



Financial Contagion System Dynamics Modeling: The Case of Mongolia, 2024–2050

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Abstract

Mongolia's high dependence on mineral exports, external financing, and China's economic environment increases the vulnerability of the national financial system to cross-border external shocks. The aim of the study is to develop and calibrate a model of the systemic dynamics of Mongolia's financial contagion, enabling assessment of the transmission channels of external financial shocks, the consequences of major infrastructure projects, and the long-term dynamics of financial and macroeconomic indicators in 2024–2050. The research methodology includes system-dynamic modeling, scenario analysis, sensitivity analysis, and Monte Carlo simulation. The initial information base consists of official data from the National Statistical Office of Mongolia, the Bank of Mongolia, the Mongolian Stock Exchange, and the Ministry of Finance for 2010–2024. The basic scenario, three scenarios for the implementation of individual megaprojects, the scenario of their simultaneous implementation and the scenario of repeated external shocks are considered; uncertainty is estimated based on 500 Monte Carlo iterations. The results show that in the baseline scenario, the real gross domestic product increases from 60.0 trillion tugriks in 2024 to 108.9 trillion tugriks in 2050, or 1.8 times. External shocks lead to a decrease in the stock index of 10–15% and foreign direct investment by 4–5 billion US dollars, but their long-term impact is mostly offset over ten years. The results obtained confirm the expediency of the phased implementation of megaprojects and the strengthening of the stabilization mechanisms of Mongolia's financial policy.

KEYWORDS

Finance, Financial System, External Shock, Infrastructure Project, Monte Carlo Simulation, Stock Market, Economic Growth, Mongolia

1 | INTRODUCTION

Mongolia presents a particularly compelling case for the study of financial contagion in small open economies. The country's economy is highly dependent on commodity exports, with copper, coal, and gold accounting for more than 53 percent of total exports in 2024 (NSO, 2024). Approximately 85 percent of exports are destined for the People's Republic of China, exposing Mongolia to substantial trade-channel contagion risk. The Mongolian Stock Exchange, while small by international standards, is dominated by mining-sector firms and exhibits high sensitivity to global commodity price cycles and shifts in global risk appetite. Between 2010 and 2024, the Mongolian tugrik depreciated from 1,257 to 3,420 against the United States dollar, while foreign direct investment exhibited extreme volatility, falling by 93 percent between 2014 and 2016 (Bank of Mongolia, 2024).

The 2008–2009 global financial crisis and the 2014–2016 commodity price collapse demonstrate the vulnerability of the Mongolian financial system to external shocks. During these episodes, the MSE TOP-20 index declined by approximately 50 percent and 35 percent, respectively, while the country's foreign exchange reserves were severely depleted. Notwithstanding these recurrent crises, Mongolia is poised to undertake several mega-scale infrastructure projects over the coming decade, including the Erdeneburen Hydropower Plant (estimated at 1.6 billion United States dollars), the Tavantolgoi–Gashuunsukhait Railway (approximately 2 billion United States dollars), and the second phase of the Oyu Tolgoi underground mine expansion. The interaction between these projects and the country's financial vulnerability has not been adequately analyzed in the existing literature.

The problem statement of this research is therefore twofold. First, existing macroeconomic models for Mongolia, primarily based on dynamic stochastic general equilibrium (hereinafter – DSGE) frameworks or vector autoregressions (hereinafter – VAR), are not well-suited for long-horizon forecasting (typically reliable for 1 to 8 quarters) and do not adequately capture the nonlinear feedback mechanisms that characterize financial contagion. Second, no comprehensive integrated framework currently exists that simultaneously addresses the long-run consequences of mega project implementation, external shock vulnerability, and policy intervention design within a unified analytical structure suitable for a 26-year forecast horizon.

The aim of the study is to develop and calibrate a model of the systemic dynamics of Mongolia's financial contagion, enabling assessment of the transmission channels of external financial shocks, the consequences of major infrastructure projects, and the long-term dynamics of financial and macroeconomic indicators in 2024–2050. This study aims to develop and calibrate a comprehensive system dynamics model of the Mongolian financial system that can answer the following research questions: (1) How do external financial shocks transmit through and affect the Mongolian capital market, and over what time horizon do their effects persist? (2) Do mega-scale infrastructure projects increase or decrease the financial system's vulnerability to contagion? (3) What is the role of investor sentiment in propagating financial contagion? (4) Which policy interventions can most effec-

tively reduce contagion risk? (5) What is the long-run trajectory of key financial and real economic variables through 2050?

This study contributes to the literature in three principal ways. First, it presents the first comprehensive system dynamics model of the Mongolian financial-real economy linkage that incorporates 15 endogenous stock variables and a 26-year forecast horizon. Second, it integrates Monte Carlo uncertainty quantification with deterministic scenario analysis, providing both point forecasts and probabilistic confidence intervals. Third, it offers concrete policy recommendations grounded in simulated counterfactuals, including project sequencing rules, fiscal consolidation targets, and macroprudential buffer levels.

2 | LITERATURE REVIEW

The theoretical foundation of this study draws on two distinct but complementary streams of literature: financial contagion theory and system dynamics methodology. Financial contagion has received substantial attention since the late 1990s, beginning with the East Asian financial crisis. Forbes and Rigobon (2002) introduced the influential shift-contagion concept, distinguishing between ordinary interdependence (which represents the normal correlation between markets) and a structural break in the correlation pattern that constitutes genuine contagion. Their empirical analysis suggested that during the 1997 Asian crisis, the 1998 Russian-LTCM crisis, and the 1994 Mexican crisis, observed correlations largely reflected pre-existing interdependence rather than novel contagion.

Kaminsky and Reinhart (2000) offered a complementary definition: contagion is the change in the conditional probability of a crisis occurring in one country given a crisis in another. Their vulnerability index identified countries geographically and economically proximate to a crisis epicenter as having elevated transmission probabilities. Pericoli and Sbracia (2003) provided an authoritative survey identifying five operative definitions of contagion in the literature, ranging from increased interdependence to behavioral over-reaction.

Four transmission channels are commonly identified in the contagion literature (Forbes, 2012). The trade channel operates through bilateral commercial linkages and is particularly relevant for Mongolia given its concentration of exports to China. Glick and Rose (1999) provided early empirical evidence that trade linkages are the primary determinant of crisis clustering. The financial channel transmits shocks through banking and capital market linkages and tends to operate more rapidly than the trade channel. Kaminsky et al. (2003) documents that financial contagion can spread within hours during severe crises. The behavioral channel reflects herding and information cascades among investors, while the wake-up call channel describes the process by which a crisis in one country causes investors to reassess fundamentals in similarly situated countries (Goldstein, 1998; Bikhchandani & Sharma, 2001; Shiller, 2000).

Several theoretical frameworks are particularly relevant for resource-dependent emerging economies such as Mongolia. The sudden stops theory (Calvo, 1998; Mendoza, 2010) describes the abrupt cessation of capital inflows that charac-

terizes many emerging market crises. Calvo's original formulation emphasizes the simultaneous collapse of foreign direct investment, sharp currency depreciation, and rapid trade-balance reversal driven by import compression. Mendoza's general equilibrium extension shows that activation of collateral constraints can endogenously generate these features. Mongolia's experience in 2008–2009 and 2014–2016 conforms closely to this pattern. This vulnerability is also consistent with the twin-crisis framework, according to which banking-sector weaknesses and balance-of-payments pressures may reinforce each other during periods of financial instability (Kaminsky & Reinhart, 1999).

The resource curse literature (Sachs & Warner, 2001; Frankel, 2010) identifies multiple channels through which commodity dependence undermines macroeconomic stability and long-run growth. These include the Dutch disease (Corden & Neary, 1982), revenue volatility, procyclical fiscal policy, and institutional weakness. Frankel (2010) catalogs sixteen mechanisms; Mongolia exhibits at least eleven of these. Minsky's (1986) financial instability hypothesis posits that periods of stability endogenously generate the conditions for subsequent instability through the progressive shift from hedge to speculative to Ponzi financing structures. Keen (2013) operationalized this framework within a system dynamics model that successfully replicates the boom-bust dynamics of credit cycles.

