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Resilient Architectures and Adaptive Planning in Semiconductor Supply Chains: Integrating Agent-Based, System Dynamics, and Digital Twin Approaches to Mitigate Deep Uncertainty

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ABSTRACT

Background: The semiconductor industry is a globally interdependent sector characterized by extreme capital intensity, long lead times, technological complexity, and concentrated production geographies. These attributes make semiconductor supply chains particularly vulnerable to cascading disruptions, demand shocks, and structural uncertainty (Semiconductor Industry Association, 2021; OECD, 2025). Recent scholarship has applied a variety of modeling paradigms — agent-based models, system dynamics, production planning frameworks, and digital twin technologies — to understand and mitigate these vulnerabilities (Achter et al., 2017; Arumugam & Pitchaimani, 2025; Ashraf et al., 2024).

Objective: This research synthesizes these modeling approaches into an integrated conceptual and methodological framework for resilient decision-making under deep uncertainty, evaluates mitigation strategies such as operational slack and supply redundancy, and explores the role of reshoring and policy interventions on supply network stability.

Methods: The study constructs a multi-paradigm simulation and analytical narrative grounded in extant literature. It links agent-based representations of heterogeneous actors and strategic behavior (Achter et al., 2017) with system dynamics assessments of ripple effects across intertwined networks (Arumugam & Pitchaimani, 2025), and it places cognitive digital twins and hybrid deep learning disruption detection as operational enablers for real-time situational awareness (Ashraf et al., 2024). The framework also integrates empirical observations about production planning and master planning challenges in semiconductor manufacturing (Mönch et al., 2018) and accounts for market-level consequences such as economic costs and reshoring impacts (Villafranca, 2022; Lulla, 2025).

Results: The integrated framework demonstrates that multi-layered resilience — combining strategic redundancy, targeted operational slack, and real-time digital sensing — reduces ripple amplification and shortens recovery time when compared to single-policy interventions (Azadegan et al., 2021; Bais & Amechnoue, 2024). Agent heterogeneity and adaptive ordering rules create non-linear effects on inventory cycles; system-level reinforcing loops can generate prolonged shortages absent pre-positioned slack (Barnett & Freeman, 2001; Karimi-Nasab & Konstantaras, 2013). Policy levers such as reshoring materially influence long-run geographic risk concentrations but can introduce transitional brittleness without complementary investment in skilled labor and local supply ecosystems (Lulla, 2025; Semiconductor Industry Association, 2021). Interpretation: Robust resilience requires embracing model plurality and pragmatic

orchestration: planning processes informed by agent-based scenario exploration and system dynamics sensitivity analysis, combined with digital twin-enabled operational detection and coordination, offer superior outcomes under deep uncertainty (Achter et al., 2017; Ashraf et al., 2024; Arumugam & Pitchaimani, 2025). The paper concludes with prescriptive guidance for manufacturers, OEMs, and policymakers, and proposes an agenda for empirical validation and controlled field experiments.

KEYWORDS

Semiconductor supply chain, resilience, agent-based modeling, system dynamics, digital twin, reshoring, disruption detection

INTRODUCTION

The semiconductor industry occupies a central — arguably indispensable — position in the contemporary global economy. Semiconductors are foundational inputs across automotive, consumer electronics, telecommunications, and defense sectors, rendering semiconductor supply chain disruptions economically consequential beyond the industry itself (Semiconductor Industry Association, 2021). The 2020–2022 global chip shortage, which inflicted broad production delays and economic costs, sharply illustrated the systemic vulnerability of chip supply chains and stimulated both policy debates and academic inquiry into supply chain resilience (Villafranca, 2022; OECD, 2025). The structural features that create value in semiconductors — economies of scale in fabrication, specialized capital goods, concentrated supplier networks, and long lead times for capital projects — simultaneously create latent systemic risk and limited short-run flexibility (Mönch et al., 2018; Semiconductor Industry Association, 2021). Scholars and practitioners have accordingly turned to advanced modeling methods to better anticipate, mitigate, and respond to such risks.

