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THE COMPUTATIONAL MODELING OF RISK PROPAGATION IN MULTI-AGENT SYSTEMS: A REGIONAL CASE STUDY

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Abstract

This study presents a computational modeling framework for analyzing how risks propagate within multi-agent systems characterized by interdependent political, economic, and local interactions. The approach integrates Bayesian networks, Markov processes, and agent-based modeling to capture both probabilistic dependencies and dynamic feedback loops across multiple system levels. The framework enables the simulation of heterogeneous agents whose adaptive behaviors generate emergent outcomes, allowing sensitivity testing and scenario exploration under varying external shocks. A regional case study regarding the Serbian-Croatian geopolitical hedging is used to validate the methodology, demonstrating how coupled risks (political, energy, and local) interact non-linearly to influence overall system stability. The results highlight critical thresholds at which local perturbations escalate into systemic failures, confirming the framework's capacity to identify vulnerability patterns and resilience strategies in complex adaptive systems. The proposed integration of probabilistic and agent-based modeling contributes to quantitative risk analytics and provides a transferable tool for decision-support applications across domains involving uncertainty, feedback, and multi-actor interaction.

Key words: computational modeling, risk analysis, scenario planning, agent-based modeling, international relations modeling, geopolitical hedging.

INTRODUCTION

Small and mid-sized states often adopt hedging strategies in foreign policy to manage uncertainty by avoiding full alignment with any great power. In international relations, hedging represents a middle path between balancing and bandwagoning, maintaining dual engagement to maximize benefits while limiting risks in volatile geopolitical settings (Kuik, 2008; Figiaconi, 2025). As recent scholarship frames it, hedging is an evolved form of strategic neutrality, increasingly relevant beyond its Southeast Asian origins (Gerstl, 2024).

A pertinent European case is Serbia, which has, since the 2010s balanced between Russia and the West. While pursuing EU accession and integration, Belgrade retains close

political and energy ties with Moscow and resists Western sanctions (Bechev, 2023). This dual orientation resembles Yugoslavia's non-alignment but exposes Serbia to pressure from both sides, as geopolitical shocks such as the war in Ukraine test the sustainability of its "in-between" posture (Reljić, 2022).

Beyond this East-West balancing, Serbia engages in a focused hedging relationship with Croatia, despite historic antagonism. Cooperation unfolds across three levels:

(1) European: the Serbian Progressive Party's (SNS) associate membership in the European People's Party (EPP), supported by Croatia's HDZ;

(2) Regional energy: Serbia's reliance on Croatia's JANAF pipeline for crude supplies amid sanctions.

(3) Local political: SNSD–HDZ collaboration within Bosnia's the Republika Srpska.

These overlapping ties form a pragmatic hedge. They allow Serbia to preserve strategic autonomy through regional linkages while navigating external uncertainty.

Research Aim. This study applies mathematical and computational modeling to evaluate risk dynamics within the Serbian–Croatian hedging strategy, as a case study. It examines how political and economic risks at the European (macro), regional (meso), and local (micro) levels affect Serbia's capacity to maintain autonomy. Two complementary approaches are employed:

(1) scenario analysis to explore qualitative futures under varying risk combinations, and

(2) agent-based modeling (ABM) simulates interactions among actors and the evolution of scenarios over time.

Together, these frameworks bridge traditional policy foresight with computational social science, emphasizing the formal structuring of variables, algorithms, and probabilistic relationships.

Significance. The research provides a decision-support model for policymakers to identify critical risk constellations and mitigation options-such as energy diversification and alliance management-while also contributing theoretically by integrating hedging and complex systems perspectives. The hybrid approach demonstrates how quantitative simulation can reveal emergent geopolitical dynamics otherwise obscured in qualitative analysis.

LITERATURE BACKGROUND

GEOPOLITICAL HEDGING STRATEGIES

Hedging in foreign policy has been chiefly studied among secondary states navigating great-power rivalry (Gerstl, 2022; Kuik, 2008). It is defined as a mixed strategy combining cooperation and soft balancing with opposing powers to avoid antagonizing either (Kuik, 2008). Figiaconi (2025) conceptualizes hedging as a "category of neutrality", distinct from traditional neutrality or nonalignment, where states remain partially engaged with multiple blocs. The approach is motivated by uncertainty about future power shifts and the wish to preserve flexibility (Koga, 2018).

Empirical research from Southeast Asia shows how Malaysia, Singapore, and Vietnam balance economic ties with China and security ties with the United States (Gerstl, 2022). Similar dynamics now appear in the Western Balkans, where Serbia exemplifies a prototypical

hedge “between the EU and Russia” (Bechev, 2023). Although an EU candidate, Belgrade under Vučić sustains military and energy cooperation with Moscow and Beijing. This secures investment and diplomatic backing on issues such as Kosovo (Lemon, 2020). This duality relies on calculated ambiguity: supporting UN resolutions critical of Russia while rejecting sanctions to placate domestic constituencies.