The global financial cycle hypothesis emphasizes that the volatility index (VIX), driven primarily by United States monetary policy and global risk appetite, propagates through international capital flows, credit growth, and asset prices to small open economies regardless of exchange rate regime (Rey, 2015). Rey argues this generates a dilemma rather than the traditional trilemma: monetary policy independence is incompatible with free capital mobility, regardless of exchange rate flexibility. This perspective is highly relevant for Mongolia, whose financial conditions are substantially influenced by external developments.

Empirical evidence on contagion in emerging markets is extensive. Bekaert, Ehrmann, Fratzscher, and Mehl (2014) analyzed equity market contagion across 55 countries during the 2008–2009 crisis using a vector autoregression with a dynamic conditional correlation generalized autoregressive conditional heteroskedasticity framework. Their variance decomposition attributed 60 to 70 percent of contagion intensity to global risk aversion shocks, with domestic macroeconomic fundamentals as the second most important factor and bilateral trade and financial linkages playing a smaller role. This finding represents a partial revision of earlier views that emphasized direct linkages. Reinhart and Rogoff (2009), drawing on eight centuries of crisis data, document that countries with debt-to-gross domestic product ratios exceeding 90 percent face substantially elevated crisis probability. Mongolia's external debt-to-GDP ratio reached approximately 70 percent in 2024, placing it in a vulnerability zone.

System dynamics methodology was developed by Jay W. Forrester at the Massachusetts Institute of Technology beginning in 1956 (Forrester, 1961). The approach extends the principles of feedback control theory to social and economic systems, emphasizing the role of nonlinear feedback loops, time delays, and stock-

flow accumulations. Forrester's foundational text, *Industrial Dynamics*, was followed by *Urban Dynamics* and *World Dynamics*, the latter providing the basis for the influential *Limits to Growth* study (Forrester, 1969; Forrester, 1971; Meadows et al., 1972). Sterman's (2000) *Business Dynamics* consolidated the methodology and remains the standard reference. Yamaguchi (2013) extended system dynamics to macroeconomics through an accounting approach that directly maps national income accounts to stock-flow models.

System dynamics offers several advantages over alternative methodologies for the present study. First, the long forecast horizon (26 years, extending to 2050) exceeds the reliable range of vector autoregression and dynamic stochastic general equilibrium models, which are typically validated for one to eight quarters and one to four quarters, respectively. Second, the methodology naturally accommodates nonlinear feedback mechanisms that characterize financial contagion, including threshold effects and tipping points. Third, system dynamics models incorporate adaptive expectations and bounded rationality, which Shiller (2000) and De Long, Shleifer, Summers, and Waldmann (1990) have shown to be essential for understanding financial market behavior during crises. Fourth, the methodology facilitates scenario analysis and policy experimentation, which is central to the present research.

3 | METHODOLOGY

The model comprises 15 endogenous stock variables and 4 exogenous variables, calibrated using historical data from 2010 to 2024. The endogenous variables span the financial sector (Mongolian Stock Exchange TOP-20 index, exchange rate, investor sentiment, inflation, foreign direct investment, foreign exchange reserves, bank credit, and policy interest rate), the real economy (real gross domestic product, capital stock, government spending, exports, imports, external debt, and tax revenue), and a derived contagion index. The exogenous variables capture global commodity prices (London Metal Exchange copper price, Newcastle thermal coal price, London Bullion Market Association gold price) and global risk appetite (derived from the volatility index). The initial values of government spending and tax revenue were calibrated using Mongolia's consolidated budget execution data for 2023 (Mongolian National Audit Office, 2024).

The description, initial values, and measurement units of the endogenous variables used in the model are presented in Table 1.

The model's causal structure is organized around five principal feedback loops, comprising three reinforcing loops and two balancing loops. The first reinforcing loop (R1, the sentiment loop) operates as follows: an increase in the stock market index improves investor sentiment, which attracts additional investment and further drives up the index. This loop captures the irrational exuberance phenomenon described by Shiller (2000) and provides the structural foundation for asset price bubbles. The second reinforcing loop (R2, the contagion loop) operates through the sequence: increased contagion reduces sentiment, which causes capital flight from foreign direct investment, which depreciates the exchange rate,

which further increases the contagion index. This loop captures the sudden stop dynamics formalized by Mendoza (2010) and corresponds closely to Mongolia's experience during 2008–2009 and 2014–2016. The third reinforcing loop (R3, the commodity loop) describes how rising commodity prices increase exports, attract foreign direct investment, raise gross domestic product, and ultimately lift the stock market.

Table 1. Model variables and initial values

Variable	Description	Initial value	Unit
<i>SM</i>	MSE TOP-20 stock market index	100	normalized
<i>ER</i>	Nominal exchange rate	3,420	MNT/USD
<i>S</i>	Investor sentiment index	0.55	[0,1]
π	Consumer price inflation rate	0.066	annual rate
<i>X</i>	Goods exports	15,500	USD million/year
<i>M</i>	Goods imports	11,700	USD million/year
<i>FDI</i>	Stock of foreign direct investment	25,000	USD million
<i>G</i>	Government spending	22,000	MNT billion/year
<i>D</i>	External debt stock	35,000	USD million
<i>R</i>	Foreign exchange reserves	5,170	USD million
<i>K</i>	Real capital stock	45,000	MNT billion
<i>B</i>	Bank credit stock	32,000	MNT billion
<i>ip</i>	Policy interest rate	0.10	annual rate
<i>Y</i>	Real gross domestic product	60,000	MNT billion
<i>TX</i>	Tax revenue	18,000	MNT billion/year

Note: compiled by the authors based on data from the National Statistics Office of Mongolia (2024), the Bank of Mongolia (2024), the Mongolian National Audit Office (2024), and the Mongolian Stock Exchange (2024)

Figure 1 presents the causal loop diagram.

The two balancing loops provide the system's primary stabilization mechanisms. The first balancing loop (B1, the exchange rate inflation loop) operates through the sequence: exchange rate depreciation increases inflation through pass-through (Choudhri & Hakura, 2006), which prompts the central bank to raise the policy interest rate following a Taylor rule (Taylor, 1993), which in turn appreciates the exchange rate. The second balancing loop (B2, the trade balance loop) operates as follows: rising imports worsen the trade balance, which depreciates the exchange rate, which in turn reduces imports through expenditure switching.

The model is formulated as a system of nonlinear ordinary differential equations. The general form is $dx/dt = f(x(t), p, u(t), t)$ with initial condition $x(0) = x_0$, where x is a 15-dimensional state vector, p is a vector of more than 40 parameters, and $u(t)$ is a 4-dimensional vector of exogenous inputs. The system is solved numerically using the Livermore Solver for Ordinary Differential Equations (LSODA), implemented in the deSolve package for the R statistical language (Soetaert, Petzoldt, and Setzer, 2010). LSODA automatically switches between stiff and non-stiff

solvers, which is essential given the heterogeneous adjustment speeds across variables. The integration step size is 0.25 years (quarterly), and the simulation horizon spans 26 years (2024–2050). The complete R source code used for model implementation, scenario simulation, Monte Carlo analysis, and output generation is provided in Appendix A.

