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An Agent-Based Model of Geopolitical Risk: Agents, Multi-Layer Linkages, and Network Contagion

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Abstract

We present an agent-based model of geopolitical risk in which heterogeneous country agents, each described by twenty-five indicators across five risk pillars, are coupled by three distinct empirically-grounded linkage layers — trade, capital and security — and generate a composite Geopolitical Country Risk Index (GC-GRI) from the bottom up. Shocks propagate through channel-specific dynamics: a Leontief demand pass on the trade layer (built from a gravity model and IMF Direction of Trade Statistics), escalation along a signed security network, and an iterative DebtRank clearing pass on the cross-border exposure matrix. Five institutional sub-agents — government, central bank, households, firms and foreign investors — drive within-country dynamics, and a calibration feed maps news-attention and market-implied signals into shock probabilities and magnitudes. The engine is fully vectorized: state is a (paths × countries × indicators) tensor, so Monte-Carlo evaluation of roughly 190 countries over thousands of paths is batched linear algebra. We give the agent architecture, the multi-layer network construction, and the interaction dynamics, and report validation evidence: byte-identical reproducibility, Monte-Carlo convergence, monotone stress response, face-valid country ordering, and contagion that demonstrably follows the capital network (exposure–impact correlation ≈ 0.79).

Keywords: *agent-based modelling, geopolitical risk, financial contagion, DebtRank, multi-layer networks, Monte Carlo simulation, systemic risk, Simudyne Platform*

1. Introduction

Geopolitical risk is a system-level phenomenon. Shocks originate in one country and propagate through trade, capital and security linkages to others, and the macro consequences emerge from the interaction of many heterogeneous actors rather than from a single closed-form equation. Top-down scenario tools impose outcomes; agent-based modelling (ABM) lets them emerge from specified actors, their state and their behavioural rules embedded in a shared, structured environment.

This paper documents the agent-based model underpinning Simudyne's geopolitical risk platform, focusing on its three defining features: heterogeneous country agents with institutional sub-structure; a multi-layer network of real economic and financial linkages; and channel-specific propagation, including a DebtRank capital-contagion pass. Section 2 situates the work; Section 3 gives the model overview; Sections 4–5 specify the agents and environment; Section 6 the multi-layer networks; Section 7 the interaction dynamics; Section 8 the risk aggregation; Section 9 the validation; and Sections 10–11 discuss limitations and future work.

2. Background

Agent-based computational approaches reproduce macro regularities from local interaction, from artificial societies to agent-based computational economics to post-crisis calls for bottom-up models of financial systems. In parallel, the systemic-risk literature developed network measures of financial contagion — notably DebtRank (Battiston et al., 2012) and clearing-vector models (Eisenberg & Noe, 2001) — that quantify how distress amplifies through exposure networks. This model unites the two: a behavioural ABM of country agents whose financial coupling is cleared by a DebtRank pass each period.

3. Model Overview

The model is a discrete-time, stochastic ABM advanced in monthly steps over a 24-month horizon and evaluated by Monte Carlo. Its distinguishing engineering property is full vectorization: the state is a tensor of shape (P paths, N countries, K=25 indicators), and all paths advance simultaneously through array broadcasting, so propagation and clearing are batched matrix algebra rather than nested loops. Every stochastic draw derives from a seed, so runs are reproducible; an ensemble of seeded paths forms the Monte-Carlo distribution used for stress testing. The same equations run a single path under an SDK model wrapper (agents, recorder, mechanism summary) and thousands of paths under the batch backend.

4. Agent Architecture

4.1 Country agents

The primary agents are countries. Each carries twenty-five indicators in five pillars (Table 1), held in native orientation with a fixed risk orientation applied at scoring time, plus derived quantities: five pillar scores, the composite GC-GRI, a power index used by the network rules, financial capital used by the capital channel, and a position in linkage space.

Pillar	Indicators (native orientation)	Reference sources
Political	govEffectiveness, ruleOfLaw, corruptionControl, stability, democraticIntegrity	WB WGI; V-Dem
External	militaryExpenditure, conflictInvolvement, alliances, sanctions, geostrategicLocation	SIPRI; ACLED/UCDP
Economic	publicDebt, inflation, creditRating, diversification, currencyVolatility	IMF; S&P/Moody's
Social	inequality, hdi, youthBulge, factionalism, refugeeBurden	UNDP; UNHCR
Environmental	climateVulnerability, waterStress, disasterExposure, energyDependency, renewablesShare	ND-GAIN

Table 1 — Country-agent indicator catalogue.