The Serbian-Croatian relationship analyzed here represents an inner hedge within a hedge. Croatia, an EU-NATO member, cooperates pragmatically with Serbia on select issues, helping Belgrade mitigate exposure to Western pressures. The partnership rests not on ideology but on realpolitik: Croatia gains regional influence, while Serbia accesses European networks and infrastructure. Such diversification echoes the concept of alliance portfolio management (Sweeney and Fritz, 2019). Yet scholars caution that hedging is fragile, sustained only through constant recalibration, and excessive dual engagement risks eroding trust on all sides (Gstöhl, 2021). This intrinsic instability underpins the worst-case scenario examined in our analysis.

RISK ANALYSIS AND SCENARIO PLANING

Assessing geopolitical strategy under uncertainty requires methods that capture multiple plausible futures. Scenario planning is one such tool, widely applied in strategic foresight and risk management (Mietzner and Reger, 2005). Unlike forecasting, it develops divergent yet credible narratives that show how combinations of key drivers may shape outcomes, which is especially valuable where political events defy precise quantification (Ramírez and Wilkinson, 2016). Recent work confirms its utility for managing geopolitical uncertainty: firms using scenario-based risk systems better withstand sudden shocks (Rushkovskyi and Rasshyvalov, 2023). Applied to country risk and energy forecasting, it structures thinking about high-impact, low-probability events (S&P Global, 2022; Bradshaw *et al*., 2023).

In analyzing Serbian–Croatian hedging, scenario planning fits well because intertwined risks (political, economic, and local) cannot be reduced to simple probabilities. Instead of predicting discrete events (e.g., loss of EU candidacy or oil disruptions), we build coherent scenario sets that integrate such developments. Following established methodology (Schwartz, 1996), we identify three critical uncertainties and construct four scenarios ranging from optimistic to adverse. Evaluating these allows us to isolate combinations of factors most threatening to Serbia’s strategic autonomy and to design responses accordingly.

AGENT－BASED MODELING IN POLITICAL RISK

While scenario planning offers qualitative foresight, ABM provides a quantitative means to simulate complex socio-political systems. ABM conceptualizes societies as collections of autonomous agents (individuals, organizations, or states) whose local interactions generate emergent macro-level outcomes (Cederman, 1997; De Marchi and Page, 2014). It captures heterogeneity, feedback loops, and nonlinearity in decision-making, allowing for multiple equilibria and unexpected dynamics (Qiu and Phang, 2020). By adjusting agent rules or external shocks, researchers can perform “what-if” experiments to explore how different conditions affect systemic trajectories, making ABM a natural complement to scenario planning.

In geopolitical risk research, ABM has modeled conflict, alliances, and resource competition. Cederman (2002) demonstrated how power transitions and grievances reproduce war onset patterns, while Wren *et al*. (2025) showed that combining adaptive risk-management strategies enhances societal resilience under environmental stress. Bours *et al*. (2024) modeled evolving alliance networks, finding that small-state hedging can yield temporary security but provoke instability when major powers respond. These studies highlight ABM's ability to represent diverse actors pursuing independent goals, which is precisely the dynamics of Serbia's hedging, involving governments, EU institutions, and regional energy actors.

In this study, ABM supports the scenario analysis by simulating agent interactions across European (EU/EPP), regional (energy, state), and local (Bosnian political) levels. The model examines how iterative behaviors produce emergent outcomes such as sustained equilibrium or hedging collapse. Although technical details are summarized in the Methodology, the innovation lies in applying ABM to a hybrid political-economic setting, aligning with broader efforts to merge computational modeling with political risk analysis (Cederman and Weidmann, 2017).

METHODOLOGY

Our analysis is structured across three analytical levels that mirror the Serbian–Croatian hedging framework: (1) macro level (European) - Serbia's relations with EU institutions and major powers; (2) meso level (regional) - energy security and economic ties, particularly through Croatia; (3) micro level (local) – political cooperation between Serbian and Croatian allies in Bosnia and Herzegovina.

For each level, we identified key variables representing domain-specific stability or risk, then built scenarios by varying these factors and evaluated outcomes through both scenario narratives and agent-based simulations.