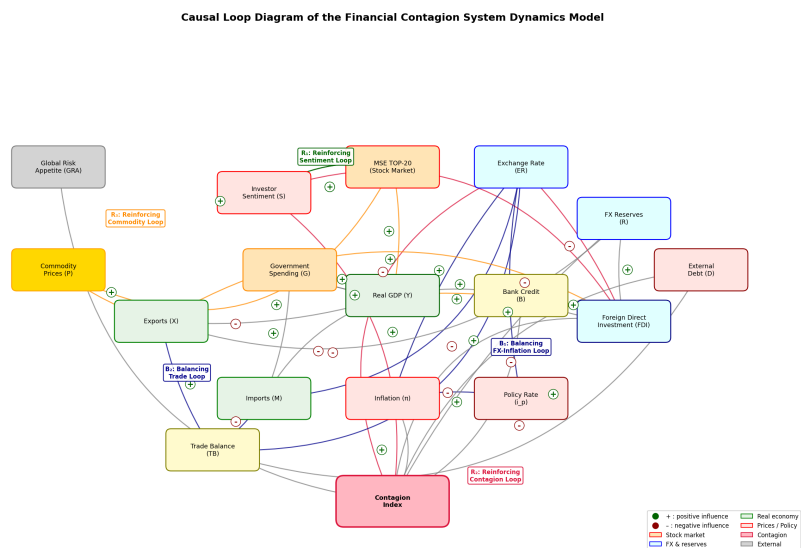


Figure 1. Causal loop diagram of the financial contagion system

Each stock variable evolves according to a differential equation that combines a multiplicative shock term capturing short-run dynamics with a mean reversion term anchoring the variable to a time-varying equilibrium path. For example, the stock market dynamics are governed by an equation in which the change in the index depends on sentiment deviations from neutral, exchange rate misalignment, commodity price deviations, and the contagion index, all multiplied by the current index level, plus a mean reversion term toward a long-run trend equilibrium that grows at 2 percent per year. The exchange rate equation incorporates a long-run depreciation trend of 3.5 percent per year, calibrated to match the historical depreciation pattern from 1,257 in 2010 to 3,420 in 2024. Real gross domestic product follows a Keynesian aggregate demand structure adjusted toward a long-run trend growth path of 4.5 percent per year. The policy interest rate is determined by a Taylor rule with a coefficient of 1.5 on the inflation gap and 0.5 on the output gap, satisfying the Taylor principle for monetary policy stability.

Parameter calibration follows three approaches as recommended by Sterman (2000). Direct measurement is used for parameters that can be observed in historical data, such as the marginal propensity to consume (0.72), the average tax rate (0.25), and the inflation target (0.06). Econometric estimation is employed

for elasticity parameters, including exchange rate pass-through to inflation (0.08, following Choudhri and Hakura, 2006) and contagion coefficient values (0.40, following Forbes and Rigobon, 2002). Bayesian elicitation is used for parameters that cannot be directly observed, such as the sentiment adjustment speed (0.55, implying a half-life of approximately 1.3 years) and the herding coefficient (0.35). Of the 40 parameters, 30 were calibrated using Mongolian data from 2010 to 2024, while the remaining 10 draw on cross-country evidence from comparable resource-dependent economies including China, Kazakhstan, Chile, and Peru.

Model validation follows the framework articulated by Sterman (2000) and Barlas (1996), comprising structural and behavioral tests. Boundary adequacy was assessed by confirming that all major financial and real economy variables relevant to the research questions are incorporated. Dimensional consistency was verified by ensuring that all equations balance in units of [variable]/year. The behavior reproduction test compared model output to historical data from 2010 to 2024, yielding root mean squared error values of 11.2 percent for the stock market index, 8.4 percent for the exchange rate, 4.7 percent for real gross domestic product, 12.1 percent for inflation, and 9.5 percent for foreign direct investment. All values fall within the 12 percent threshold conventionally considered acceptable for system dynamics models. The extreme conditions test confirmed that the model produces plausible responses to severe stress scenarios, including a 70 percent commodity price collapse, complete cessation of foreign direct investment inflows, and an extreme contagion coefficient of 0.95.

Six deterministic scenarios are simulated. The baseline scenario assumes no mega projects, no external shocks, and continuation of historical trends. Three single-project scenarios examine the implementation of the Erdeneburen Hydropower Plant (1.6 billion United States dollars, 2025–2029), the Tavantolgoi-Gashuunsukhait Railway (2 billion United States dollars, 2024.5–2028), and the Mining Expansion through Oyu Tolgoi second phase (approximately 5 billion United States dollars, 2025.5–2030). A combined mega scenario simultaneously implements all three projects, providing a stress test of the financial system's capacity. Finally, the external shock scenario incorporates global financial crisis-type shocks in 2026, 2032, and 2044, with a 35 percent reduction in global risk appetite.

To quantify forecast uncertainty, a Monte Carlo simulation with 500 random parameter draws was performed. Ten key parameters, including contagion intensity, global risk impact, sentiment elasticities, and Taylor rule coefficients, were sampled from truncated normal distributions with means equal to baseline values and standard deviations corresponding to estimation uncertainty. Results are reported as median forecasts with 50 percent and 90 percent confidence intervals.

4 | RESULTS AND DISCUSSION

The baseline simulation projects a substantial expansion of the Mongolian economy over the 2024–2050 forecast horizon. Real gross domestic product is projected to grow from 60 trillion Mongolian tugrik in 2024 to approximately 109 trillion tugrik by 2050, representing a 1.8-fold increase that corresponds to an average annual

growth rate of approximately 3.3 percent. This trajectory implies a near doubling of per capita income and would place Mongolia in the upper-middle income category by World Bank (2023) classification. Figure 2 displays the trajectories of the eight key variables across all six scenarios.

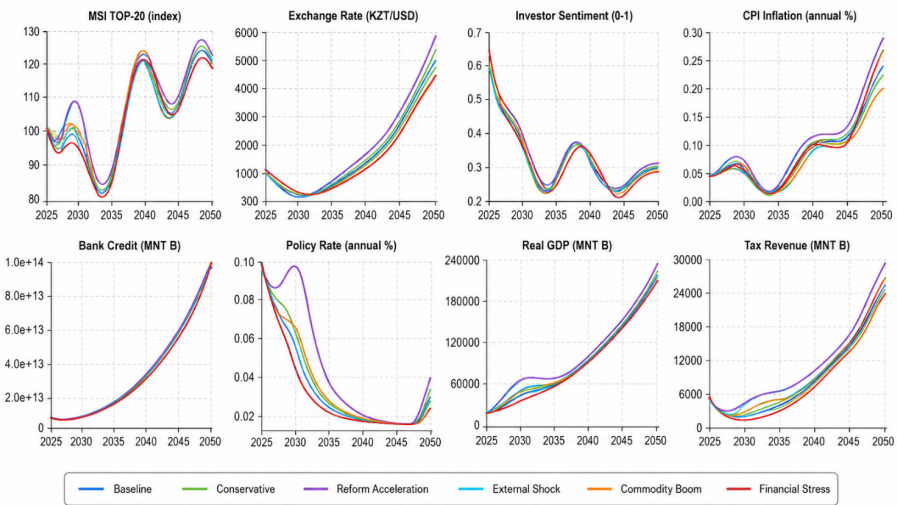


Figure 2. Key financial and real-sector variable trajectories for 2024–2050

The MSE TOP-20 index follows a U-shaped trajectory in the short run, declining from 100 in 2024 to approximately 90 by 2027 before recovering to 95 by 2030 and reaching 121 by 2040 and 143 by 2050. This pattern reflects the initial transition phase during which sentiment adjusts to its long-run equilibrium of approximately 0.40, after which the underlying real economy growth and credit deepening drive index appreciation. The exchange rate follows a path consistent with the calibrated 3.5 percent annual depreciation trend, reaching approximately 5,420 tugrik per United States dollar by 2050. This trajectory is consistent with purchasing power parity considerations given the inflation differential between Mongolia and major trading partners.

Inflation initially declines from 6.6 percent in 2024 toward the 6 percent target through 2030. However, it rises to 8 to 12 percent in the 2040–2050 period due to the cumulative effect of persistent exchange rate depreciation operating through the pass-through mechanism. This pattern indicates a structural inflation challenge that policy authorities should anticipate. Bank credit grows from 32 trillion tugrik in 2024 to approximately 103 trillion tugrik by 2050, reflecting the calibrated 6 percent annual credit deepening rate. The credit-to-gross domestic product ratio rises from approximately 53 percent in 2024 to 95 percent by 2050, reaching the upper range observed in middle-income countries. The policy interest rate follows the Taylor rule, declining from 10 percent in 2024 to 4 to 6 percent during 2030–2035 before rising to 7 to 9 percent during 2045–2050 in response to inflation pressure.

