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Research Article

An Agent-Based Computational Framework for Macroeconomic Policy Simulation: Scenario Analysis of Fiscal and Monetary Interventions

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Abstract

Abstract: Traditional macroeconomic models can have difficulty representing heterogeneous behavior, nonlinear interactions, and path-dependent adjustment. This study develops a stylized agent-based model (ABM) as a computational laboratory for examining macroeconomic policy transmission. The framework contains heterogeneous households and firms together with a fiscal authority and a central bank, and it is interpreted as a proof-of-concept Economic Digital Twin (EDT) rather than a real-time data-synchronized replica of a national economy. Three scenarios are considered: a baseline, a fiscal expansion, and a monetary easing. In the reported simulations, fiscal expansion increases mean output by approximately 2.28%, whereas monetary easing raises mean output by about 0.34%. Inflation remains close to the model's 3% target, while unemployment changes very little across scenarios and remains unrealistically high at about 35.5%. The latter feature is traced to the simplified labor-market block and the absence of explicit search, matching, and wage-bargaining mechanisms. The results should therefore be interpreted as qualitative evidence on model transmission channels rather than as empirically calibrated policy forecasts. The proposed framework provides a transparent policy sandbox that can be extended through empirical calibration, richer labor and financial sectors, and additional validation procedures.

Keywords: economic digital twin, agent-based modeling, macroeconomic simulation, fiscal policy, monetary policy, policy sandbox, computational economics.
2020 Mathematics Subject Classification: 91B64; 91B55

1 Introduction

Modern macroeconomic policymaking operates under uncertainty, structural complexity, and nonlinear dynamics. Policy interventions, whether fiscal stimulus or monetary adjustment, can generate delayed feedback and spillover effects that are difficult to represent in highly aggregated frameworks.

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Representative-agent models, including standard dynamic stochastic general equilibrium (DSGE) formulations, have been criticized for restrictive assumptions concerning rationality, market completeness, and equilibrium closure. Such assumptions can limit the representation of coordination failures, heterogeneous adjustment, and path-dependent transitions [1, 2, 3].

Agent-based modeling (ABM) provides a complementary bottom-up approach in which aggregate variables emerge from decentralized interactions among heterogeneous agents rather than from a representative optimization problem. This architecture is well suited to computational policy experiments involving bounded rationality, adaptive behavior, and out-of-equilibrium dynamics [4, 5, 6].

At the same time, the concept of the digital twin has expanded from engineering applications toward complex social and urban systems [7, 8]. In engineering, a digital twin generally involves a virtual representation linked to a physical system. Directly transferring this concept to macroeconomics is difficult because economic systems contain adaptive agents, changing institutions, structural breaks, and high-dimensional feedback. For this reason, the present study uses the term *Economic Digital Twin* (EDT) in a deliberately limited sense: a stylized, transparent simulation environment for controlled policy experiments, not a continuously synchronized replica intended for real-time forecasting.

The proposed framework contains heterogeneous households, heterogeneous firms, a fiscal authority, and a central bank operating through a Taylor-type policy rule. We compare a baseline scenario with fiscal expansion and monetary easing and examine output, consumption, inflation, interest rates, and unemployment. Particular attention is given to the weak labor-market response generated by the current model structure.

The remainder of the paper is organized as follows. Section 2 reviews the relevant literature. Section 3 states the research gap and contribution. Section 4 presents the model architecture, behavioral rules, parameterization, scenario design, and the role of empirical benchmark series. Section 5 reports the simulation results, Section 6 discusses their interpretation, and Section 7 concludes.

2 Literature Review

2.1 The digital-twin paradigm and socio-economic systems

The digital-twin concept developed in engineering as a virtual representation of a physical asset or system that can support simulation, monitoring, and decision making [7]. Its extension to cities and other socio-technical systems has emphasized that digital representations of human systems are necessarily more adaptive and less deterministic than their engineering counterparts [8].