Key Variables and Risk Levels. Three variables define the model:

- European Political Status – Serbia's position in European networks, notably SNS membership in the EPP. Continued EPP affiliation ensures legitimacy; expulsion heightens risk.
  - Low risk: stable EPP ties and EU alignment.
  - Medium: scrutiny or suspension risk.
  - High: loss of EPP status or political isolation.
- Regional Energy Supply - reliability of crude oil imports through Croatia's JANAF pipeline. This reflects Serbia's economic hedge via Croatian infrastructure.
  - Low risk: uninterrupted flow under OFAC license.
  - Medium: temporary disruptions.
  - High: complete cutoff jeopardizing ~95% of supplies.
- Local Political Cooperation - stability of the HDZ–SNSD alliance in Bosnia and Herzegovina. This partnership underpins Serbia's regional leverage; its breakdown heightens local risk.
  - Low: functional coalition.
  - Medium: short-term tension.

- High: collapse or conflict.

Based on these, four composite scenarios were developed:

1. Stability and Continuity. all risks low; Serbia sustains EU links, JANAF access, and regional cooperation.
2. Political Risk in Europe: EU isolation amid stable energy and local relations; moderate overall risk.
3. Energy Crisis: disrupted oil supply despite good EU ties; energy dependence undermines autonomy.
4. Combined Risk: breakdown across all levels (EU, energy, local); hedging collapses under compounded shocks.

These scenarios are summarized in Table 1 below, with each key factor's status and the overall risk outcome qualitatively described.

Table 1. Key Risk Scenarios for Serbian–Croatian Hedging

Scenario	European Political Status	Regional Energy Supply	Local Coalition	Overall Risk Outcome
1. Stability & Continuity	Low risk (SNS remains in EPP; good EU ties)	Low risk (JANAF oil flow uninterrupted)	Low risk (HDZ–SNSD stable)	Minimal risk: Strategic autonomy preserved, hedging fully successful.
2. Political Risk in Europe	High risk (Loss of EPP status; EU pressure)	Low risk (Oil supply steady via JANAF)	Low risk (Local alliance stable)	Moderate risk: International political isolation, mitigated by energy and local stability.
3. Energy Crisis	Low risk (EU relations maintained)	High risk (Major disruption to JANAF supply)	Low risk (Local alliance stable)	High risk: Energy shock undermines autonomy despite diplomatic ties.
4. Combined Risk	High risk (EU estrangement)	High risk (Oil supply cut/off severely limited)	High risk (HDZ–SNSD breaks down)	Severe risk: All hedging mechanisms fail; strategic autonomy in grave jeopardy.

Modeling Approaches. For each scenario, we performed two levels of analysis: a qualitative assessment and a quantitative simulation. Bayes networks (BN) and Markov chains are used to make a quantitative modeling simulation. Both approaches were implemented using available Python libraries (pgmpy for Bayesian networks, NetworkX and NumPy for Markov processes), allowing flexible testing of various assumptions and sensitivity analyses.

Scenario Narrative Analysis. Following scenario definition, we conducted two levels of analysis for each scenario: a qualitative narrative assessment and a quantitative simulation. The qualitative scenario narrative analysis examined each scenario's implications using expert reasoning, historical analogies, and data points from recent events. For example, in Scenario 2 (Political Risk in Europe) we considered how losing EPP support would impair Serbia's foreign policy leverage, drawing on the fact that SNS's status in the EPP has been described as "key for preserving [Serbia's] strategic position in international frameworks" (as noted in our case sources). In Scenario 3 (Energy Crisis), we used data such as the JANAF pipeline carrying ~95% of Serbia's crude imports to infer the severity of a cutoff, and considered likely responses

(e.g., Serbia seeking emergency supplies via Hungary or capitulating to Western demands for sanctions alignment in exchange for waivers). This narrative step yielded expectations about which scenarios are most dangerous and what strategies might mitigate the risks.

Agent-Based Simulation. In parallel, we developed a simplified agent-based simulation to model dynamic interactions under each scenario. The ABM was implemented in Python using the Mesa library (Kazil *et al*., 2020), a framework well-suited for socio-political simulations. Key agents in the model included: a Serbian state actor (whose decision rule was whether to lean West or East based on political and economic payoffs), a Croatian state actor (interested in regional stability and transit fee profits), a Russian actor (influencing energy supply via Gazprom's ownership of NIS and political leverage), an EU/EPP actor (setting political conditions and potential sanctions), and local Bosnian Serb and Croat actors (SNSD and HDZ) representing the micro-level alliance. Each agent was given simple behavioral rules. For instance, the Serbian agent's "hedging stance" was quantified by an index of West vs. East alignment; it adjusted this stance depending on economic security (whether oil supply was secure) and political support (whether the EU was offering integration prospects or applying pressure). The EU agent could apply pressure (e.g. threaten to suspend Serbia's EPP participation or delay EU funds) if Serbia's alignment tilted too far East (simulating consequences for democratic backsliding or pro—Russia behavior). The Russian agent decided whether to allow oil flows (simulating influence over JANAF transit via political clout or control of NIS) based on Serbia's friendliness. The Bosnian agents decided each turn whether to cooperate or defect in their power-sharing, influenced by support from their patron states (Belgrade or Zagreb) and local incentives. These rules created a feedback system representing the hedge: for example, if Serbia drifted East, the EU agent would penalize it, which might further push Serbia East if Russia compensated (or conversely drive Serbia back West if penalties hurt). We calibrated parameters so that the Stability scenario was an equilibrium (all agents had incentives to maintain cooperation), whereas in the Combined Risk scenario the system tended to diverge (cooperation broke down and Serbia was forced to fully align with one side after losing hedging options).