4.2 Institutional sub-agents

Within each country, five institutional roles drive the transition dynamics as vectorized reaction functions:

Government — sets policy and fiscal stance; expressed through stability, rule of law and corruption-control dynamics responsive to unrest.

Central bank — manages rates and defends the currency; expressed through inflation and currency-volatility dynamics under economic stress.

Households — consume, protest and migrate; expressed through factionalism, inequality and conflict-driven displacement.

Firms — invest, hire and hedge; expressed through public-debt accumulation and diversification.

Foreign investors — allocate or withdraw capital; capital flight reduces equity and raises currency volatility, coupling the country to the capital channel.

5. Environment

Country agents share an environment with three components. First, the macro-risk state: the five pillars act as the observable environment that agents read and modify each tick. Second, exogenous shocks: global parameters for economic volatility, climate impact and instability inject system-wide stress, with downside macro shocks also eroding capital. Third, a calibration feed: per-country news-attention (0–100) and market-implied (−100..100) signals map to shock parameters,

$$p\_shock = clip(attention / 100, 0, 1) ; \quad m = clip(mds, -100, 100) / 100 \times M\_max$$

so attention governs the probability a country is shocked and the market-implied score governs the signed magnitude. Time is discrete and monthly; the default horizon is 24 months.

6. Multi-Layer Linkage Networks

Countries are coupled by three distinct directed N×N layers, replacing any single undifferentiated graph. Each is constructed from country attributes and, for trade, real data (Table 2).

Layer	Form	Construction	Channel
Trade (T)	row-stochastic shares	gravity model + IMF DOTS bilateral exports	Leontief demand propagation
Capital (A)	creditor → obligor exposures	trade intensity, financial-centre mass, bloc affinity (BIS/CPIS hook)	DebtRank clearing
Security (S)	signed [-1,1]	alliance (same bloc) / rivalry (opposing, high mutual conflict)	escalation / de-escalation

Table 2 — The three linkage layers and the propagation channel each drives.

The trade layer is a gravity model — mass proportional to GDP, friction to great-circle distance, with a regional boost — that in production is overwritten by IMF Direction of Trade Statistics (DOTS) bilateral goods exports via a cached data client, with a transparent gravity fallback for any country lacking coverage. The capital layer derives exposures from trade intensity, financial-centre mass and bloc affinity (a hook for BIS/IMF CPIS data). The security layer is a signed alliance/rivalry matrix.

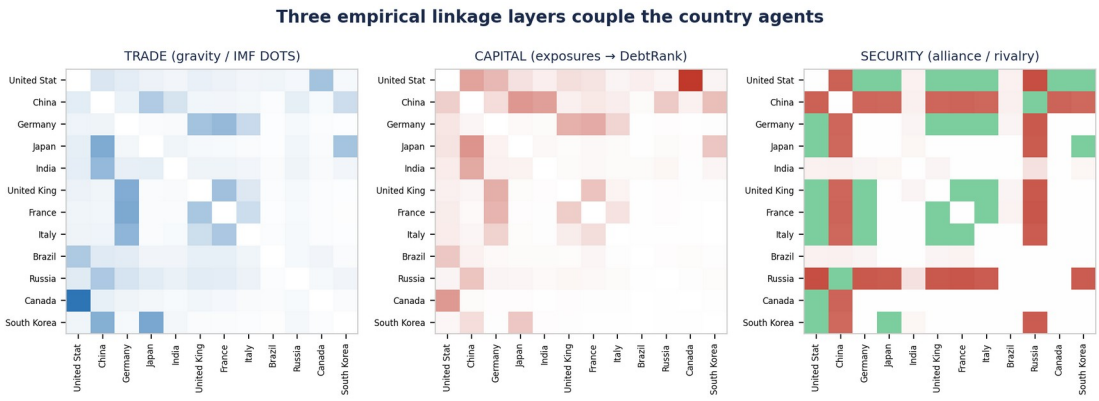

Figure 1 — The three linkage layers (largest 12 economies): trade shares, capital exposures, and signed security.