An economy is a complex adaptive system rather than a mechanical object. Expectations, institutional arrangements, heterogeneous balance sheets, and decentralized interactions all evolve over time. Consequently, an EDT cannot be interpreted literally as an exact mirror of the economy. A more defensible interpretation is a computational environment in which alternative mechanisms and policy scenarios can be tested transparently. Pobuda [9] develops this idea explicitly by linking economic architecture, digital representation, and agent-based simulation.

2.2 Agent-based macroeconomic modeling

ABM has become an important alternative approach to macroeconomic modeling. In an ABM, aggregate outcomes emerge from interactions among agents governed by explicit behavioral rules. This permits the representation of heterogeneity, bounded rationality, learning, coordination failures, and out-of-equilibrium adjustment [4, 6]. Agent-based macroeconomic models have also been used to study business cycles, crises, unemployment persistence, and nonlinear policy effects [3].

The link between ABM and an EDT is therefore natural. If the aim is to construct a virtual economy for scenario analysis, the simulation engine must be able to represent local interactions, heterogeneous states, and path dependence. ABM supplies these ingredients while keeping the behavioral assumptions explicit.

2.3 Fiscal and monetary policy in computational settings

Fiscal and monetary policy are commonly studied within DSGE-type frameworks, but agent-based approaches permit policy transmission to depend on heterogeneous financial positions, adaptive expectations, demand constraints, and market frictions. This can produce asymmetric and nonlinear responses that are difficult to summarize with a single representative agent [3, 6].

The present framework is intentionally stylized. Its objective is not to establish a quantitatively calibrated policy multiplier, but to examine how fiscal and monetary interventions propagate through a transparent set of household, firm, government, and central-bank rules.

3 Research Gap and Contribution

Despite the rapid development of digital-twin technologies and the maturity of agent-based macroeconomics, their intersection remains comparatively underdeveloped. Much of the digital-twin literature focuses on engineering and cyber-physical systems, whereas macroeconomic policy analysis is still dominated by equilibrium-based or econometric approaches.

This paper contributes in three ways. First, it translates the EDT idea into an explicit agent-based macroeconomic prototype. Second, it combines heterogeneous agents, adaptive demand expectations, fiscal intervention, and a monetary reaction rule within one simulation environment. Third, it demonstrates how the model can be used as a policy sandbox for comparing a baseline with fiscal and monetary shocks while making clear which reported outcomes are structural artifacts of the current specification.

4 Methodology and Model Architecture

4.1 Research design and analytical scope

The study adopts a computational simulation design. The model is intended as a proof of concept rather than a fully calibrated national forecasting model. Accordingly, the emphasis is on structural plausibility, controlled scenario comparison, and transparency of the transmission mechanisms. The numerical results should not be interpreted as estimated causal effects for a particular country.

The virtual economy contains four classes of agents: households, firms, a government, and a central bank. Simulations run for 60 discrete periods. The principal aggregate variables are GDP, consumption, unemployment, inflation, the average price level, and the policy interest rate.

4.2 Households

Let $i = 1, \ldots, N$ index households. Household consumption is represented by a linear rule combining lagged wealth and current disposable income,

$$C_{i,t} = \alpha_i W_{i,t-1} + \beta_i Y^d_{i,t}, \tag{1}$$

where α_i is the propensity to consume out of wealth and β_i is the marginal propensity to consume out of disposable income. Disposable income is

$$Y^d_{i,t} = Y_{i,t}(1 - \tau_t), \tag{2}$$

and wealth evolves according to

$$W_{i,t} = W_{i,t-1} + Y^d_{i,t} - C_{i,t} + r_t W_{i,t-1}. \tag{3}$$

These relations are stylized behavioral rules rather than estimated household equations.