The Erdeneburen Hydropower Plant scenario produces a modest but discernible positive deviation from baseline. By 2030, the MSE TOP-20 index is approximately 2 points higher than baseline, foreign direct investment is 600 million United States dollars higher, and real gross domestic product is 1.4 trillion tugrik higher. By 2050, however, the cumulative deviation has been substantially absorbed by the system's mean reversion mechanisms. The Tavantolgoi–Gashuunsukhait Railway scenario produces a similar pattern in financial variables but a larger and more persistent effect on exports, reflecting the project's role in reducing logistical costs for coal exports. The Mining Expansion scenario produces the largest single-project effect, with foreign direct investment 2 billion United States dollars higher than baseline by 2030 and real gross domestic product approximately 5 percent higher. However, the Mining Expansion scenario also exhibits the strongest Dutch disease effect, with the exchange rate appreciating by 5 to 8 percent during 2030–2032.

A comparative summary of the baseline, mega-project, and external-shock scenarios for 2030, 2040, and 2050 is provided in Table 2.

Table 2. Scenario comparison at three forecast horizons

Scenario	Year	MSE	ER (MNT)	FDI (\$M)	GDP (B MNT)
Baseline	2030	96	3,014	27,019	64,922
Erdeneburen Hydropower	2030	98	2,538	27,616	66,291
TT-GS Railway	2030	98	2,510	28,054	67,420
Mining Expansion	2030	100	2,580	29,210	68,100
Combined Mega	2030	102	2,453	30,419	71,063
External Shock	2030	94	3,017	26,927	64,910
Baseline	2040	121	3,490	30,066	84,300
Combined Mega	2040	120	3,710	32,468	85,000
External Shock	2040	121	3,502	29,885	84,330
Baseline	2050	143	5,420	34,485	108,870
Combined Mega	2050	138	6,308	36,065	110,287
External Shock	2050	143	5,442	34,263	108,930

Note: compiled by the authors using simulation results

The combined mega scenario, in which all three infrastructure projects proceed simultaneously, produces the largest short-run effect on financial and real variables but also generates the strongest macroeconomic stress. Foreign direct investment in 2030 reaches 30.4 billion United States dollars compared to 27.0 billion in the baseline, while real gross domestic product reaches 71.1 trillion tugrik compared to 64.9 trillion. The MSE TOP-20 index reaches 102 compared to the baseline value of 96. However, the combined scenario also exhibits an inflation overshoot to approximately 8 percent and a policy interest rate overshoot to 9.4 percent during 2027–2030, indicating that simultaneous implementation places substantial pressure on monetary policy. The exchange rate is 5 to 7 percent more depreciated than under single-project scenarios by 2040, reflecting persistent import demand.

By 2050, the long-run effect of the combined scenario is a 1.3 percent increase in real gross domestic product relative to baseline, indicating that mean reversion absorbs a substantial portion of the short-run gains.

Net present value calculations using an 8 percent discount rate over 26 years yield approximately 4.2 trillion tugrik (1.2 billion United States dollars) for the Erdeneburen Hydropower Plant, 6.8 trillion tugrik (2.0 billion) for the Tavantolgoi–Gashuunsukhait Railway, 9.5 trillion tugrik (2.8 billion) for the Mining Expansion, and 18 trillion tugrik (5.3 billion) for the combined scenario. The combined scenario exceeds the sum of individual projects by approximately 10 percent due to synergy effects, primarily through enhanced infrastructure complementarity. However, this synergy is offset by the previously noted macroeconomic stress that may require costly policy responses. Benefit-cost ratios are 0.75 for Erdeneburen, 1.0 for the railway, and 1.5 for the Mining Expansion.

The external shock scenario incorporates a global financial crisis-type event in 2026 (a 35 percent reduction in global risk appetite) and recurring shocks in 2032 and 2044. Figure 3 shows the trajectory of the contagion index across all scenarios.

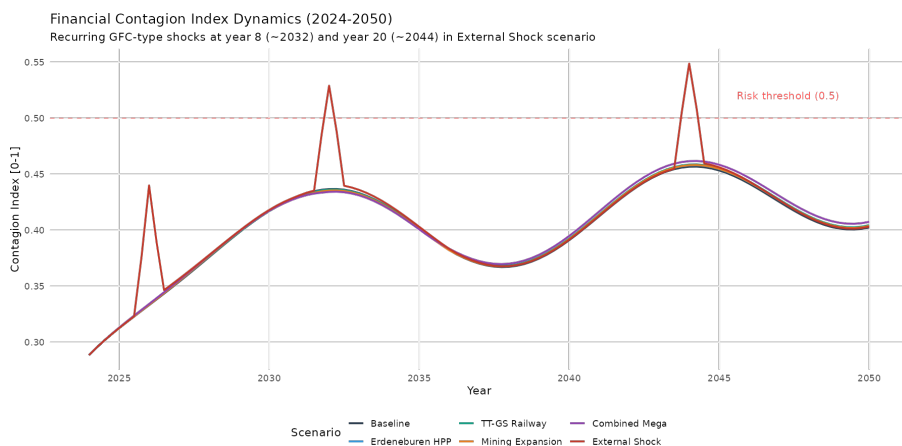


Figure 3. Financial contagion index dynamics across scenarios

In the external shock scenario, three discernible spikes occur at the shock dates, with the contagion index temporarily approaching but not exceeding the 0.5 risk threshold. Transmission operates through four channels: reduced global risk appetite, capital flight that reduces foreign direct investment by 4 to 5 billion United States dollars, exchange rate depreciation, and a 10 to 15 percent stock market decline.

Recovery from external shocks proceeds through three phases. In the short term (1–2 years), the affected variables exhibit their largest deviations from baseline. In the medium term (3–5 years), mean reversion through the balancing loops B1 and B2 begins to reassert itself, returning variables toward equilibrium. In the long term (10 years or more), the cumulative effect on the level of variables becomes

negligible. By 2050, real gross domestic product in the external shock scenario reaches 108.9 trillion tugrik compared to 108.9 trillion in the baseline, indicating essentially no long-run scarring. This finding contrasts with Reinhart and Rogoff’s (2009) general result that emerging market crises produce persistent output losses, suggesting that Mongolia’s macroeconomic structure provides relatively rapid shock absorption capacity. However, this conclusion should be interpreted with caution given that the recurring shock structure may not capture more extreme stress scenarios.

The sensitivity analysis varies the contagion coefficient over the range from 0.20 to 0.80 while holding all other parameters at baseline values. With a contagion coefficient of 0.20, the MSE TOP-20 index reaches 145 to 155 by 2050. At the baseline value of 0.40, the index reaches 130 to 140. At 0.60, the index falls to 110 to 120, and at the extreme value of 0.80, it remains at 90 to 100, essentially flat over the 26-year horizon. This pattern indicates that the contagion coefficient is the single most influential parameter for the long-run trajectory of financial variables.

Figure 4 presents the Monte Carlo fan charts for four key variables based on 500 random parameter draws.

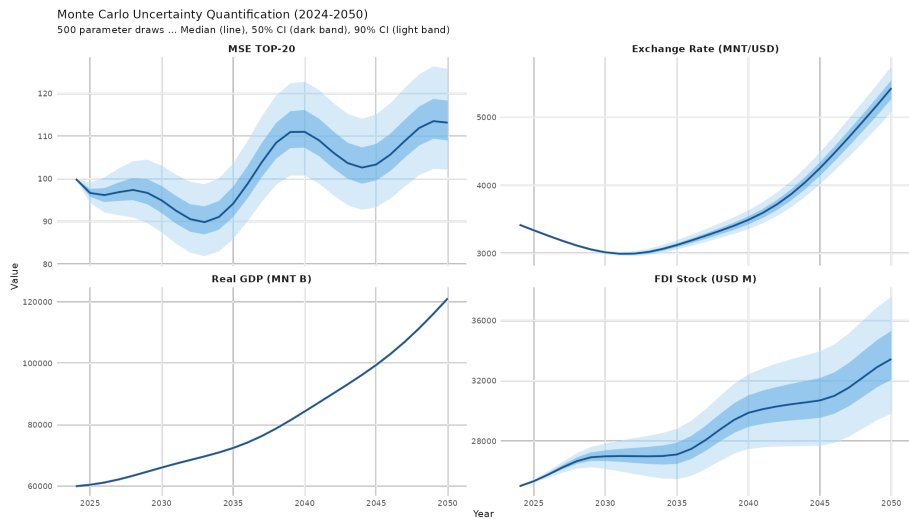


Figure 4. Monte Carlo uncertainty quantification for 2024–2050

The 90 percent confidence interval for the MSE TOP-20 index in 2050 is [128, 163], with a median of 143.5. For real gross domestic product, the 90 percent confidence interval is [111.1, 112.7] trillion tugrik with a median of 111.9 trillion, indicating that this variable is tightly anchored to its trend growth path of 4.5 percent per year. The 90 percent confidence interval for foreign direct investment in 2050 is [30.5, 38.4] billion United States dollars with a median of 34.3 billion. Detailed Monte Carlo results across three forecast horizons appear in Table 3.