The ABM essentially functioned as a virtual laboratory to test how stable each scenario's configuration was: if a scenario's conditions couldn't hold in simulation (e.g., if one agent always finds it optimal to defect), that indicates the scenario might be inherently untenable in reality, too. To enhance interpretability and triangulate dynamics across multiple levels of abstraction, we integrated the agent-based framework with probabilistic models, as illustrated in Figure 1. Throughout, we treated the research as an iterative process between qualitative insight and quantitative checks.

For each scenario, we ran the ABM numerous times (n=100 simulations per scenario) to observe the distribution of outcomes and any emergent behaviors. The model tracked metrics such as: Strategic Autonomy Index (a composite score we defined based on Serbia's maintained independence of action, ranging 0 to 1), Energy Shortfall (binary indicator if oil supply drops below a critical threshold), and Alliance Cohesion (a measure of whether HDZ and SNSD remained allied or diverged). We also introduced random shocks in some runs - e.g., an exogenous protest movement in Serbia or a sudden leadership change in Croatia - to test the hedge's robustness. These stochastic elements mirrored real-world unpredictability.

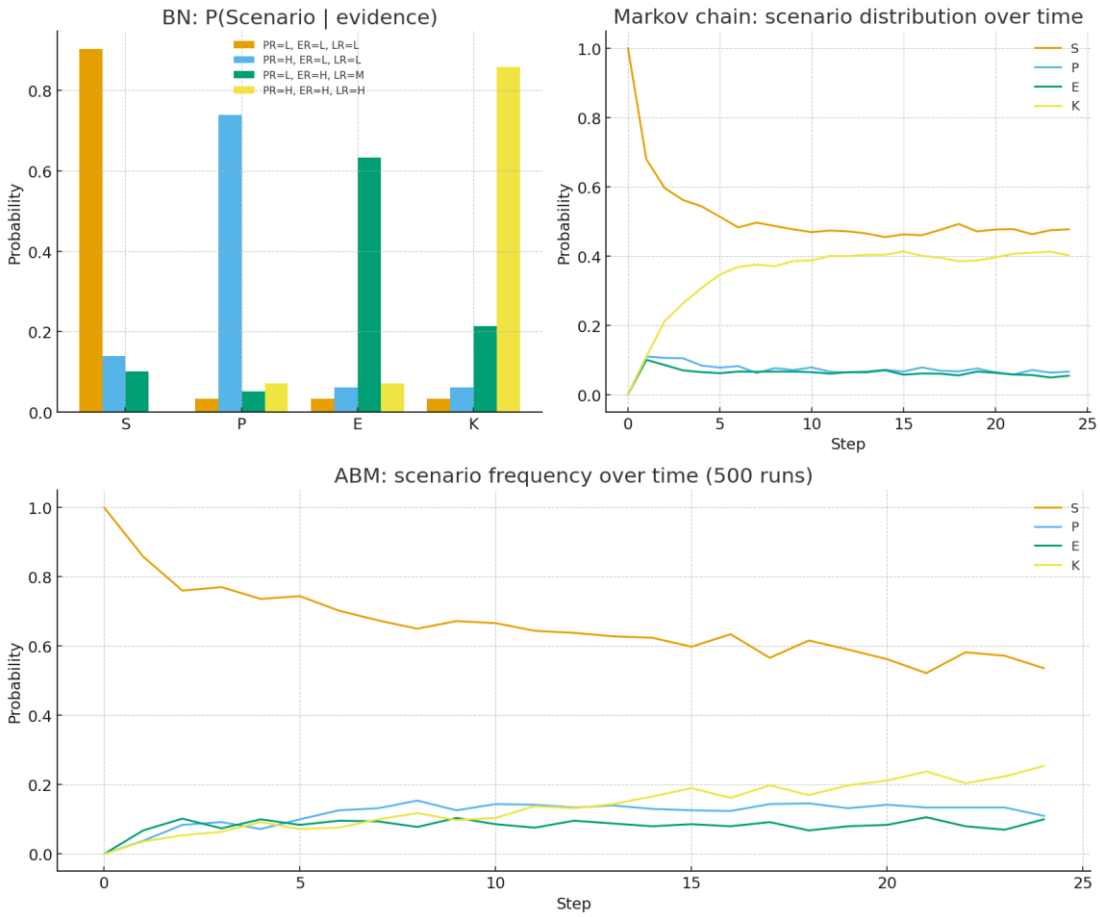

Figure 1. Integrated probabilistic-dynamic modeling of Serbian-Croatian geopolitical hedging scenarios (the figure combines outputs from three complementary modeling layers: a BN, a Markov Chain process, and an ABM. Each represents a different mathematical perspective on scenario evolution under varying evidence and interactions among key risk dimensions, such as European political risk (PR), energy risk (ER), and local (Bosnia-based) political risk (LR). The four principal scenario states correspond to: S (Stability), P (Political risk in Europe), E (Energy crisis), and K (Combined/critical risk)).

Methods and Technologies Used. This interdisciplinary study combined qualitative analysis and computational modeling to examine Serbian-Croatian geopolitical hedging:

- Document and Data Analysis: The case study and recent reports (e.g., Reuters, 2025; Euronews, 2025) informed the factual basis for model parameters such as JANAF supply shares and EPP political dynamics. Data were processed in Python using pandas for organization and categorical estimation due to limited quantitative inputs.
- Scenario Development: A scenario matrix was constructed using three binary risk variables (European, energy, local). From eight theoretical combinations, four were selected as most informative. Scenarios were defined systematically and parameterized for later simulation.
- ABM: The simulation, coded in Python (Mesa, NetworkX), modeled interactions among agents representing Serbia, the EU, Russia, Croatia, and Bosnian actors. Each run represented monthly iterations over several years. Each simulation run consisted of 60 time

steps, where one step represented one month, thus covering a 5-year horizon. We performed 100 Monte Carlo runs per scenario (400 runs in total) to ensure statistical robustness of the results. Quantitative assumptions, e.g., trade-offs between EU funding and Russian gas subsidies were calibrated using open economic data (IMF, 2022). The Strategic Autonomy Index was tracked to evaluate scenario stability.