4.3 Firms

Let $j = 1, \ldots, M$ index firms. Expected demand is updated adaptively as

$$D^e_{j,t} = D^e_{j,t-1} + \theta\big(D_{j,t-1} - D^e_{j,t-1}\big), \tag{4}$$

where θ controls the speed of expectation adjustment. Production is specified as

$$Y_{j,t} = \gamma_j L_{j,t}, \tag{5}$$

where γ_j denotes firm productivity and $L_{j,t}$ labor demand. Prices follow a markup-over-unit-labor-cost rule,

$$P_{j,t} = (1 + \mu_{j,t})\frac{w_t}{\gamma_j}, \tag{6}$$

where $\mu_{j,t}$ is the markup and w_t is the wage rate.

4.4 Aggregate output, unemployment, and inflation

Aggregate output is the sum of firm production,

$$GDP_t = \sum_{j=1}^{M} Y_{j,t}. \tag{7}$$

The unemployment rate is defined as

$$u_t = 1 - \frac{L^{\mathrm{emp}}_t}{L^{\mathrm{sup}}_t}, \tag{8}$$

where L^{emp}_t and L^{sup}_t denote total employment and labor supply, respectively. Inflation is calculated from the average price level $\bar{P}_t$,

$$\pi_t = \frac{\bar{P}_t - \bar{P}_{t-1}}{\bar{P}_{t-1}}. \tag{9}$$

4.5 Fiscal and monetary policy rules

With an income tax rate τ_t, government tax revenue is represented as

$$T_t = \sum_{i=1}^{N} \tau_t Y_{i,t}. \tag{10}$$

A fiscal expansion is introduced through government spending,

$$G_t = G_0(1 + \eta_t), \tag{11}$$

where G_0 is baseline government spending and η_t is the fiscal-shock parameter.

The central bank follows a Taylor-type reaction rule,

$$r_t = r_0 + \phi_\pi(\pi_t - \pi^*) + \phi_y \left(\frac{GDP_t - GDP^*}{GDP^*} \right), \tag{12}$$

where r_0 is the baseline nominal interest rate, π^* is the inflation target, GDP^* is potential output, and ϕ_π and ϕ_y are response coefficients. The inflation gap is written as $\pi_t - \pi^*$; this sign convention is consistent with a standard stabilizing reaction rule and with the reported interest-rate magnitudes.

4.6 Computational sequence

Each simulation period follows the same sequence: (i) firms update expected demand; (ii) production and labor demand are planned; (iii) firms set prices; (iv) households receive income and determine consumption; (v) demand is realized and aggregate output is computed; (vi) unemployment and inflation are updated; (vii) fiscal and monetary policy rules are applied; and (viii) macroeconomic and agent-level variables are recorded.

4.7 Reported core parameters

Table 1 consolidates the core numerical parameters reported in the accepted manuscript. Other behavioral coefficients appearing in the model equations are structural quantities in the proof-of-concept implementation; because their complete numerical specification is not reported, the model should not be regarded as fully reproducible from the article alone.

Table 1: Core simulation parameters reported in the model specification.

Parameter	Symbol	Value	Description
Number of households	N	100	Heterogeneous consumers
Number of firms	M	10	Heterogeneous producers
Simulation horizon	T	60	Number of periods
Baseline interest rate	r_0	0.04	Initial nominal rate
Inflation response	ϕ_π	1.5	Policy-rule coefficient
Output response	ϕ_y	0.5	Policy-rule coefficient
Inflation target	π^*	0.03	Target inflation
Baseline tax rate	τ	0.20	Income tax rate

4.8 Scenario design

Three scenarios are considered. In the baseline, the economy evolves under the default parameterization. In the fiscal-shock scenario, government spending is increased exogenously. In the monetary-shock scenario, the policy rate is reduced relative to the baseline to examine expansionary monetary transmission. All scenarios are evaluated over the same 60-period horizon.