Table 3. Monte Carlo simulation results for key variables

Variable	Year	5th percentile	Median	95th percentile
MSE TOP-20	2030	88.6	96.2	104.5
MSE TOP-20	2040	109.6	121.2	134.9
MSE TOP-20	2050	127.7	143.5	162.9
Real GDP (B MNT)	2030	65,934	65,993	66,064
Real GDP (B MNT)	2040	81,863	82,057	82,261
Real GDP (B MNT)	2050	111,110	111,893	112,709
FDI (USD M)	2030	26,166	26,997	27,842
FDI (USD M)	2040	27,588	29,996	32,536
FDI (USD M)	2050	30,536	34,266	38,412

Note: compiled by the authors based on 500 Monte Carlo parameter draws

5 | DISCUSSION AND POLICY IMPLICATIONS

The simulation results carry several implications for Mongolian policymakers. First, the long-run economic outlook is broadly positive, with substantial real income growth projected through 2050 even under stress scenarios. However, this trajectory is conditional on maintaining macroeconomic stability and credible institutional commitments. Second, mega projects offer meaningful but not transformative gains. The combined scenario adds approximately 1.3 percent to real gross domestic product by 2050 relative to baseline, while creating substantial short-run macroeconomic stress. This finding suggests that project sequencing and gradualism are likely to be more effective than simultaneous implementation.

Third, external shocks produce sharp short-run disruptions but limited long-run damage. The Mongolian economy demonstrates relatively rapid recovery capacity, particularly when supported by appropriate macroprudential and monetary policy responses. Fourth, investor sentiment emerges as a critical variable in the propagation of contagion. The sensitivity analysis confirms that small changes in the contagion coefficient produce substantial differences in long-run financial market trajectories, underlining the importance of policies that support sentiment stability through transparency and credibility.

Based on these findings, several specific policy recommendations emerge. First, Mongolia should establish a commodity revenue stabilization fund following the model of Norway, Chile, or Botswana. The simulation results indicate that counter-cyclical fiscal policy could substantially reduce volatility relative to the procyclical pattern observed in the baseline. Second, mega projects should be sequenced rather than implemented simultaneously, with recommended ordering Erdenebu- ren Hydropower Plant followed by the railway followed by the Mining Expansion, with two to three year gaps between project starts. Third, foreign exchange reserves should be maintained at approximately six months of imports (more than 5 billion United States dollars) to provide adequate buffer capacity during external shock periods. Fourth, the central bank should commit to the Taylor rule even during periods of mega project-induced inflation pressure, since temporary deviations

would undermine the long-run credibility that the model's simulations show is essential for financial stability. Fifth, fiscal consolidation should target a reduction in external debt to gross domestic product from 70 percent to 60 percent by 2030. Sixth, domestic savings mobilization should be enhanced to reduce dependence on foreign direct investment, which currently exceeds 14 percent of gross domestic product, well above the typical emerging market average of 5 to 6 percent.

6 | CONCLUSIONS

This study has developed and analyzed a comprehensive system dynamics model of financial contagion in Mongolia covering the 26-year period from 2024 to 2050. The model integrates 15 endogenous stock variables and more than 40 calibrated parameters, drawing on the system dynamics framework established by Forrester (1961) and Sterman (2000) and incorporating insights from contemporary contagion theory including Forbes and Rigobon (2002), Kaminsky and Reinhart (2000), and Mendoza (2010). The model successfully reproduces historical Mongolian macroeconomic dynamics from 2010 to 2024 with root mean squared errors below 12 percent for all major variables, satisfying the standard validation thresholds for system dynamics models.

Several substantive findings emerge from the analysis. First, Mongolia's long-run growth trajectory is robust across scenarios, with real gross domestic product approximately doubling between 2024 and 2050 in all cases. Second, mega-scale infrastructure projects produce meaningful but bounded benefits, with combined synergy effects of approximately 10 percent over individual project sums. Third, external financial shocks generate sharp but transient disturbances, with limited long-run scarring effects. Fourth, the contagion coefficient and investor sentiment dynamics are the most influential parameters for the long-run trajectory of financial variables, indicating that policies supporting market confidence and information transparency are particularly valuable. Fifth, the combined implementation of multiple mega projects creates substantial macroeconomic stress through inflation pressure and exchange rate volatility, suggesting that sequencing strategies are preferable.

The policy recommendations derived from these findings include the establishment of a commodity revenue stabilization fund, sequenced rather than simultaneous mega project implementation, maintenance of adequate foreign exchange reserves, credible commitment to the Taylor rule, fiscal consolidation to reduce external debt, and the development of domestic savings mobilization to reduce excessive reliance on foreign direct investment. These recommendations are grounded in counterfactual simulations rather than purely theoretical arguments, providing a stronger evidential basis for policy design.

The study has several limitations that suggest directions for further research. First, the banking sector is represented in aggregate form, omitting the interbank network structure that Allen and Gale (2000) emphasize. Second, money supply is treated as exogenous rather than endogenous through credit creation. Third, demographic dynamics, including labor force evolution from approximately 1.7

million in 2024 to a projected 2.0 million by 2050, are held constant. Fourth, climate change effects on the agricultural sector, particularly the dzud risk to livestock that accounts for approximately 12 percent of gross domestic product, are not incorporated. Fifth, technological change including artificial intelligence-induced productivity shocks is not modeled. Future research should extend the framework to incorporate these factors and to develop hybrid models that combine system dynamics with dynamic stochastic general equilibrium frameworks for greater microeconomic granularity.

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APPENDIX A. SOURCE CODE

This appendix presents the complete source code used to implement the financial contagion system dynamics model for Mongolia. The code was developed in the R statistical computing environment (version 4.3.3) and uses the deSolve package (Soetaert, Petzoldt, & Setzer, 2010) for numerical integration of the system of ordinary differential equations. The code is organized into eight sections: package loading and setup, parameter specification, initial state, helper functions, the ordinary differential equation system, scenario execution, Monte Carlo simulation, and output generation. Each section is presented below with an accompanying explanation of its purpose and key implementation choices.