7. Interaction Dynamics

7.1 Within-country dynamics

Each tick, coupled transition rules evolve the indicators (e.g. factionalism erodes stability; inflation feeds debt; capital flight raises currency volatility), after which every indicator mean-reverts toward the country's own baseline anchor a_c, preserving cross-country differentiation over long horizons:

$$v(t+1) = v(t) + \varepsilon + \kappa\,(\,a\_c - v(t)\,), \quad \varepsilon \sim U(-0.25, 0.25), \;\; \kappa = 0.005$$

7.2 Trade and security channels

On the trade layer, economic stress propagates to partners in proportion to bilateral share via a Leontief demand pass with geometric feedback. On the security layer, conflict escalates along rivalry edges and de-escalates along alliances, weighted by neighbours' current conflict.

7.3 Capital channel: DebtRank clearing

The capital channel implements financial contagion. A country's fresh equity loss this tick seeds an initial distress ψ; distress then spreads to creditors through the exposure matrix and is cleared to convergence by DebtRank, where the impact of obligor j on creditor i is its exposure relative to i's capital, A_ij / C_i:

$$h\_i(t+1) = \min(\,1,\; h\_i(t) + \Sigma\_\{j \in \text{active}\}\,(A\_ij \,/\, C\_i)\cdot h\_j(t)\,)$$

Nodes propagate distress for one active step before becoming inactive, avoiding reverberation, and the resulting distress feeds back into economic-pillar risk and equity. The power index used by the network rules is Π = (100 − S_economic) + (100 − S_external).

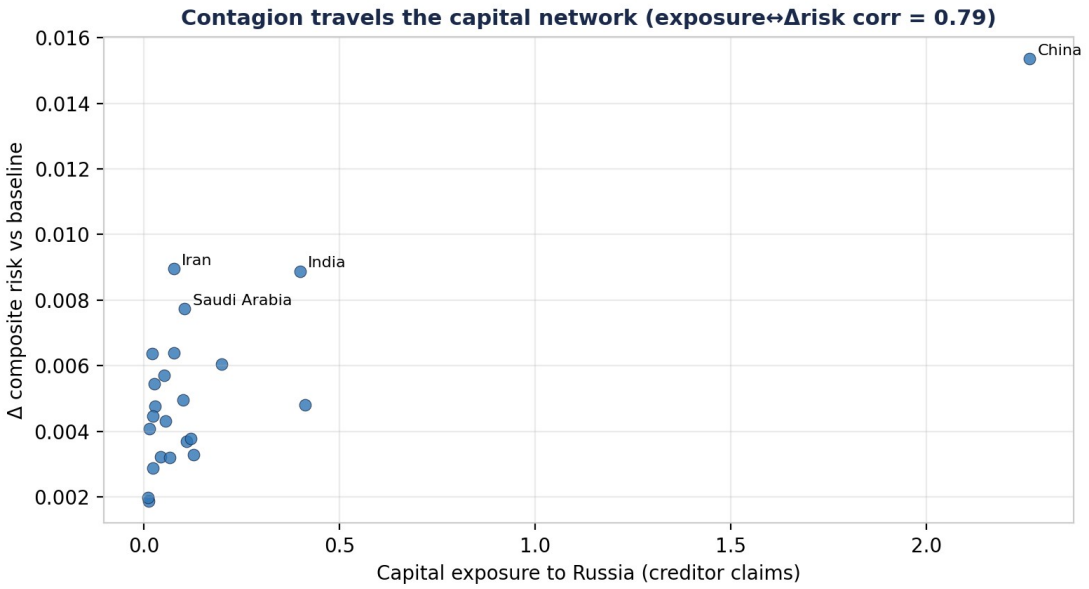

Figure 2 — A counterfactual equity shock to one sovereign raises risk most in its highest-exposure creditors (exposure ↔ Δrisk corr ≈ 0.79).

8. Risk Aggregation

Each indicator is oriented so higher means more risk: for value v and orientation o ∈ {+1,−1}, the risk value is r = v if o=+1 else 100−v. A pillar score is the mean of its risk-oriented indicators, and the composite is the pillar-weighted mean,

$$S_p = (1/|I_p|)\, \Sigma_{i \in I_p}\, r_i \;; \quad GC\text{-}GRI = (\, \Sigma_p\, w_p\, S_p\,) / (\, \Sigma_p\, w_p\,)$$

with user-configurable pillar weights w_p. Correct orientation is essential: summing protective indicators as if they raised risk would invert the country ranking.