4.9 Empirical benchmark series

The manuscript also uses U.S. macroeconomic series from the Federal Reserve Economic Data (FRED) database as descriptive benchmarks. Figures 1–4 display real GDP, the Personal Consumption Expenditures Price Index, unemployment, and the effective federal funds rate. These series provide empirical context only; they are not used to estimate the behavioral coefficients of the simulation and therefore should not be interpreted as a formal validation sample.

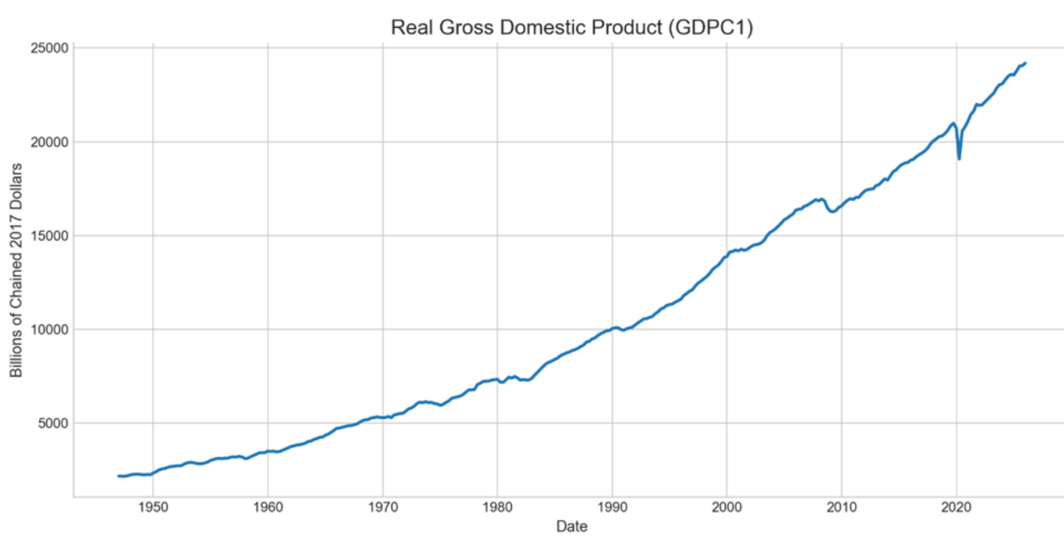

Figure 1: Historical trajectory of U.S. real gross domestic product (GDPC1), in billions of chained 2017 dollars. Source: U.S. Bureau of Economic Analysis, retrieved through FRED.

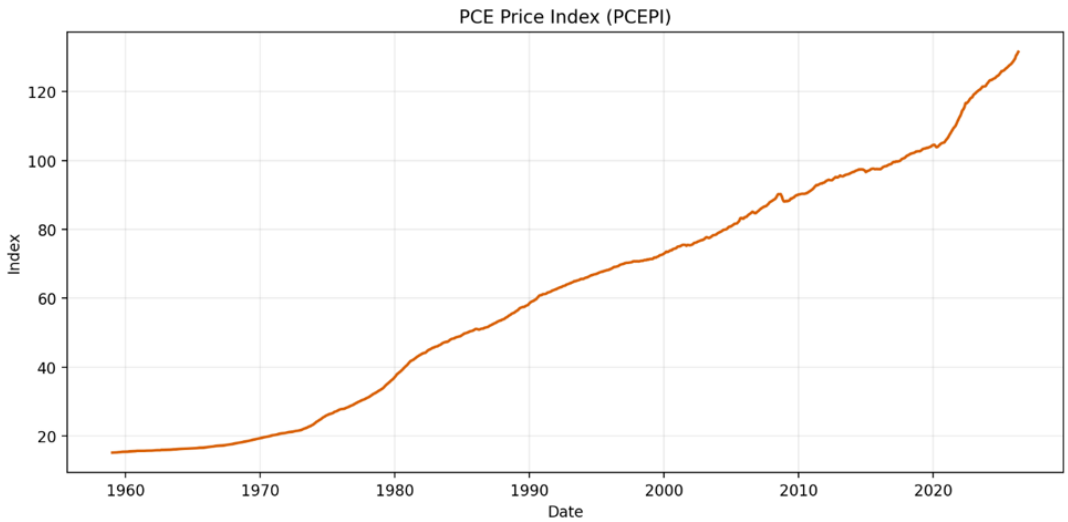

Figure 2: Historical trajectory of the U.S. Personal Consumption Expenditures Price Index (PCEPI). Source: U.S. Bureau of Economic Analysis, retrieved through FRED.