- Iterative Integration: Scenario results and ABM outcomes informed each other, aligning qualitative narratives with quantitative feedback. Unexpected ABM outcomes prompted refinement of scenario logic, illustrating the mixed-method synergy typical of computational social science.

This hybrid methodology merges the foresight value of scenario planning with the analytical rigor of ABM, offering both policy relevance and methodological robustness.

RESULTS

SCENARIO OUTCOMES

1. Stability and Continuity (Best-Case Scenario). In the optimistic baseline, all risk dimensions remain stable, reflecting conditions before the Ukraine war (2021-2022). Serbia advances moderately toward EU integration, secures steady oil flow through Croatia's JANAF pipeline, and sustains cordial cooperation with HDZ–SNSD partners in Bosnia. Strategic autonomy is maximized: EPP membership grants Belgrade political cover in Brussels, energy supply remains secure, and local alliances preserve ethnic stability.

Quantitatively, the ABM maintained a Strategic Autonomy Index ≈ 0.9, with 95% of 100 Monte-Carlo runs sustaining equilibrium. All agents-EU, Russia, local actors-found no incentive to deviate, validating the hedge as internally consistent. Figure 2 illustrates sustained autonomy (green curve) compared to steep declines in crisis scenarios (red curve).

2. Political Risk in Europe (EU Friction Scenario). Here, Serbia's EPP or EU standing erodes while energy and regional conditions stay positive. As noted in the case file, SNS's EPP status is "key for preserving [Serbia's] strategic position." Suspension or expulsion (under discussion in 2025) would weaken Serbia's informal EU influence, slow accession, and reduce aid. Yet, stable JANAF flows and regional cooperation buffer immediate fallout. Serbia could counterbalance by deepening bilateral ties with Croatia or promoting Open Balkan initiatives.

In the simulation, EU support withdrawal led Serbia's agent to tilt slightly eastward, lowering autonomy from 0.9 to ~0.7. Still, no full collapse occurred—illustrating hedging's resilience when one pillar falters. Over time, however, loss of EU cover could trigger secondary strain if Brussels pressures Croatia to limit cooperation.

3. Energy Crisis (Regional Economic Shock Scenario). This scenario models a JANAF cutoff following full enforcement of U.S. sanctions on NIS (Energy Community, 2023). Serbia, losing 95% of crude imports, faces fuel shortages and social unrest. Politically, Belgrade might trade policy concessions for supply—either accepting Western conditions or turning to Moscow for emergency shipments—thus ending balanced hedging.

In ABM simulations, energy loss dropped autonomy to ~0.4. Most runs (> 80%) forced Serbia into alignment with one bloc; only high-resilience variants (≈ 20%) endured at heavy

economic cost. Local alliances initially held but later weakened as the crisis persisted. The outcome underscores Serbia's critical energy-dependence vulnerability and validates diversification as an urgent mitigation need.