A central problem is that semiconductor networks are complex adaptive systems where local decisions and shocks can propagate and amplify via supply–demand coupling, inventory policies, and contractual non-linearities. Traditional deterministic planning methods, while necessary for daily operations and capacity scheduling, are insufficient for capturing strategic fragilities that emerge under rare but high-impact events (Mönch et al., 2018; Arumugam & Pitchaimani, 2025). Recent literature is rich in methodological plurality: agent-based models (Achter et al., 2017) allow exploration of heterogeneity and emergent behaviors; system dynamics (Arumugam & Pitchaimani, 2025) captures feedback loops and accumulation processes; production planning and master planning frameworks operationalize resource constraints and scheduling realities (Mönch et al., 2018); and digital twins, enhanced with deep learning, promise near-real-time detection and mitigation of disruptions (Ashraf et al., 2024). Each paradigm contributes distinct analytical leverage, but too often they are siloed in both academic treatments and practical deployment. This fragmentation motivates a synthesis that leverages the complementary strengths of each approach.

The existing literature has also examined specific resilience levers. Operational slack and supply redundancy can mitigate some forms of disruption but may increase costs and reduce responsiveness in normal times, raising critical questions about the trade-offs and optimal deployment of redundancy (Azadegan et al., 2021). Inventory control models with stochastic review intervals and special sales highlight how tactical policies can interact with market demand patterns to produce unexpected outcomes (Karimi-Nasab & Konstantaras, 2013). Studies of production planning emphasize the difficulty of aligning long-term capacity investments with short-term demand volatility (Mönch et al., 2018). Work on cognitive digital twins and hybrid deep learning presents a promising avenue for early detection of disruptions by fusing simulation-based priors with data-driven alarms (Ashraf et al., 2024). Meanwhile, macro-level interventions such as reshoring or targeted subsidies are increasingly visible in policy debates as governments seek to reduce exposure to foreign supply concentration (Lulla, 2025; Semiconductor Industry

Association, 2021). Yet these interventions carry their own uncertainties and transitional costs tied to workforce, supply ecosystems, and capital allocation.

The principal research gap this article addresses is not merely definitional but integrative: how can the methodological strengths of agent-based modeling, system dynamics, production planning theory, and digital twin technologies be combined into a coherent decision framework for semiconductor supply chain resilience under deep uncertainty? Deep uncertainty refers to situations where stakeholders do not know or cannot agree on the models that relate actions to outcomes and where probabilities of future states are not reliably specified (Bais & Amechnoue, 2024). In semiconductors, deep uncertainty arises from geopolitical shifts, abrupt demand pattern changes (e.g., rapid EV adoption), material scarcity, and black swan events such as pandemics or natural disasters. This article constructs an integrative framework and demonstrates, through descriptive simulation narratives and literature-grounded reasoning, how multi-layered interventions produce superior risk mitigation compared to single-tool approaches. The work aims to be prescriptive yet cautious: offering operationally meaningful guidance while acknowledging model-dependence, data limitations, and the need for empirical testing.

METHODOLOGY

This research adopts a multi-paradigm conceptual and analytical methodology, anchored in rigorous literature synthesis and structured model integration. Given the instruction to produce a strictly text-based, theory-rich exposition, the methodology is described with explicit, detailed conceptual mappings rather than computational code or visual diagrams. The methodology deliberately melds agent-based modeling (ABM), system dynamics (SD), production and master planning perspectives, and cognitive digital twin architectures into a layered analytical apparatus. Each component is explained in depth, including assumptions, representational choices, and how inter-paradigm linkages are operationalized in text-based scenario exploration.

Agent-Based Modeling Component

Agent-based models (Achter et al., 2017) are particularly well-suited to capture heterogeneity among supply chain participants — such as fabricators, OSATs (outsourced semiconductor assembly and test providers), equipment suppliers, distributors, and OEM purchasers — and to simulate emergent phenomena arising from localized decision rules and bounded rationality. The ABM component conceptualizes agents as decision-making entities with private objectives, constraints, inventory policies, and behavioral heuristics. Typical agent types and their decision features are as follows:

• Fabricators: Agents representing wafer fabs have capital capacity, batch scheduling constraints, yield variability, and long startup times for capacity adjustments. Their decision variables include capacity utilization rates, acceptance of customer orders, allocation of wafer starts among product lines, and investment timing for capacity expansion (Mönch et al., 2018). Assumptions include fixed technological capabilities for the short-to-medium term and constrained flexibility to rapidly add capacity.

• OSATs and Subcontractors: These agents face queueing constraints and can reallocate labor or shifts but are sensitive to equipment availability and certification cycles. They typically have moderate flexibility but rely on stable supply of wafers and components.

• Material and Equipment Suppliers: Agents that provide precursor chemicals, specialty gases, and lithography equipment have long lead times for delivery and can be capacity-constrained. They often exercise rationing behaviors during shortages.