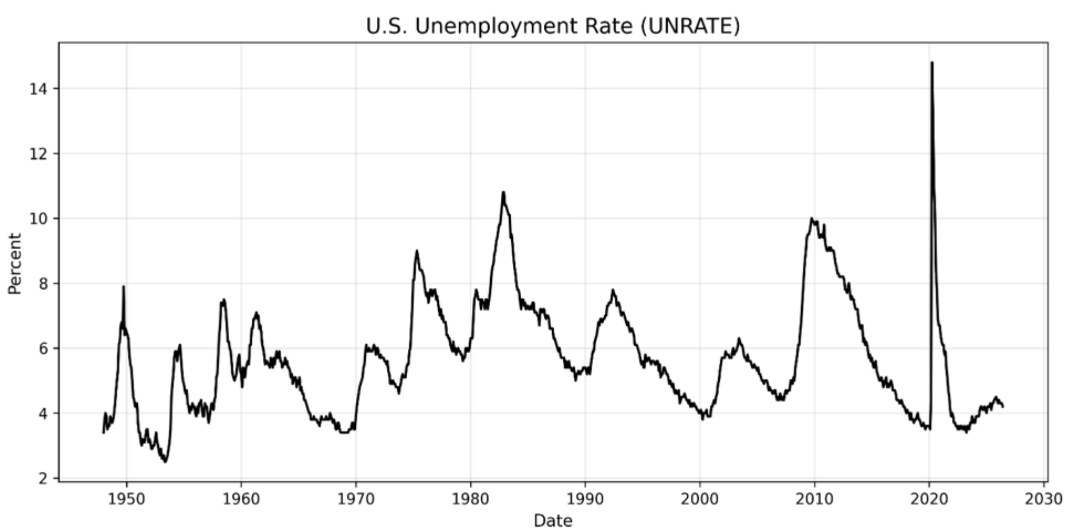

Figure 3: Historical evolution of the U.S. unemployment rate (UNRATE). Source: U.S. Bureau of Labor Statistics, retrieved through FRED.