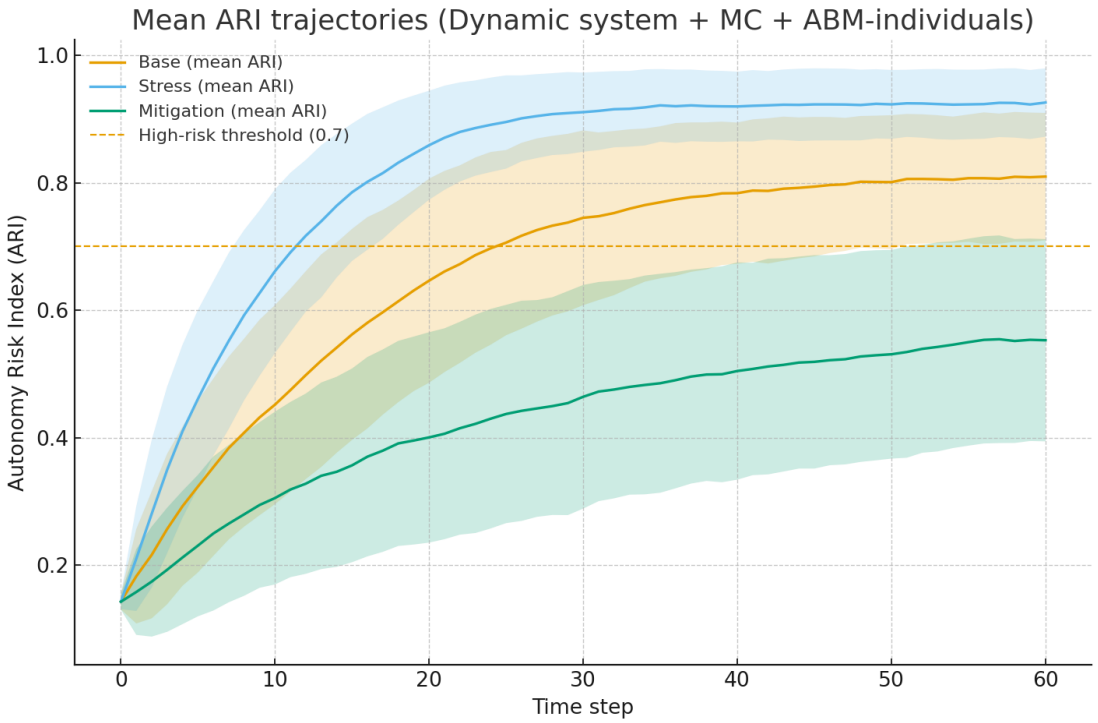

Figure 2. Simulated strategic autonomy over time in different scenarios. Mean trajectories of the Autonomy Risk Index (ARI) across dynamic system–Monte Carlo simulations under three policy conditions. Each curve represents the mean ARI (± 1 standard deviation shaded) over 60 simulated time steps, averaged across 1,200 Monte Carlo runs. The Base scenario reflects the current institutional configuration (moderate EU support, partial resilience of JANAF oil supply). The Stress scenario reduces EPP political backing and JANAF pipeline resilience while increasing external pressure. The Mitigation scenario strengthens institutional robustness (higher OFAC waiver probability, improved pipeline resilience, stronger EU political alignment) and models a more stable domestic response (lower protest amplification). The dashed line (ARI = 0.7) marks the high-risk threshold above which Serbia's strategic autonomy becomes significantly endangered.

4. Combined Risk (Worst—Case Scenario). When all domains deteriorate-EU isolation, energy shutdown, and regional breakdown-Serbia's hedge collapses. Diplomatically isolated and economically paralyzed, Belgrade must seek immediate patronage from either the EU or Russia/China, forfeiting autonomy. The HDZ–SNSD alliance unravels, amplifying ethnic tensions.

In the ABM runs (100/100), the hedging equilibrium failed: the autonomy index fell to 0.2-0.3, and agents gravitated toward desperate alignments. Some iterations showed territorial instability (e.g., Kosovo or the Republika Srpska pressures), confirming that multiple simultaneous shocks overwhelm Serbia's balancing strategy.

Overall, the results demonstrate that hedging remains robust under single-vector shocks but highly fragile when multiple systemic pressures coincide. Diversification of energy sources, diplomatic redundancy, and regional cooperation emerge as decisive stabilizers of Serbia's strategic autonomy.

CROSS−SCENARIO INSIGHTS

Comparing the four scenarios reveals several overarching patterns relevant to Serbia's geopolitical hedging strategy.