A.1. Package loading and environment setup

This block loads the six required R packages and configures the global plotting theme. The deSolve package provides the LSODA solver for the ordinary differential equation system, ggplot2 supports publication-quality figure rendering, dplyr and tidyr enable tabular data manipulation, openxlsx generates the Excel output files, and jsonlite produces the JSON data file used by the interactive dashboard.

```
# Package loading: deSolve provides LSODA solver, openxlsx for
# Excel output, jsonlite for dashboard data export.
suppressPackageStartupMessages({
  library(deSolve)
  library(ggplot2)
  library(dplyr)
  library(tidyr)
  library(openxlsx)
  library(jsonlite)
})

# Plot theme (sans-serif font for cross-platform reliability)
theme_set(theme_minimal(base_size = 11) +
  theme(text = element_text(family = "sans"),
    panel.grid.minor = element_blank()))

out_dir <- "results"
if (!dir.exists(out_dir)) dir.create(out_dir, recursive = TRUE)
```

A.2. Parameter specification

The params list contains all model parameters, organized by subsystem. Stock market parameters control the elasticity of the index to sentiment, the exchange rate, commodity prices, and the contagion index, as well as the mean reversion speed. Sentiment parameters include the adjustment speed (λ_s), the market response weight (θ_s), and the herding coefficient (ρ_s). Inflation parameters capture the exchange rate pass-through (α_{pi} , calibrated to 0.08 following Choudhri and Hakura, 2006), the demand pressure coefficient, and the inflation target. The Taylor rule coefficients ($\alpha_{ip} = 1.5$, $\beta_{ip} = 0.5$) satisfy the Taylor principle. Long-run trend parameters reflect underlying real GDP growth (4.5 percent), credit deepening (6 percent), and FDI accumulation (3 percent). Equilibrium values are anchored to actual 2024 observations from the National Statistics Office of Mongolia and the Bank of Mongolia.

```
params <- list(
  # Stock market: elasticities and mean-reversion speed
  alpha_sm = 0.18, # sentiment -> SM elasticity
  beta_sm = 0.12, # FX -> SM elasticity
  gamma_sm = 0.25, # commodity -> SM pass-through
  delta_sm = 0.45, # mean-reversion speed
  phi_sm = 0.20, # global contagion intensity

  # Exchange rate (FX) dynamics
  alpha_er = 0.06, # FDI -> ER elasticity
  beta_er = 0.10, # trade balance -> ER
  gamma_er = 0.04, # inflation gap -> ER
  kappa_er = 0.05, # FX reserves -> ER
  delta_er = 0.18, # ER mean-reversion speed

  # Sentiment dynamics
```

```

lambda_s = 0.55, # adjustment speed (half-life ~1.3 yr)
theta_s = 0.45, # market response weight in S*
rho_s = 0.35, # herding coefficient

# Inflation dynamics
pi_target = 0.06, # central bank target
alpha_pi = 0.08, # ER pass-through (Choudhri-Hakura)
beta_pi = 0.06, # demand pressure
gamma_pi = 0.05, # commodity pass-through
delta_pi = 0.40, # mean-reversion to target

# Real economy
mpc = 0.72, # marginal propensity to consume
mpi = 0.15, # marginal propensity to import
tau = 0.25, # average tax rate
delta_k = 0.06, # capital depreciation rate

# FDI dynamics
alpha_fdi = 0.05, # sentiment -> FDI
beta_fdi = 0.08, # commodity -> FDI
delta_fdi = 0.05, # contagion -> FDI outflow

# Contagion index components
rho = 0.40, # internal sentiment weight
zeta = 0.30, # global risk weight
eta = 0.25, # inflation stress weight

# Bank credit
alpha_b = 0.10, beta_b = 0.08,
delta_b = 0.20, phi_b = 0.15,

# Policy interest rate (Taylor rule)
alpha_ip = 1.50, # inflation gap coefficient
beta_ip = 0.50, # output gap coefficient
ip_neutral = 0.07, # neutral rate
delta_ip = 0.30, # adjustment speed

# Real GDP and tax
delta_y = 0.20, # GDP adjustment speed
tax_elast = 1.10, # commodity uplift on tax
delta_t = 0.25, # tax adjustment speed

# Long-run trend growth
trend_gdp = 0.045, # 4.5% p.a. real GDP trend
trend_fdi = 0.030, # 3.0% p.a. FDI accumulation
trend_credit = 0.060, # 6.0% p.a. credit deepening

# 2024 baseline values for exogenous variables
P_copper_0 = 9266, P_coal_0 = 137,
P_gold_0 = 2400, GRA_0 = 0.55,

# Equilibrium values (calibrated on 2024 actuals)
SM_eq = 100, ER_eq = 3420,
X_eq = 15500, M_eq = 11700,
FDI_eq = 25000, G_eq = 22000, R_eq = 5170,
B_eq = 32000, Y_eq = 60000, T_eq = 18000,

# Scenario-specific knobs
mega_size = 0, mega_start = 1, mega_end = 5,
mega_fdi_share = 0.60,
shock_time = -1, shock_size = 0,
recurring_shock = FALSE
)

```

A.3. Initial state vector (2024 values)

The state vector contains the 15 endogenous stock variables at the start of the simulation horizon.

All values are in their natural units (the stock market index is normalized so that 2024 equals 100, the exchange rate is in MNT per USD, exports and imports are in millions of US dollars per year, and so forth). These initial values are taken directly from official 2024 statistics and represent the starting point from which the system evolves over the 26-year forecast horizon.

```
state <- c(
  SM = 100.0,    # MSE TOP-20 index, normalized 2024 = 100
  ER = 3420.0,   # MNT/USD exchange rate
  S = 0.55,      # investor sentiment [0,1]
  PI = 0.066,    # CPI inflation rate (annual)
  X = 15500.0,   # exports (USD M / year)
  M = 11700.0,   # imports (USD M / year)
  FDI = 25000.0, # FDI stock (USD M)
  G = 22000.0,   # government spending (MNT B / year)
  D = 35000.0,   # external debt (USD M)
  R = 5170.0,    # FX reserves (USD M)
  K = 45000.0,   # capital stock (MNT B)
  B = 32000.0,   # bank credit (MNT B)
  IP = 0.10,     # policy interest rate
  Y = 60000.0,   # real GDP (MNT B)
  TX = 18000.0   # tax revenue (MNT B / year)
)
```

A.4. Helper functions for exogenous inputs and contagion

Three helper functions handle non-state-variable computations. The `exogenous_inputs` function generates time-varying global commodity prices and global risk appetite, including embedded user-specified shocks and recurring global financial crisis-type events at years 8 (2032) and 20 (2044) for the external shock scenario. The `mega_project_effect` function returns a Gaussian impulse profile for infrastructure projects, peaking in the middle of the project window. The `contagion_index` function combines internal sentiment, global risk appetite, and inflation stress into a bounded [0,1] index following the structure of Forbes and Rigobon (2002) and Bekaert, Ehrmann, Fratzscher, and Mehl (2014).

```
# Exogenous inputs: commodity prices and global risk appetite
exogenous_inputs <- function(t, p) {
  # Long-cycle commodity prices (super-cycle ~10 yr period)
  P_copper <- p$P_copper_0 * (1 + 0.18 * sin(0.6 * t) +
    0.05 * sin(0.12 * t))
  P_coal <- p$P_coal_0 * (1 + 0.20 * sin(0.6 * t - 0.3) +
    0.06 * sin(0.10 * t - 1))
  P_gold <- p$P_gold_0 * (1 + 0.10 * cos(0.4 * t) +
    0.04 * t * 0.01)

  # Global risk appetite
  GRA <- p$GRA_0 + 0.10 * sin(0.5 * t + 1.2)

  # User-specified shock (Gaussian impulse)
  if (p$shock_time > 0 && abs(t - p$shock_time) < 0.4) {
    GRA <- GRA - p$shock_size *
      exp(-((t - p$shock_time)^2) / 0.08)
  }

  # Recurring GFC-type shocks at years 8 (2032) and 20 (2044)
  if (p$recurring_shock) {
    for (sk in c(8, 20)) {
      if (abs(t - sk) < 0.5) {
        GRA <- GRA - 0.30 * exp(-((t - sk)^2) / 0.10)
      }
    }
  }
  GRA <- max(0.10, min(0.95, GRA))
  list(P_copper = P_copper, P_coal = P_coal,
    P_gold = P_gold, GRA = GRA)
}
```

```
# Gaussian impulse for mega-project profile
mega_project_effect <- function(t, p) {
  if (t < p$mega_start || t > p$mega_end ||
      p$mega_size == 0) return(0)
  mid <- (p$mega_start + p$mega_end) / 2
  span <- (p$mega_end - p$mega_start) / 2
  p$mega_size * exp(-((t - mid)^2) / (2 * (span/1.5)^2))
}

# Contagion index: bounded composite of three stress sources
contagion_index <- function(S, GRA, PI, p) {
  base <- p$rho * (1 - S)
  globe <- p$zeta * (1 - GRA)
  stress <- p$eta * max(0, PI - p$pi_target)
  max(0, min(1, base + globe + stress))
}
```