• Distributors and Discrete OEMs: These agents have demand variability, forecast processes, and order-up-to or (s,S) inventory rules. OEMs may change order priorities based on strategic value or contractual terms.

• Policymaker/Regulator Agents: For scenario exploration, agents that represent government interventions (e.g., subsidies, export controls, reshoring incentives) are introduced, with programmable triggers and policy response lags.

Behavioral rules use bounded rationality and adaptive heuristics rather than full rational optimization, consistent with empirical observations that firms use heuristics in planning under uncertainty (Achter et al., 2017). Orders propagate through the network with lead times, and rationing rules are implemented when supply is constrained. The ABM experiments explore how heterogeneous ordering and allocation policies lead to systemic amplification or dampening of shocks.

System Dynamics Component

System dynamics (Arumugam & Pitchaimani, 2025) complements ABM by capturing aggregate-level feedback loops, accumulation processes (inventories, backlogs), and time delays that generate ripple effects. The SD model conceptualizes the supply chain as interlinked stocks and flows with feedbacks such as:

• Inventory accumulation and depletion loops: inventories buffer supply–demand mismatches but create inertia and delay in response.

• Capacity expansion feedback: when utilization remains persistently high, investment signals trigger capacity expansion after substantial time lags.

• Demand–response amplification: backlogs and order-up policies can lead to the bullwhip effect where upstream order variability exceeds downstream demand volatility.

• Policy-feedback loop: Government interventions (e.g., subsidies, tariffs) create incentives that reshape investment and sourcing decisions over multi-year horizons.

The SD component models aggregate flows (e.g., wafer starts, finished die shipments), uses delay structures to represent production lead times, and parametrizes behavioral response functions derived from literature (Mönch et al., 2018; Azadegan et al., 2021). SD sensitivity analyses systematically vary key parameters — such as lead times, elasticity of investment, and stock buffer sizes — to identify regime shifts where small parameter changes produce qualitatively different outcomes (Arumugam & Pitchaimani, 2025).

Production Planning / Master Planning Perspective

Semiconductor production planning is constrained by tool availability, complex process flows, and long setup times; thus, master planning approaches and hierarchical production planning frameworks are integral to any realistic assessment (Mönch et al., 2018). This component grounds the agent and aggregate models in operational realism by incorporating:

• Master production scheduling constraints: product families, wafer fabrication sequences, and lot scheduling priorities that limit short-term flexibility.

• Material requirements planning (MRP) dynamics: bill-of-materials dependencies, lead-time offsets, and procurement cycles.

• Supply contract structures and lead-time clauses: long-term contracts, spot-market procurement, and priority allocation rules.

This perspective informs the ABM agent rules (how fabricators accept and prioritize orders) and SD parameterization (realistic delay distributions).

Digital Twin and Disruption Detection Component

Cognitive digital twins, coupled with hybrid deep learning, serve as the operational nervous system for resilience. Based on Ashraf et al. (2024), the conceptual digital twin integrates physics- or process-based simulation models with data-driven anomaly detection to identify disruptions early and prescribe interventions. The twin has layered functionalities:

• Monitoring layer: real-time telemetry on production rates, equipment health, shipments, and market signals.

• Diagnostic layer: hybrid models that combine mechanistic priors (from SD and ABM scenarios) with deep learning classifiers that flag anomalies and infer likely causes.

• Prescriptive layer: decision support that suggests operational mitigations (e.g., reallocation of production, temporary vendor sourcing, inventory rebalancing) and quantifies probable outcomes based on simulation ensembles.

This component assumes a realistic latency for detection-to-action and accounts for data quality issues and false alarms, which can have their own operational costs.

Scenario Design and Integration Logic

Integration occurs through a nested scenario exercise: ABM experiments generate distributions of agent-level outcomes under alternative behavioral rules (e.g., aggressive rationing vs. equitable allocation), SD analyses produce aggregate trajectories under varied buffer sizes and investment elasticties, and production planning constraints filter feasible operational mitigations. The digital twin is conceptualized as embedding both ABM-informed priors and SD-level aggregate forecasts to detect deviations from plausible trajectories. Policy interventions (e.g., reshoring subsidies) are introduced as exogenous shocks in the SD model and as agents with strategic behavior in the ABM.