Interdependence of Factors. Political, energy, and local risks are tightly connected. A weakness in one domain can cascade into others: political isolation may hinder energy negotiations, while an energy crisis can provoke unrest that alienates the EU. The scenarios thus represent dynamic transitions, not static states, underscoring the need for holistic risk management across all domains rather than isolated policy fixes.

European Link as Strategic Anchor. Despite Serbia's multi-vector diplomacy, maintaining constructive ties with the EU proves decisive. When this link persisted (Scenarios 1 and 3), Serbia retained flexibility and support; when lost (Scenarios 2 and 4), autonomy eroded quickly. This aligns with findings that hedgers typically lean toward the system-dominant power supplying public goods (Cho and Park, 2013). Sustaining EU goodwill through reforms and reliability substantially reduces risk, even while engaging Russia or China.

Energy Security as a Tactical Lever. Energy control emerged as the fastest-acting variable in the model. Political or diplomatic shifts unfold gradually, but a JANAF cutoff would trigger immediate instability. Consistent with our scenario results, diversification of supply routes and fuel sources-through storage expansion, alternative pipelines (e.g., via Hungary or the Danube), or renewables-is essential to convert an energy crisis from collapse to manageable disruption.

Local Alliances as Multipliers. The HDZ–SNSD partnership amplifies Serbia's regional leverage by ensuring cooperative voices in Bosnia and maintaining Croatian goodwill. Its stability contributed to favorable outcomes in Scenario 1 and mitigated EU fallout in Scenario 2. When weakened (Scenario 4), Serbia's neighborhood turns less hospitable, magnifying external stress. Investing diplomatic capital in such pragmatic regional ties therefore strengthens the hedge's resilience.

Quantitative Synthesis. Average Strategic Autonomy Index results rank as: Scenario 1 (≈ 0.9) > Scenario 2 (≈ 0.7) > Scenario 3 (≈ 0.5) > Scenario 4 (≈ 0.2). The steep gap between Scenarios 3 and 4 illustrates how compounding risks sharply degrade autonomy, while even moderate political friction (Scenario 2) carries measurable costs.

Suma sumarum, Serbia's hedge functions well under stability but remains highly shock-sensitive. Sustained political flexibility, energy diversification, and regional cooperation are essential to preserve strategic autonomy in an evolving geopolitical environment. The mean trajectories of the Strategic Autonomy Index across all scenarios and Monte Carlo runs are visualized in Figure 2, where the Stability scenario (green) maintains high autonomy, while the Combined Risk scenario (dark red) rapidly falls below the critical threshold of 0.7.

DISCUSSION

Our analysis of Serbian–Croatian geopolitical hedging highlights both the strengths and vulnerabilities of hedging as a small-state strategy. Quantitative insights from scenario analysis and ABM were interpreted through a qualitative policy lens to link modeling with practical implications.

Strategic Hedging Effectiveness. The findings confirm that hedging can provide resilience and flexibility for states like Serbia. In stable conditions, Serbia minimized risks by maintaining multiple channels of cooperation, consistent with IR theories viewing hedging as adaptive behavior under uncertainty (Gerstl, 2022). Both scenario and simulation results showed that Serbia avoided the worst consequences of single-bloc alignment, supporting the claim that "strategic hedging enables the Serbian nation to maintain flexibility and resilience". However, hedging's success depends on continuous management: Croatia's cooperation on oil transit, EU tolerance of Serbia's trajectory, and on local Bosnian partnerships (which were decisive). As scholars note, hedging requires constant recalibration, not passive neutrality (Gerstl, 2022).

Policy Implications. Several lessons emerge for policymakers:

- Diversify and Secure Energy: Energy dependence on JANAF and Gazprom-linked NIS poses major vulnerability. Diversifying supply routes, expanding reserves, and exploring renewables are crucial-aligning with expert warnings (Energy Community, 2023).
- Maintain Balanced Diplomacy: Serbia must sustain engagement with both the EU and Russia without crossing critical red lines. Continued EU reforms and stable EPP ties are essential for political legitimacy. Investment in diplomatic capacity and confidence-building with EU partners would mitigate shocks.
- Strengthen Regional Cooperation: The HDZ–SNSD partnership and Serbia-Croatia dialogue exemplify productive hedging. Institutionalizing such cooperation through regular consultations and broadening dialogue to trade or infrastructure can transform tactical pragmatism into durable stability.
- Plan for Contingencies: Preparedness for energy or political crises-including emergency supply protocols, fiscal buffers, and diplomatic "Plan C" options-can improve resilience. Scenario-based planning should become part of Serbia's institutional risk management.