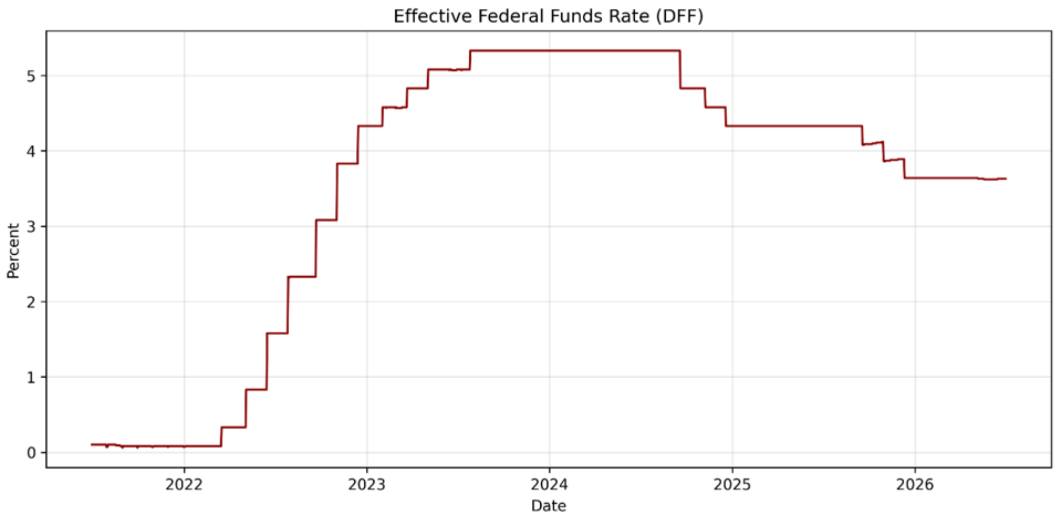

Figure 4: Historical evolution of the effective federal funds rate (DFF). Source: Board of Governors of the Federal Reserve System, retrieved through FRED.

4.10 Interpretation of labor-market dynamics

A central feature of the simulation is the weak response of unemployment to the fiscal and monetary shocks. This behavior follows from the model structure, which gives a prominent role to production, pricing, inventory, and capacity adjustment but does not contain explicit search-and-matching frictions or wage bargaining. Firms can therefore accommodate demand changes largely through intensive-margin adjustments. The resulting unemployment path is best interpreted as a limitation of the current labor-market block rather than as an empirical forecast.

5 Simulation Results

5.1 Baseline scenario

The baseline provides the reference trajectory. Inflation remains close to the 3% target and the policy rate stabilizes near 4.5%, while unemployment remains persistently high. The descriptive statistics are reported in Table 2.

Table 2: Descriptive statistics for the baseline scenario.

Variable	Mean	Std. Dev.	Minimum	Maximum
GDP	76.0603	4.2973	75.3641	109.0788
Unemployment	0.3553	0.0243	0.1900	0.3600
Inflation	0.0298	0.0013	0.0200	0.0300
Interest rate	0.0448	0.0009	0.0400	0.0450
Average price	5.5982	2.8184	2.0600	11.7832
Consumption	283.8082	30.4737	254.0412	363.4247

The high mean unemployment rate, approximately 35.53%, is not empirically plausible as a generic macroeconomic benchmark. It is retained because it is an outcome of the reported model, but it reinforces the proof-of-concept interpretation of the exercise.

5.2 Fiscal shock scenario

The fiscal scenario raises government spending exogenously. Relative to the baseline, mean GDP and consumption increase, while the reported inflation response remains small. Table 3 summarizes the fiscal scenario.

Table 3: Descriptive statistics for the fiscal-shock scenario.

Variable	Mean	Std. Dev.	Minimum	Maximum
GDP	77.7923	4.2734	77.1164	109.7088
Unemployment	0.3555	0.0242	0.1900	0.3600
Inflation	0.0300	0.0013	0.0200	0.0300
Interest rate	0.0448	0.0009	0.0400	0.0450
Average price	5.6650	2.8110	2.0600	11.8400
Consumption	286.1200	30.5100	255.0000	366.8000

Using the reported means, the percentage increase in GDP relative to the baseline is

$$\frac{77.7923 - 76.0603}{76.0603} \times 100 \approx 2.28\%. \tag{13}$$

Within the model, this is consistent with a positive demand effect from fiscal expansion. It should not, however, be interpreted as an estimated fiscal multiplier for an actual economy.

5.3 Monetary shock scenario

The monetary scenario reduces the policy interest rate. The reported mean GDP rises modestly, consumption increases slightly, and unemployment remains almost unchanged. The comparison of mean outcomes is given in Table 4.

Table 4: Comparative mean outcomes across scenarios.

Variable	Baseline	Fiscal shock	Monetary shock
GDP	76.06	77.79	76.32
Inflation	2.98%	3.00%	2.95%
Unemployment	35.53%	35.55%	35.50%
Interest rate	4.48%	4.48%	3.90%
Consumption	283.81	286.12	284.45

The reported monetary-shock increase in mean GDP is

$$\frac{76.32 - 76.0603}{76.0603} \times 100 \approx 0.34\%. \tag{14}$$

Thus, in the tabulated results, the output response to monetary easing is positive but considerably smaller than the response to the fiscal shock.