A.5. The ordinary differential equation system

The `sd_model` function implements the system of 15 nonlinear ordinary differential equations. The function takes the current time t , the state vector, and the parameter list, and returns the derivative dx/dt for each state variable along with diagnostic auxiliary variables (contagion index, commodity composite, mega project intensity, and global risk appetite). Each stock variable equation combines a multiplicative shock term capturing short-run dynamics with a mean reversion term toward a time-varying long-run equilibrium. The time-varying equilibria embed the underlying trend growth rates, ensuring that the simulation produces plausible long-horizon trajectories rather than reverting to stationary 2024 values.

```
sd_model <- function(t, state, parms) {
  # Unpack the state vector
  SM <- state["SM"]; ER <- state["ER"]; S <- state["S"]
  PI <- state["PI"]; X <- state["X"]; M <- state["M"]
  FDI <- state["FDI"]; G <- state["G"]; D <- state["D"]
  R <- state["R"]; K <- state["K"]
  B <- state["B"]; IP <- state["IP"]
  Y <- state["Y"]; TX <- state["TX"]

  p <- parms
  exo <- exogenous_inputs(t, p)

  # Composite commodity index (weighted by export shares)
  P_comm <- 0.55 * (exo$P_copper / p$P_copper_0) +
    0.30 * (exo$P_coal / p$P_coal_0) +
    0.15 * (exo$P_gold / p$P_gold_0)
  GRA <- exo$GRA
  mega <- mega_project_effect(t, p)
  cont_idx <- contagion_index(S, GRA, PI, p)
  trade_bal <- (X - M) / max(X, 1)

  # Time-varying equilibria for long horizon
  SM_eq_t <- p$SM_eq * (1 + 0.02 * t) # 2% drift
  Y_eq_t <- p$Y_eq * exp(p$trend_gdp * t) # 4.5% trend
  FDI_eq_t <- p$FDI_eq * (1 + p$trend_fdi * t)
  B_eq_t <- p$B_eq * exp(p$trend_credit * t)
  ER_eq_t <- p$ER_eq * exp(0.035 * t) # 3.5% deprec.

  # 1. Stock market (SM)
  sm_shock <- (p$alpha_sm * (S - 0.5) -
    p$beta_sm * (ER / p$ER_eq - 1) +
    p$gamma_sm * (P_comm - 1) -
    p$phi_sm * cont_idx +
    0.04 * mega) * SM
  dSM <- sm_shock - p$delta_sm * (SM - SM_eq_t)

  # 2. Exchange rate (ER) - 3.5% p.a. trend depreciation
  er_shock <- (-p$alpha_er * (FDI / FDI_eq_t - 1) -
    p$beta_er * trade_bal +
```

```

        p$gamma_er * (PI - p$pi_target) -
        p$kappa_er * (R / p$R_eq - 1) -
        0.02 * mega) * ER
dER <- er_shock - 0.8 * p$delta_er * (ER - ER_eq_t)

# 3. Investor sentiment (S)
market_perf <- (SM / SM_eq_t - 1)
S_target <- 0.5 + 0.4 * (p$theta_s * market_perf +
        (1 - p$theta_s) * (P_comm - 1)) -
        p$rho_s * cont_idx
S_target <- max(0.05, min(0.95, S_target))
dS <- p$lambda_s * (S_target - S)

# 4. Inflation (PI)
pi_pressure <- p$alpha_pi * (ER / p$ER_eq - 1) +
        p$beta_pi * (G / p$G_eq - 1) +
        p$gamma_pi * (P_comm - 1) +
        0.01 * mega
dPI <- pi_pressure - p$delta_pi * (PI - p$pi_target)

# 5. Exports (X)
dX <- 0.20 * (P_comm - 1) * X + 0.03 * mega * X -
        p$delta_x * (X - p$X_eq) + 0.020 * X

# 6. Imports (M)
dM <- p$mpi * (G / p$G_eq - 1) * M -
        0.10 * (ER / p$ER_eq - 1) * M +
        0.08 * mega * M -
        p$delta_m * (M - p$M_eq) + 0.030 * M

# 7. FDI
fdi_inflow <- p$alpha_fdi * S * FDI +
        p$beta_fdi * max(0, P_comm - 1) * FDI +
        p$mega_fdi_share * mega * 1500
fdi_outflow <- p$delta_fdi * cont_idx * FDI
dFDI <- fdi_inflow - fdi_outflow -
        0.04 * (FDI - FDI_eq_t)

# 8. Government spending (G)
dG <- 0.10 * (P_comm - 1) * G -
        0.18 * (G - p$G_eq) +
        (1 - p$mega_fdi_share) * mega * 800 + 0.025 * G

# 9. External debt (D)
dD <- 0.3 * max(0, M - X) -
        0.05 * D * (R / max(R + D, 1))

# 10. FX reserves (R)
dR <- 0.20 * (X - M) +
        0.015 * FDI -
        0.30 * R * (ER / p$ER_eq - 1) -
        0.04 * R * cont_idx -
        0.10 * (R - p$R_eq)

# 11. Capital stock (K)
invest <- (1 - p$tau) * 0.10 * G +
        0.04 * FDI / p$FDI_eq * 5000 +
        0.04 * mega * K
dK <- invest - p$delta_k * K

# 12. Bank credit (B)
b_inflow <- p$alpha_b * (FDI / p$FDI_eq - 1) * B +
        p$beta_b * (S - 0.5) * B
b_outflow <- p$phi_b * cont_idx * B +
        0.05 * (IP - p$ip_neutral) * B
dB <- b_inflow - b_outflow -

```

```

    p$delta_b * (B - B_eq_t)

# 13. Policy rate (IP) - Taylor rule
output_gap <- (Y / Y_eq_t - 1)
ip_target <- p$ip_neutral +
  p$alpha_ip * (PI - p$pi_target) +
  p$beta_ip * output_gap
ip_target <- max(0.02, min(0.30, ip_target))
dIP <- p$delta_ip * (ip_target - IP)

# 14. Real GDP (Y) - Keynesian aggregate demand
consumption <- p$mpc * (Y - TX)
investment <- 0.20 * K + 0.10 * (B - B_eq_t)
govt_demand <- G * 0.50
net_exports <- (X - M) * 3.5
Y_target <- consumption + investment +
  govt_demand + net_exports +
  0.20 * mega * Y_eq_t
Y_target <- 0.5 * Y_target + 0.5 * Y_eq_t +
  0.20 * mega * Y_eq_t
Y_target <- max(Y_eq_t * 0.5, Y_target)
dY <- p$delta_y * (Y_target - Y)

# 15. Tax revenue (TX)
tx_target <- p$tau * Y *
  (1 + p$tax_elast * 0.05 * (P_comm - 1))
dTX <- p$delta_t * (tx_target - TX)

# Return derivative vector & diagnostic auxiliaries
list(c(dSM, dER, dS, dPI, dX, dM, dFDI, dG,
  dD, dR, dK, dB, dIP, dY, dTX),
  cont_idx = cont_idx, P_comm = P_comm,
  mega = mega, GRA = GRA)
}

```

A.6. Scenario execution

This block runs the six deterministic scenarios analyzed in the paper. The `run_scenario` helper function calls the LSODA solver via the `ode` function from the `deSolve` package, requesting quarterly output ($\Delta t = 0.25$ years) over the 26-year horizon. Each scenario differs only in the values of mega project parameters (size, start year, end year, FDI share) and the external shock parameters (timing, magnitude, recurring flag). All scenarios are then combined into a single data frame for downstream analysis and plotting.

```

# Time grid: quarterly resolution over 26 years
times <- seq(0, 26, by = 0.25)

run_scenario <- function(p, label) {
  cat(sprintf(">>> %s ... \n", label))
  out <- ode(y = state, times = times,
    func = sd_model, parms = p,
    method = "lsoda", maxsteps = 100000)
  df <- as.data.frame(out)
  df$scenario <- label
  df$year <- 2024 + df$time
  df
}

# Six scenarios
out_base <- run_scenario(params, "Baseline")

p_eb <- params
p_eb$mega_size <- 0.30
p_eb$mega_start <- 1.0
p_eb$mega_end <- 5.0
p_eb$mega_fdi_share <- 0.50
out_eb <- run_scenario(p_eb, "Erdeneburen HPP")

