The Hold-Up Problem as a Barrier to Green Industrial Symbiosis: An Agent-Based Model of Sunk Costs, Trust, and Institutional Design

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1 Introduction

Industrial Symbiosis (IS) networks, where firms exchange waste streams as valuable inputs, offer a critical pathway to the circular economy. However, despite clear environmental and economic benefits, many potential networks fail to materialize. This study isolates a fundamental microeconomic barrier to IS adoption: the Hold-Up Problem.

In IS networks, producers must often incur non-recoverable "sunk costs" (specialized piping, treatment facilities) to participate. This asset specificity creates a vulnerability: once the investment is made, downstream "offtakers" may renegotiate terms or act opportunistically, knowing the producer cannot exit. This study makes use of Agent-Based Modeling (ABM) to investigate how investment barriers interact with market turbulence, contract enforcement, and reputation systems to determine network resilience.

2 Methodology

We developed a spatially explicit ABM in NetLogo to simulate the evolutionary dynamics of the IS coordination game. The model features heterogeneous agents (Producers and Consumers) operating under bounded rationality.

- **Core Dynamic:** Producers decide whether to invest (pay sunk costs) based on expected utility; Consumers decide whether to cooperate (share surplus) or defect (exploit locked-in partners).

- **Variables:** Using the BehaviorSpace tool, we conducted a global sensitivity analysis (N= 4,320 runs) across six dimensions (see Table 1).

- **Mechanism:** Agents update strategies via social learning (imitating wealthy peers) and stochastic mutation.

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Table 1: BehaviorSpace Parameter Sweep Configuration

Parameter	**Values**	**Description**
Investment Cost	0, 5, 10	Upfront sunk cost for IS participation
Market Turbulence	0–5	Price volatility (std. dev. of shocks)
Contract Strength	0, 0.5, 1.0	Probability of legal enforcement
Memory Duration	10, 100	Reputation horizon (ticks)
Synergy Surplus	5, 15	Value of cooperative exchange
Lock-In Period	10, 30	Minimum contract duration (ticks)

3 Results

Our simulation results challenge prevailing assumptions about market risks in the circular economy:

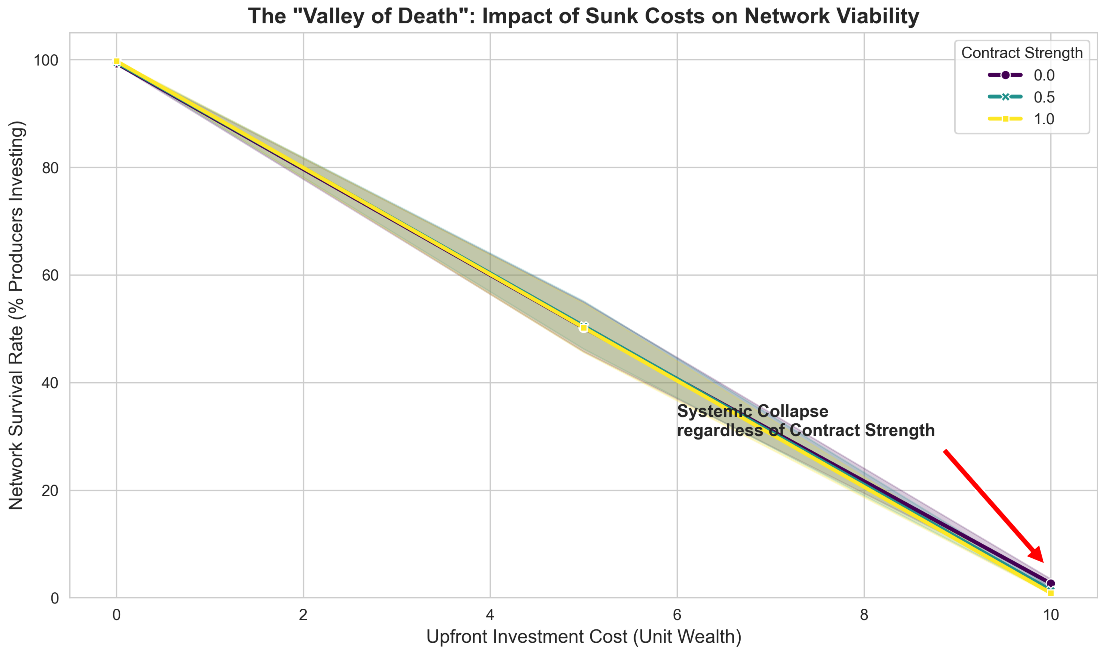

Figure 1: Network survival rate vs. investment cost. All contract enforcement levels converge to collapse at high cost (N=4,320, 95% CI).

1. **Investment Cost is the Dominant Filter:** The magnitude of the "sunk cost" barrier overwhelms all other institutional and market factors. In scenarios with zero investment cost, cooperative networks achieved a 99.5% survival rate regardless of legal or market conditions. However, introducing a high investment cost (10 units) caused survival rates to collapse to 1.6%, even under optimal contract enforcement. This represents a 97.9 percentage point viability gap driven solely by entry barriers.

2. **The "J-Curve" Trap:** The collapse is driven by a "Valley of Death" dynamic. Even when long-term cooperation is profitable, the initial liquidity dip from CAPEX makes "Investing" agents appear less fit than "Cautious" agents in the short run, causing the population to converge to a non-cooperative equilibrium before returns are realized.

3. **Turbulence is Secondary:** Counterintuitively, market price volatility (turbulence) had a negligible independent effect on network survival. Investment cost barriers demonstrated an

effect magnitude approximately 200 times greater than that of price volatility. This suggests that the perceived risk of market fluctuation is often overstated relative to structural capital barriers.

4. **Reputation as a Substitute for Law:** In the absence of formal contracts, extended "institutional memory" (reputation horizons) functioned as a near-perfect substitute for legal enforcement, suggesting informal institutions may complement formal contracts under uncertainty.

4 Conclusions

The findings offer a sharp correction to policy priorities. Efforts to stabilize recyclable material prices or improve contract enforceability are necessary but insufficient conditions for IS emergence.

Primary Intervention: Policies must target the "J-Curve" problem directly. Capital subsidies, green grants, or public co-investment models are required to lower the effective sunk cost below the critical threshold.

Secondary Intervention: Once entry barriers are lowered, reputation systems and contracts become relevant for maintaining stability.

We conclude that the primary failure mode of Industrial Symbiosis is not a lack of trust or market stability, but a **structural liquidity trap** caused by asset specificity.

References

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