5.4 Volatility comparison

Table 5 compares the reported volatility measures. The fiscal scenario changes output volatility only slightly, while the monetary scenario has the lowest reported inflation volatility.

Table 5: Volatility of key variables across scenarios.

Scenario	GDP Std. Dev.	Inflation Std. Dev.
Baseline	4.29	0.0013
Fiscal shock	4.27	0.0013
Monetary shock	4.31	0.0011

6 Discussion

The simulation produces three main qualitative findings. First, the fiscal shock has a larger effect on mean GDP than the monetary shock in the reported scenarios. Within the present model, this follows from the direct role of government spending in aggregate demand, whereas the interest-rate channel operates through a simplified behavioral structure.

Second, inflation remains close to the model target in all three scenarios. This indicates nominal stability within the specified rules, but it should not be interpreted as evidence that comparable real-world fiscal interventions would necessarily be non-inflationary. The model does not include many channels that may matter empirically, including detailed wage formation, financial constraints, supply bottlenecks, and expectation formation beyond the simple adaptive rules.

Third, unemployment is both unrealistically high and nearly insensitive to policy. This is the clearest indication that the labor-market block requires further development. The current structure lacks search and matching, wage bargaining, endogenous labor-force participation, and richer hiring and firing rules. Consequently, the model should not be used to draw quantitative labor-market conclusions.

Table 6 summarizes the intended relationship between the simulation and the empirical benchmark series. The terminology is deliberately *qualitative comparison* rather than *empirical validation*, because the FRED series are not used to estimate or statistically test the model.

Table 6: Qualitative comparison of simulation outcomes with empirical benchmark series.

Variable	Empirical benchmark	Reported model outcome	Interpretation
GDP	Real GDP (GDPC1)	Fiscal shock raises mean GDP by 2.28%; monetary shock by 0.34%	Directional responses are internally interpretable, but magnitudes are not empirically estimated.
Inflation	PCE price index (PCEPI)	Inflation remains near 3%	Price dynamics are stable by construction; quantitative validation remains necessary.
Interest rate	Effective federal funds rate (DFF)	Baseline rate is about 4.0–4.5%	The initial monetary environment is broadly plausible as a stylized benchmark.
Unemployment	Unemployment rate (UNRATE)	Unemployment remains about 35.5%	The level is unrealistically high and indicates a weak labor-market block.
Policy sensitivity of unemployment	Historical cyclical response	Almost unchanged across scenarios	Additional labor-market mechanisms are required before policy sensitivity can be interpreted empirically.

Agent-based computational economics is particularly useful for experiments in which macroeconomic patterns emerge from decentralized and heterogeneous interactions [4, 6]. The present study illustrates that potential, but it also shows why transparency about model scope is essential. The EDT label is most useful here as a policy-sandbox metaphor: the framework organizes counterfactual experiments, but it does not yet satisfy the stronger requirements of a continuously data-linked digital twin.

7 Conclusion

This study develops a stylized Economic Digital Twin prototype for macroeconomic policy simulation using an agent-based computational framework. The model integrates households, firms, a fiscal authority, and a central bank and compares baseline, fiscal-expansion, and monetary-easing scenarios.

The reported results show a stronger mean output response to fiscal expansion than to monetary easing, while inflation remains close to target. At the same time, unemployment remains around 35.5% and responds very little to either intervention. These outcomes imply that the present model is best viewed as a proof of concept for qualitative policy experimentation, not as a calibrated forecasting system or a basis for quantitative policy recommendations.

Several extensions are necessary for a more operational EDT. The most important are empirical calibration of the behavioral parameters, explicit labor-market search and matching, wage bargaining and labor-force participation, a banking and credit sector, endogenous investment, open-economy linkages, and a systematic validation strategy. Real-time or machine-learning-assisted parameter updating could be considered only after the underlying economic blocks are sufficiently identified and empirically grounded.

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