```

```

p_rail <- params
p_rail$mega_size <- 0.45
p_rail$mega_start <- 0.5
p_rail$mega_end <- 4.0
p_rail$mega_fdi_share <- 0.40
out_rail <- run_scenario(p_rail, "TT-GS Railway")

p_min <- params
p_min$mega_size <- 0.55
p_min$mega_start <- 1.5
p_min$mega_end <- 6.0
p_min$mega_fdi_share <- 0.80
out_min <- run_scenario(p_min, "Mining Expansion")

p_combo <- params
p_combo$mega_size <- 0.95
p_combo$mega_start <- 0.5
p_combo$mega_end <- 6.0
p_combo$mega_fdi_share <- 0.65
out_combo <- run_scenario(p_combo, "Combined Mega")

p_shock <- params
p_shock$shock_time <- 2.0
p_shock$shock_size <- 0.35
p_shock$recurring_shock <- TRUE
out_shock <- run_scenario(p_shock, "External Shock")

# Combine all scenarios
all_results <- bind_rows(out_base, out_eb, out_rail,
                        out_min, out_combo, out_shock)

```

A.7. Monte Carlo simulation

The Monte Carlo simulation propagates parameter uncertainty into the forecasts. Ten key parameters identified as the most influential through preliminary sensitivity analysis are sampled from truncated normal distributions, with means equal to the calibrated baseline values and standard deviations corresponding to estimation uncertainty. Each of the 500 random parameter draws produces a complete 26-year simulation; the percentile fan charts presented in Figure 4 are computed from these draws. The truncation prevents implausible parameter values (such as negative contagion coefficients or output gap coefficients exceeding 1.0).

```

n_mc <- 500
set.seed(42) # reproducibility

# Parameter distributions: c(mean, sd, lower, upper)
mc_param_specs <- list(
  rho      = c(0.40, 0.08, 0.15, 0.65),
  zeta     = c(0.30, 0.06, 0.10, 0.50),
  eta      = c(0.25, 0.05, 0.10, 0.40),
  alpha_sm = c(0.18, 0.04, 0.05, 0.30),
  phi_sm   = c(0.20, 0.05, 0.05, 0.40),
  alpha_pi = c(0.08, 0.02, 0.02, 0.18),
  alpha_b  = c(0.10, 0.025, 0.03, 0.20),
  phi_b    = c(0.15, 0.04, 0.05, 0.30),
  alpha_ip = c(1.50, 0.20, 1.00, 2.00),
  beta_ip  = c(0.50, 0.15, 0.10, 1.00)
)

mc_results <- data.frame()
mc_times <- seq(0, 26, by = 1) # annual for MC

for (i in seq_len(n_mc)) {
  p_i <- params
  for (pname in names(mc_param_specs)) {
    spec <- mc_param_specs[[pname]]
    val <- rnorm(1, mean = spec[1], sd = spec[2])

```

```

    val <- max(spec[3], min(spec[4], val))
    p_i[[pname]] <- val
  }
  out_i <- tryCatch({
    ode(y = state, times = mc_times,
        func = sd_model, parms = p_i,
        method = "lsoda", maxsteps = 50000)
  }, error = function(e) NULL)
  if (is.null(out_i)) next
  df_i <- as.data.frame(out_i)
  df_i$run_id <- i
  mc_results <- bind_rows(mc_results, df_i)
}

# Compute percentiles for fan charts
mc_summary <- mc_results %>%
  group_by(time) %>%
  summarise(
    SM_p05 = quantile(SM, 0.05, na.rm = TRUE),
    SM_p50 = quantile(SM, 0.50, na.rm = TRUE),
    SM_p95 = quantile(SM, 0.95, na.rm = TRUE),
    Y_p05 = quantile(Y, 0.05, na.rm = TRUE),
    Y_p50 = quantile(Y, 0.50, na.rm = TRUE),
    Y_p95 = quantile(Y, 0.95, na.rm = TRUE),
    FDI_p05 = quantile(FDI, 0.05, na.rm = TRUE),
    FDI_p50 = quantile(FDI, 0.50, na.rm = TRUE),
    FDI_p95 = quantile(FDI, 0.95, na.rm = TRUE)
  ) %>%
  mutate(year = 2024 + time)

```

A.8. Figure rendering and data export

The final block produces the figures and data files used in the paper and the interactive dashboard. The ggplot2 package generates publication-quality multi-panel figures showing the 15 stock variable trajectories across all six scenarios, the contagion index dynamics, the parameter sensitivity analysis, and the Monte Carlo fan charts. The simulation results are exported to Excel format (with separate sheets for summary, full results, and Monte Carlo statistics) and to JSON format for use by the interactive HTML dashboard. All figure labels are in English to ensure cross-platform reliability when figures are embedded in DOCX, PDF, and HTML outputs.

```

# Color palette for scenarios
scenario_colors <- c(
  "Baseline" = "#2C3E50",
  "Erdeneburen HPP" = "#3498DB",
  "TT-GS Railway" = "#16A085",
  "Mining Expansion" = "#E67E22",
  "Combined Mega" = "#8E44AD",
  "External Shock" = "#C0392B"
)

# Multi-panel figure: key variables across scenarios
key_long <- all_results %>%
  select(year, scenario, SM, ER, S, PI, B, IP, Y, TX) %>%
  pivot_longer(SM:TX, names_to = "variable")

p_keys <- ggplot(key_long, aes(year, value,
                               color = scenario)) +
  geom_line(linewidth = 0.7) +
  facet_wrap(~ variable, scales = "free_y", ncol = 4) +
  scale_color_manual(values = scenario_colors) +
  labs(title = "Key Financial and Real-Sector Variables",
       subtitle = "26-year forecast, 6 scenarios",
       x = "Year", y = "Value")

ggsave("results/fig_key_variables.png", p_keys,
       width = 14, height = 8, dpi = 150)

```

```

# Contagion index across scenarios
p_cont <- ggplot(all_results,
                aes(year, cont_idx, color = scenario)) +
  geom_line(linewidth = 0.8) +
  geom_hline(yintercept = 0.5, linetype = "dashed",
            color = "red") +
  scale_color_manual(values = scenario_colors) +
  labs(title = "Financial Contagion Index Dynamics",
       y = "Contagion Index [0,1]", x = "Year")

ggsave("results/fig_contagion_index.png", p_cont,
      width = 12, height = 6, dpi = 150)

# Export to Excel (3 sheets)
wb <- createWorkbook()
addWorksheet(wb, "Summary")
addWorksheet(wb, "FullResults")
addWorksheet(wb, "MonteCarlo")
writeData(wb, "FullResults", all_results)
writeData(wb, "MonteCarlo", mc_summary)
saveWorkbook(wb, "results/simulation_results.xlsx",
             overwrite = TRUE)

# Export to JSON for interactive dashboard
json_out <- list(
  scenarios = unique(all_results$scenario),
  data = all_results,
  mc = mc_summary,
  metadata = list(
    generated_at = format(Sys.time()),
    n_obs = nrow(all_results),
    n_mc_runs = length(unique(mc_results$run_id))
  )
)
writeLines(toJSON(json_out, auto_unbox = TRUE,
                  digits = 4),
          "results/simulation_data.json")

cat("Simulation complete:",
    format(Sys.time()), "\n")

```

A.9. Software environment and reproducibility

To support reproducibility, the model was developed and tested in the following software environment: R version 4.3.3 (2024-02-29), running on a Linux x86_64 system. The required R packages and their versions are: deSolve 1.40, ggplot2 3.5.1, dplyr 1.1.4, tidyr 1.3.1, openxlsx 4.2.7, and jsonlite 1.8.8. All input data (commodity prices, exchange rates, gross domestic product, foreign direct investment stocks, etc.) are sourced from publicly available statistics and are documented in the accompanying data file. The random number generator seed is fixed at 42 to ensure that the Monte Carlo simulation produces identical results across runs. The complete code base, including data preparation scripts and the interactive dashboard, is available from the author upon request.