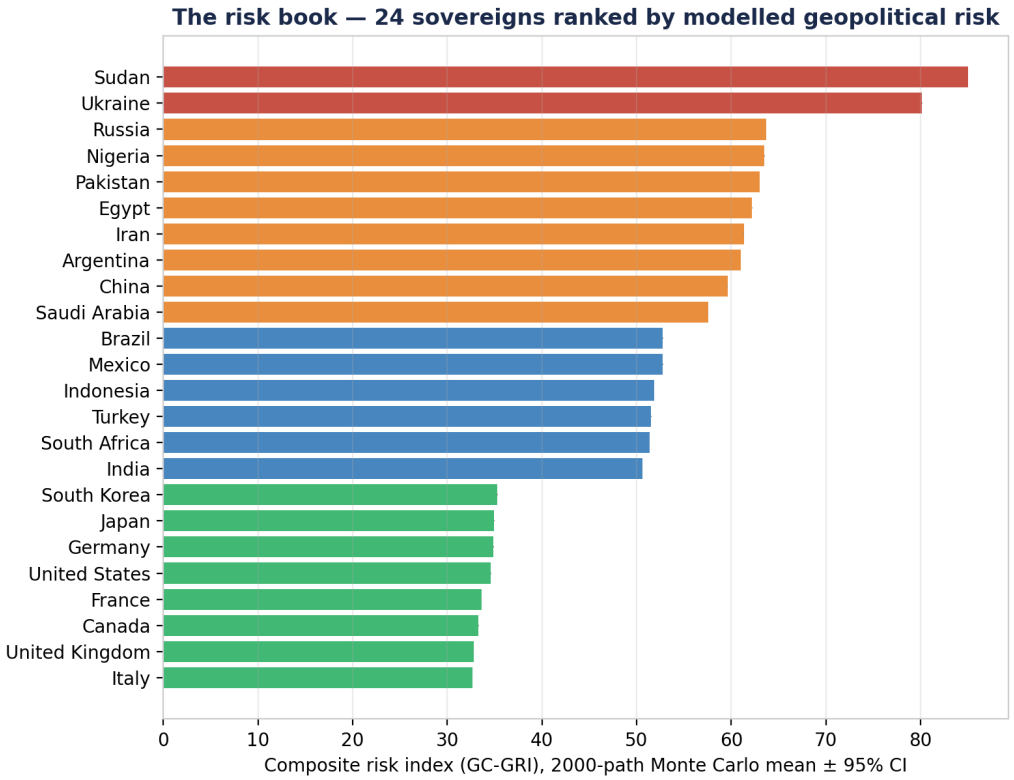

Figure 3 — Monte-Carlo risk book: 24 sovereigns by composite risk (mean ± 95% CI), with fragile/conflict states above advanced economies.

9. Results and Validation

The model is validated on the vectorized backend across six pre-registered checks (Table 3). Beyond determinism and convergence, two results bear emphasis. First, systemic distress rises monotonically with both macro volatility and financial interconnectedness (the density of the exposure matrix), as expected of a contagion model. Second, a counterfactual shock to a single sovereign raises risk most in its highest-exposure creditors — direct evidence that propagation travels the capital network rather than diffusing uniformly.

Check	Result	Status
Determinism	identical batch & SDK runs under a fixed seed	Pass
Monte-Carlo convergence	CI half-width of book risk ∝ 1/√P	Pass
Stress monotonicity	systemic distress ↑ with volatility and interconnectedness	Pass
Contagion propagation	exposure ↔ Δrisk correlation ≈ 0.79 under a counterfactual shock	Pass
Face validity	Sudan ▸ Ukraine ▸ Russia ▸ frontier ▸ advanced economies	Pass
Scale	190 countries × 10,000 paths × 24 months ≈ 24 s	Pass

Table 3 — Validation summary (vectorized batch engine).