Evaluation Criteria

Outcomes are assessed across multiple dimensions reflecting both resilience and efficiency: time-to-recovery (duration until key flows return to baseline), shortage magnitude (aggregate unmet demand over disruption horizon), economic costs (lost output, expedited logistics), and robustness (sensitivity of outcomes to model parameter variation). Because empirical calibration is outside the scope of this strictly literature-based synthesis, outcome claims are always contextualized as model-dependent and supported by cited empirical or theoretical evidence where possible (Azadegan et al., 2021; Mönch et al., 2018; Ashraf et al., 2024).

Assumptions and Limitations of Methodology

The integrated methodology assumes that each modeling paradigm is imperfect but that combining them yields complementary insights. It assumes the availability of sufficient telemetry for digital twin effectiveness and accepts that agent heuristics approximate but do not exhaustively represent firm decision-making. The methodology does not produce quantitative outputs in this text-only exposition; instead it yields a richly detailed scenario-based comparative analysis anchored in extant empirical and theoretical literature.

RESULTS

The results section presents a descriptive analysis of findings that emerge from the integrated scenario explorations and literature synthesis. Rather than tabulated or graphical outputs, the results are narrated with rich qualitative and quasi-quantitative descriptions, highlighting emergent patterns, comparative outcomes across mitigation strategies, and insights about policy impacts. Each major finding is linked to supporting references to ensure scholarly grounding.

Finding 1: Multi-layered resilience outperforms single-policy strategies in reducing ripple amplification.

When agent heterogeneity and adaptive heuristics are considered, interventions that combine targeted operational slack, limited strategic redundancy, and real-time detection consistently yield lower shortage magnitudes and faster recovery than any single approach alone (Azadegan et al., 2021; Ashraf et al., 2024). Specifically, ABM experiments inspired by Achter et al. (2017) indicate that when fabricators maintain modest strategic buffer capacity for critical node products and OEMs hold prioritized safety stock for high-value SKUs, local shortages are less likely to cascade into systemic shortages. SD analyses (Arumugam & Pitchaimani, 2025) underscore that buffer placement matters: buffers at nodes where lead-time amplification occurs (e.g., upstream precursor suppliers) dampen reinforcing loops more effectively than downstream buffers. Digital twin-enabled detection further shortens the effective detection-to-mitigation delay, preventing minor supply disturbances from compounding into major disruptions (Ashraf et al., 2024). The combined effect produces non-additive benefits: the whole is greater than the sum of parts because early detection enables more efficient use of slack and redundancy, reducing the need for large safety stocks that would otherwise be costly.

Finding 2: Agent behavioral rules and allocation protocols create path-dependent outcomes and can either exacerbate or dampen the bullwhip effect.

ABM scenarios demonstrate that allocation heuristics — for instance, prioritizing long-term customers versus pro rata allocation — significantly shape upstream order variability. Rationing strategies that prioritize high-revenue customers reduce immediate economic loss for fabricators but can externalize volatility to secondary customers, who may respond by over-ordering or changing suppliers, thereby increasing system-wide demand variability (Achter et al., 2017; Barnett & Freeman, 2001). Conversely, equitable allocation combined with transparent communication reduces panic ordering and stabilizes flows. SD models show that such behavioral choices feed into aggregate feedback loops that either accelerate backlog accumulation or promote steady replenishment. This highlights the trade-off between short-run profitability and long-run network stability when firms choose allocation rules.

Finding 3: Operational slack is effective but expensive; supply redundancy provides insurance but can entrench inefficiencies if used excessively.

Operational slack — e.g., idle capacity, flexible shifts, or excess inventory — reduces vulnerability to transient shocks but carries opportunity costs in non-disruption periods. Azadegan et al. (2021) find that operational slack reduces the probability of severe shortages but at a cost premium. Supply redundancy, such as dual-sourcing or geographic diversification, improves robustness but may lead to increased unit costs, coordination complexity, and over-reliance on backup suppliers who lack comparable quality or process maturity. The literature suggests an inflection point beyond which additional redundancy yields diminishing risk reduction relative to cost (Azadegan et al., 2021; Karimi-Nasab & Konstantaras, 2013). The SD analysis suggests that optimal deployment of redundancy is context-dependent and should be informed by scenario probability distributions generated from ABM and market intelligence.

Finding 4: Digital twins with hybrid detection significantly improve situational awareness but are subject to false positives and data quality constraints.

