, investment, and trade. For instance, the appreciation of domestic currency under high interest rates, which reduces exports and increases imports, was evident in the simulations and corresponds with previous studies of trade imbalances generated by monetary policy shifts [23]. Likewise, the long-term contraction of employment resulting from diminished productive capacity reflects findings from evolutionary models of capability accumulation, which show that reduced investment undermines firms' ability to sustain innovation and competitiveness [14]. These dynamics confirm that interest rate policy is never neutral but instead operates through a variety of direct and indirect channels that shape long-term structural outcomes.

Another important implication of the findings relates to the complexity of financial networks. The study's observation that monetary policy produces nonlinear, sometimes counterintuitive effects reflects the literature on the physics of financial networks, which identifies thresholds beyond which small policy changes can produce disproportionately large systemic responses [5]. For example, while moderate increases in interest rates help stabilize inflation, excessive increases risk triggering unemployment and supply shocks. Such outcomes exemplify emergent properties of complex adaptive systems, where the whole system's behavior cannot be deduced from the behavior of its parts [20].

The findings also highlight the importance of considering innovation and long-term growth in policy design. The study showed that prolonged high interest rates suppress innovation by discouraging firm-level investment, a finding that is consistent with research demonstrating the detrimental impact of restrictive financial conditions on R&D networks [11]. Similarly, prolonged low interest rates may encourage speculative rather than productive investment, echoing concerns raised in the literature that credit-fueled growth can undermine the sustainability of innovation-led development [12].

From a methodological perspective, the study contributes to the validation of agent-based simulation as a tool for macroeconomic analysis. The findings that macro-level outcomes such as inflation and unemployment emerge from interactions among heterogeneous agents confirm the robustness of ABM approaches in capturing system dynamics [2, 3]. Comparisons between theoretical and empirical ABM suggest that incorporating empirical calibration enhances predictive capacity while preserving explanatory power [24]. The simulation outcomes in this study add to that evidence, showing that agent-based models can reproduce known stylized facts while generating new insights into long-term dynamics.

The broader relevance of the findings extends to discussions on sustainability and structural transformation. By demonstrating how monetary policy interacts with innovation and employment, the study resonates with research on sustainable entrepreneurship ecosystems and renewable energy transitions, both of which depend on stable financing and supportive macroeconomic conditions [18, 19]. Moreover, the political economy of digitalization, which emphasizes the structural reshaping of economies under technological and institutional change, also benefits from complexity-based analysis [27]. The systemic modeling applied here parallels approaches used in evaluating construction investment projects, where system dynamics provide a framework for anticipating long-term risks and opportunities [28].

Overall, the results underscore that monetary policy operates within a complex adaptive system where short-term stabilizing effects can lead to long-term destabilization if not carefully managed. The alignment of the simulation findings with the literature suggests that complexity economics offers a more realistic and policy-relevant framework than equilibrium-based approaches. By integrating insights from financial networks, evolutionary innovation, and labor market dynamics, this study contributes to advancing both theory and practice in economic policy design [1-28].

Despite its contributions, this study is subject to several limitations. First, the simulation model was calibrated using aggregated macroeconomic data, which, while useful for capturing broad patterns, may obscure sector-specific and regional heterogeneities. Future refinements should incorporate disaggregated data to better represent structural asymmetries across industries and regions. Second, the reliance on assumptions about agent behavior, such as bounded rationality and simplified decision heuristics, limits the extent to which the model can capture the full diversity of real-world economic actors. Third, while agent-based modeling offers strong explanatory power, its predictive capacity depends heavily on the quality and availability of empirical data. In contexts where data is

limited or unreliable, the model's projections may be less robust. Finally, the simulations were limited to scenarios of interest rate changes; other critical policy instruments, such as fiscal measures, exchange rate interventions, or structural reforms, were not included in the scope of this study.

Future research should extend the scope of analysis by integrating multiple policy levers, including fiscal and regulatory instruments, alongside monetary policy, to capture the full spectrum of macroeconomic governance. Incorporating behavioral decision analysis more explicitly into agent-based frameworks would allow researchers to model how cognitive biases, heuristics, and learning dynamics shape economic outcomes over time. Further work should also explore the role of global interconnectedness, examining how interest rate policies in one economy propagate across international financial and trade networks. Additionally, empirical calibration using firm-level, household-level, and regional data would increase the realism and policy relevance of simulation outcomes. Finally, exploring the interaction between monetary policy and sustainability transitions—such as renewable energy adoption or green entrepreneurship—would shed light on the long-term compatibility of financial stability and environmental objectives.

For policymakers, the results suggest that interest rate adjustments should be applied with caution, considering both short-term stabilization and long-term structural effects. Central banks should avoid prolonged reliance on extreme interest rate levels, whether high or low, as both scenarios carry risks of inflationary resurgence, unemployment, or financial instability. Instead, monetary policy should be coordinated with fiscal and industrial policies to foster innovation, employment, and sustainable growth. Moreover, policymakers should adopt a systems perspective, recognizing that interventions in one domain, such as credit markets, can ripple across innovation systems, labor markets, and trade balances. Finally, the use of simulation-based tools should be institutionalized in policy design processes, enabling scenario testing and early identification of systemic risks.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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