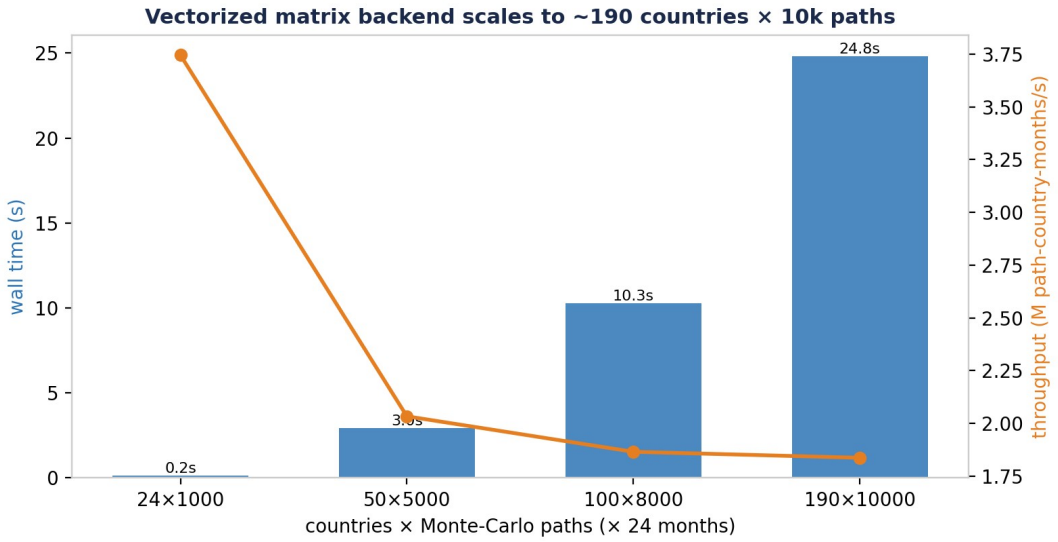

Figure 4 — The vectorized matrix backend scales to ~190 countries × 10,000 paths × 24 months in seconds.

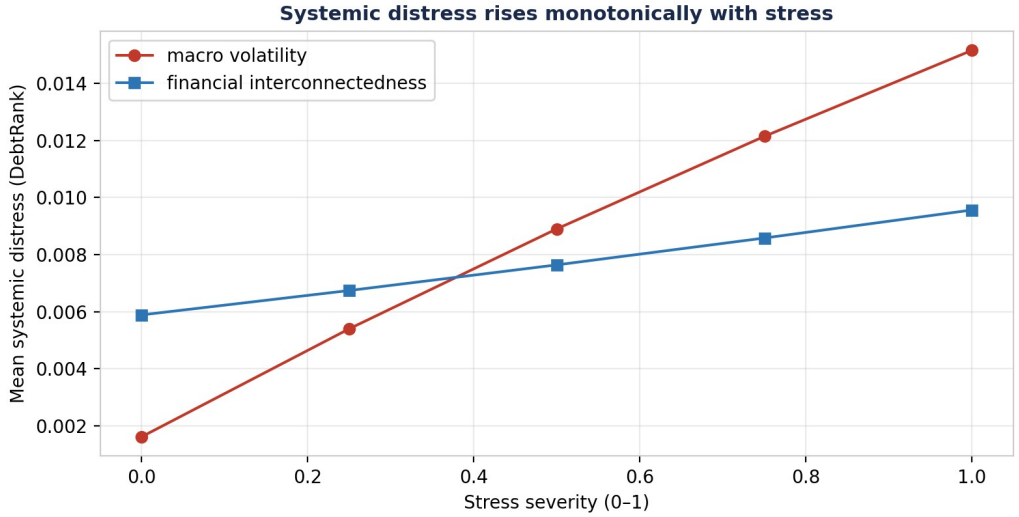

Figure 5 — Systemic (DebtRank) distress rises monotonically with macro volatility and with financial interconnectedness.

10. Discussion and Limitations

Three limitations bear noting. The institutional sub-agents are encoded as country-level reaction functions rather than explicit micro-agent populations, limiting within-country heterogeneity. The capital and security layers are presently modelled from country attributes (with data hooks specified) while only the trade layer is wired to a live feed (IMF DOTS); BIS/CPIS exposures and ATOP/Correlates-of-War alliances are the natural next ingestions. And calibration, performed here by Method of Simulated Moments against target moments, should in production be estimated against realised contagion episodes.

11. Conclusion and Future Work

The model specifies geopolitical risk as an emergent property of heterogeneous country agents coupled by real, multi-layer linkages, with channel-specific propagation and a DebtRank

capital-clearing pass, executed on a vectorized backend that scales to global coverage and thousands of Monte-Carlo paths. Future work promotes the institutional roles to explicit sub-agent populations, ingests live capital and security networks, and calibrates against historical episodes so that scenario stress tests recalibrate as the world changes.

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