Relevance to Political Science. The case illustrates complex interdependence (Keohane and Nye, 1977): Serbia's fate hinges on transnational political, economic, and ethnic networks. Methodologically, integrating scenario analysis with ABM reflects the growing trend toward computational social science. As Qiu and Phang (2020) and Cederman (2019) emphasize, ABM clarifies assumptions and reveals emergent dynamics that traditional qualitative methods miss. Presenting results through accessible narratives and visuals (Table 1; Figure 1) demonstrates how mathematical tools can enhance political analysis without sacrificing interpretability.

Limitations. The study faces data and modeling constraints: risk levels were qualitatively categorized; the ABM used simplified behavioral rules; and risk dimensions were treated as largely independent. Future work could integrate econometric data, Bayesian or

system-dynamics models, and account for "black swan" events such as leadership change or wider war. Findings are context-specific to 2025 but adaptable to new conditions.

Generalizability. Though centered on Serbia and Croatia, the framework applies to other hedging contexts-from Asia-Pacific states balancing the U.S. and China to Middle Eastern or Latin American cases. The combined use of scenario planning and ABM offers a transferable template for analyzing multi-domain risk and strategic flexibility across regions.

CONCLUSION

This study applied mathematical and computational modeling-combining scenario analysis and agent-based simulation-to assess risks in the Serbian-Croatian geopolitical hedge. Within a social science framework, the research demonstrated that quantitative methods such as risk matrices and simulation algorithms can significantly enhance political risk assessment.

Key findings indicate that Serbia's hedging strategy performs best under conditions of overall stability, where European political links, regional energy flows, and local alliances reinforce each other. The major vulnerabilities lie in over-reliance on a single energy corridor and possible detachment from European political networks; the simultaneous failure of both, especially amid local unrest, produces a systemic crisis. Sustaining an effective hedge thus requires mitigation through diversification of energy imports, consistent EU engagement, and maintenance of cooperative regional ties.

Agent-based modeling revealed the dynamic and non-linear nature of these interactions: independent risks can compound rapidly through feedback loops, producing threshold effects where minor shocks trigger collapse-insights that static analyses often miss. Methodologically, the study illustrates how computational modeling can be embedded in social science research to strengthen empirical grounding and cross-disciplinary rigor.

Ultimately, the Serbian-Croatian hedge exemplifies the dual logic of small-state strategy: flexibility can preserve autonomy, yet the balance is fragile. Serbia's position-simultaneously engaging the EU, cooperating regionally with Croatia, and maintaining pragmatic links to Russia-has enabled short-term stability but remains exposed to cascading shocks. For policymakers, the lesson is to "hedge wisely": build redundancy, cultivate trust, and anticipate disruption. For scholars, the work underscores the value of integrating modern analytical tools to better understand how hedging strategies evolve and survive under real—world uncertainty.

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APPENDIX A: SIMULATION CODE

The complete Python-based simulation code has been made available as a runnable script. It can be accessed and downloaded from the following repository:

https://drive.google.com/drive/folders/1Tqs7GxQj_2r5dC3OZZw6mnFSadxa6nZ4?usp=sharing

Researchers can modify transparency regimes, cognitive threshold distributions, and agent behaviors to replicate or extend our results.

РАЧУНАРСКО МОДЕЛОВАЊЕ ПРОПАГАЦИЈЕ РИЗИКА У МУЛТИАГЕНТНИМ СИСТЕМИМА: РЕГИОНАЛНА СТУДИЈА СЛУЧАЈА

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Сажетак

Представљен је својеврсни оквир за рачунарско моделовање усмјерен на анализу начина на који се ризици шире у мултиагентним системима, а које карактеришу међузависне политичке, економске и локалне интеракције. Приступ интегрише Бејзове мреже, Марковљеве процесе и агентно моделовање ради обухватања и вјероватносних зависности и динамичких повратних спрега на више нивоа система. Омогућена је симулација хетерогених агената чија адаптивна понашања доводе до спонтаних новонастајућих исхода, што омогућава тестирање осјетљивости и анализу сценарија под различитим спољним поремећајима. Регионална студија случаја која се односи на српско-хрватски геополитички хеџинг коришћена је за валидацију методологије, при чему је показано како спрегнути ризици (политички, енергетски и локални) нелинеарно дјелују на укупну стабилност система. Резултати истичу критичне прагове на којима локални поремећаји ескалирају у системске отказе, потврђујући способност предложеног оквира да идентификује обрасце рањивости и стратегије отпорности у сложеним адаптивним системима. Предложена интеграција вјероватносног и агентног моделовања доприноси квантитативној аналитици ризика и пружа преносиво оруђе за примјену подршке одлучивању у доменима који укључују неизвјесност, повратне спреге и интеракцију више учесника.

Кључне ријечи: рачунарско моделовање, анализа ризика, планирање сценарија, агентно моделовање, моделовање међународних односа, геополитички хеџинг

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