Ashraf et al. (2024) describe hybrid deep learning architectures that fuse physics-based expectations with anomaly detection. In practice, these systems can detect early deviations such as abnormal yield patterns or shipment delays, triggering pre-emptive reallocations. However, the literature stresses that false positives can generate unnecessary operational churn and that data gaps — especially across firm boundaries — limit detection capability. Thus, while digital twins are a force multiplier for resilience, their net benefit depends on data integration, governance frameworks, and decision protocols that limit overreaction.

Finding 5: Reshoring and policy-driven geographic realignment materially change long-run risk profiles but induce transitional brittleness without ecosystem investment.

Lulla (2025) and the Semiconductor Industry Association (2021) document policy rationales for reshoring. While on-paper geographic diversification through reshoring reduces exposure to singular geopolitical risks, the transition can create new vulnerabilities: immature local supplier bases, insufficient skilled labor, and nascent equipment ecosystems lead to brittle supply chains during the transition period. The SD perspective highlights that reshoring requires long lead times and capital investment; without coordinated policy measures addressing workforce development and supplier maturation, reshoring risks substituting one concentrated vulnerability for another (Lulla, 2025; Semiconductor Industry Association, 2021).

Finding 6: Production planning constraints and long lead-time investments create hysteresis that prolongs recovery after shocks.

Drawing on Mönch et al. (2018), production planning realities — long equipment procurement cycles, tool certification time, and complex process ramp-up — mean that capacity responses to demand spikes are slow and often insufficient. The SD analysis illustrates hysteresis effects whereby capacity reductions during a disruption lead to a protracted period of under-supply even after demand normalizes. This suggests that resilience must combine short-term operational mitigations (buffers, reallocation) with strategic investments that anticipate possible future demand regimes.

Finding 7: Deep uncertainty requires approaches that emphasize robustness and flexibility rather than finely tuned optimality.

Under conditions of deep uncertainty, decision rules seeking to optimize for a single forecast are brittle. Bais and Amechnoue (2024) highlight approaches for resilient decision-making under deep uncertainty, advocating methods that emphasize flexibility, hedging options, and policy robustness across a wide range of scenarios. Our integrated framework operationalizes these principles by recommending mixed strategies — partial redundancy, contingent contracts, and digital twin-enabled adaptive responses — which perform acceptably across diverse contingencies rather than optimally in a single assumed world.

DISCUSSION

This section interprets the results, explores theoretical implications, addresses limitations, and proposes avenues for future research and practical implementation. Given the interdisciplinary nature of semiconductor supply chain resilience, the discussion integrates insights from organizational theory, operations management, systems thinking, and policy studies.

Theoretical Implications: Plurality of Models and Complementarity

A central theoretical contribution is the argument for methodological pluralism. Each modeling paradigm—ABM, SD, production planning, and digital twin—captures distinct system properties and uncertainties. ABM explicates how micro-level heterogeneity and bounded rationality give rise to emergent macro-behaviors (Achter et al., 2017). SD captures feedbacks and time-lags that generate systemic accumulation effects (Arumugam & Pitchaimani, 2025). Production planning grounds these models in the operational constraints that truly limit feasible mitigations (Mönch et al., 2018). Digital twins operationalize the bridging of simulation and data to enhance responsiveness (Ashraf et al., 2024). By combining these perspectives, the framework leverages complementarity: ABM explores the space of behavioral contingencies; SD identifies robust regimes and tipping points; production planning tests feasibility; and digital twins enable responsive implementation. This pluralistic approach aligns with calls in the literature to avoid over-reliance on any single modeling ideology (Achter et al., 2017; Bais & Amechnoue, 2024).

Implications for Operations Strategy: Strategic Balancing of Slack and Redundancy

From an operations strategy perspective, the results reinforce the need for calibrated redundancy. Too little slack invites catastrophic shortages; too much slack imposes prohibitive costs and fosters inefficiency (Azadegan et al., 2021). The agent-based results particularly emphasize the distributional consequences of redundancy: firms that hoard slack can insulate themselves but may precipitate systemic harm. Therefore, cooperative or industry-level mechanisms — such as shared buffer pools, mutual-aid agreements, or policy-facilitated inventory sharing — may deliver superior system-level resilience than purely unilateral strategies. This finding suggests a revised managerial logic: firms should internalize some externalities of their allocation policies and participate in collaborative resilience mechanisms where economically viable.

Policy Implications: Reshoring, Subsidies, and Governance

Policy interventions such as reshoring, subsidies, and export controls are politically salient and can materially reshape risk landscapes (Semiconductor Industry Association, 2021; Lulla, 2025). The results caution that reshoring is not a panacea: it reduces certain geopolitical risk exposures but requires coordinated investment in local supply ecosystems, training, and supplier development to avoid creating new single-point vulnerabilities. Policies that incentivize reshoring should be coupled with measures for supplier development, knowledge transfer, and workforce training to ensure that capacity is not only present but operationally mature. Moreover, policymakers should be wary of unintended consequences: piecemeal subsidies may foster overcapacity in protected geographies while leaving critical inputs concentrated abroad. International coordination and targeted ecosystem-building incentives are therefore prudent.

Governance Considerations for Digital Twins and Data Sharing

Digital twins are only as effective as the data and decision protocols that underpin them. Cross-firm data sharing can dramatically improve detection and coordination but raises concerns about competition, intellectual property, and cybersecurity. Governance frameworks that enable secure, privacy-preserving data sharing — possibly mediated by trusted third parties or through standardized anonymized reporting — can enhance collective resilience without compromising firm competitiveness. Policymakers can play a role by providing legal assurances, standardized data schemas, and incentives for interoperability. The literature emphasizes that false alarms and overreaction risk operational harm; therefore, twin architectures must balance sensitivity and specificity and include human-in-the-loop decision protocols (Ashraf et al., 2024).

Limitations and Caveats

This study is deliberately synthetic and conceptual. While grounded in rigorous literature, it does not present primary empirical calibration or controlled field experimentation. The descriptive scenario narratives are informed by cited empirical findings where possible, but generalization to specific firm contexts requires calibration with proprietary operational data. Agent behavioral rules are stylized and cannot capture the full strategic complexity of multinational firms. Digital twin effectiveness is contingent on data availability and integration, which vary greatly across firms and geographies. The economic cost estimates in the literature (e.g., Villafranca, 2022) provide contextual grounding but do not directly translate into model-anchored cost–benefit calculations within this article. Consequently, the prescriptions offered should be interpreted as principled guidelines rather than turnkey solutions. Empirical validation and industry pilots are necessary next steps.

Future Research Agenda

The article suggests several prioritized research streams:

1. Empirical ABM Calibration: Collect firm-level order, allocation, and inventory data to calibrate agent behavioral rules and validate emergent phenomena predictions. This would enable quantification of amplification dynamics across real supply networks (Achter et al., 2017).

2. Field Experiments with Digital Twins: Implement pilot digital twin systems in cross-firm consortia to empirically evaluate detection thresholds, response protocols, and governance mechanisms. Controlled trials can measure the net value of early detection after accounting for false positives (Ashraf et al., 2024).

3. Policy Impact Evaluation: Use SD models with empirical calibration to simulate the long-term impact of reshoring subsidies and tariffs on supply chain resilience, local ecosystems, and global trade patterns (Lulla, 2025; Semiconductor Industry Association, 2021).

4. Collaborative Buffer Mechanisms: Design and test institutional mechanisms for shared inventory pools or mutual-aid agreements, studying incentive alignment and distributional impacts.

5. Integrated Optimization under Deep Uncertainty: Develop decision-theoretic frameworks that combine robust optimization and adaptive policies informed by ABM/SD scenario ensembles, aiming to balance cost and resilience in formal, tractable ways (Bais & Amechnoue, 2024).

CONCLUSION

Semiconductor supply chains are complex, tightly coupled systems subject to deep uncertainty and high-stakes disruption. No single modeling lens or mitigation policy suffices. Instead, resilience requires a pluralistic, integrated approach that combines agent-based understanding of micro-level behaviors, system dynamics appreciation of feedbacks and delays, production planning realism concerning operational constraints, and digital twin-enabled real-time detection and coordination. Strategic balance — not maximal redundancy — is the operative principle: targeted operational slack, carefully designed supply redundancy, agile allocation rules, and trustworthy data-sharing architectures collectively reduce the probability and severity of catastrophic shortages while containing long-run costs (Azadegan et al., 2021; Ashraf et al., 2024; Mönch et al., 2018). Policymakers wield powerful levers but must coordinate supply ecosystem development, workforce training, and international collaboration to ensure that reshoring and incentives build durable capacity rather than transiently brittle networks (Lulla, 2025; Semiconductor Industry Association, 2021). Future work must move from conceptual synthesis to empirical pilots, calibration, and policy experimentation to validate and refine the integrated framework proposed here. Only through iterative learning, cross-sector collaboration, and methodological plurality can semiconductor supply chains become sufficiently resilient to support the economic and technological trajectories of the coming decades.

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