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Research article

Conditional effects of network position, payoff uncertainty, and strategic inertia on supply chain greenwashing evolution

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Appendix A. Simulation algorithm and reproducibility details

A.1. Simulation algorithm

The numerical experiments are conducted using a stochastic evolutionary game model on BA networks. The simulation procedure integrates network generation, initial strategy allocation, triangular payoff sampling, asynchronous updating, and statistical aggregation.

The network is represented by an undirected and unweighted graph $G = (V, E)$, where V denotes the set of enterprises and E denotes their interaction relationships. Each enterprise adopts either genuine green production (G) or greenwashing (B). The baseline updating mechanism follows the inertia-modified Fermi rule defined in Section 3.

Algorithm A1. Stochastic evolutionary simulation on a BA supply chain network

Input: Network size N; attachment parameter m; hub count K; simulation horizon T; root random seed s_0; triangular payoff parameters $\tilde{R}$, $\tilde{S}$, $\tilde{T}$, $\tilde{P}$; learning intensity η; strategic inertia parameters; initial strategy configuration; payoff evaluation mechanism; stochastic payoff-sampling mechanism; number of network realizations M; and number of Monte Carlo replicates R_{MC}.

```
for each independent BA network a do
    Generate G_a and identify hub nodes
    for each Monte Carlo replicate r do
        Initialize strategies and payoff records
        for t = 1, ..., T do
            Select update nodes without replacement
```

```
                for each selected enterprise i do
                    Select a random neighbor j
                    if strategy(i) != strategy(j) then
                        Evaluate payoffs Pi_i and Pi_j
                        Compute Fermi imitation probability
                        Update strategy(i) if accepted
                    end if
                end for
                Record greenwashing density
            end for
        end for
end for
Compute network-level summary statistics
Construct 95% Student's t confidence intervals
Export simulation outputs and metadata
```

Output: Evolutionary trajectories; terminal greenwashing densities; network-level summary statistics; homogeneous absorption records; quasi-convergence diagnostics; confidence intervals; statistical test results; and reproducibility metadata.

The algorithm provides a common computational framework for all experiments. Experiment-specific modifications to the network parameters, initial strategy allocation, payoff evaluation, stochastic sampling, and strategic inertia are described in Section A.3.

A.2. Baseline Parameters

Table A1. Baseline parameters of the stochastic evolutionary game.

Parameter	Symbol	Baseline value
Number of enterprises	N	100
BA attachment parameter	M	3
Number of hub enterprises	K	5
Initially greenwashing hub enterprises	—	2
Initially genuine green hub enterprises	—	3
Initial peripheral greenwashing proportion	$f_P(0)$	0.30
Learning intensity	η	1.2
Minimum inertia parameter	ρ_{min}	0.3
Maximum inertia parameter	ρ_{max}	0.7
Updating proportion per time step	λ	0.20
Simulation horizon	T	1,000
Root random seed	s_0	42
Number of independent networks, Experiments 2–6	M	20
Monte Carlo replicates per network	R_{MC}	20
Number of simulations per condition, Experiments 2–6	MR_{MC}	400
Quasi-convergence observation window	L	20
Quasi-convergence tolerance	δ	0.005
Baseline payoff aggregation	—	Accumulated payoff
Baseline stochastic sampling	—	Comparison-level sampling

The baseline parameter configuration is summarized in Table A1. Unless otherwise specified, the numerical experiments use the same baseline payoff matrix, asynchronous updating mechanism, and observation horizon.

A.3. Experiment-specific configurations

Six numerical experiments are designed to investigate the effects of initial strategy placement, payoff uncertainty, payoff boundaries, social learning, network structure, and initial greenwashing proportions.

In Experiment 1, the baseline network topology is held fixed while alternative initial hub strategy configurations are compared. The resulting uncertainty estimates describe variation across Monte Carlo replicates conditional on the selected network realization.

In Experiments 2–6, independently generated BA networks are used to account for variation in the network's topology. Within each network, 20 Monte Carlo replicates are performed for each condition. Matched comparisons use corresponding network realizations to reduce variation attributable to differences in network topology.

Experiment 2 additionally considers alternative stochastic payoff-sampling mechanisms. Under comparison-level sampling, stochastic payoffs are sampled when payoff comparisons are evaluated. The edge-fixed and run-fixed alternatives retain payoff realizations over longer intervals, as specified by their respective implementation rules.

Table A2. Experimental configurations and sensitivity settings.

Experiment	Main configuration	Purpose
Experiment 1	One fixed BA network, 20 matched replicates; alternative initial hub strategy configurations	Examine the effects of initial hub strategies
Experiment 2	20 networks × 20 replicates; alternative fuzzy payoff widths, defuzzification operators, and stochastic payoff-sampling mechanisms	Examine payoff uncertainty and sampling assumptions
Experiment 3	20 networks × 20 replicates; extreme payoff-boundary adjustments and mean-controlled interval width variations	Distinguish payoff-level effects from interval width effects
Experiment 4	20 networks × 20 replicates; $\eta \in \{0.5, 1.2, 2.5\}$, with low- and high-inertia specifications	Examine learning intensity and strategic inertia
Experiment 5	20 networks × 20 replicates; alternative BA connectivity, fixed-count initial placement, payoff normalization, network size, hub classification, and inertia mechanisms	Examine structural heterogeneity and mechanism robustness
Experiment 6	20 networks × 20 replicates; initial peripheral greenwashing proportions of 10%, 30%, 50%, and 70%	Assess sensitivity to the initial strategy proportions

Experiment 3 distinguishes changes in the extreme payoff boundaries from changes in interval width under controlled central payoff specifications. Experiment 4 varies the learning intensity and strategic inertia jointly. Experiment 5 includes degree-normalized payoff comparisons and mechanism-ablation configurations to assess whether the effects of network position depend on payoff accumulation or inertia. Experiment 6 varies the initial peripheral greenwashing proportion while retaining the specified initial hub configuration.

The experiment-specific initialization procedures, payoff configurations, and random seed records are included in the corresponding simulation scripts and configuration files.

A.4. Statistical inference and confidence interval construction

To avoid treating Monte Carlo replicates on the same network as independent network observations, statistical inference for Experiments 2–6 is performed at the independent-network level.

Let $f_{a,r,c}(t)$ denote the greenwashing density at time t for network a, replicate r, and experimental condition c. The network-level mean is defined as

$$\bar{f}_{a,c}(t) = \frac{1}{R_{\mathrm{MC}}} \sum_{r=1}^{R_{\mathrm{MC}}} f_{a,r,c}(t).$$

The mean across independent networks is

$$\bar{f}_{c}(t) = \frac{1}{M} \sum_{a=1}^{M} \bar{f}_{a,c}(t).$$

The sample standard deviation of the network-level means is

$$s_c(t) = \sqrt{\frac{1}{M-1} \sum_{a=1}^{M} \left[\bar{f}_{a,c}(t) - \bar{f}_{c}(t) \right]^2}.$$

The two-sided 95% Student's t confidence interval is constructed as

$$CI_{95\%,c}(t) = \bar{f}_{c}(t) \pm t_{0.975,M-1} \frac{s_c(t)}{\sqrt{M}}.$$

For Experiments 2–6, $M = 20$, yielding 19 degrees of freedom. The same procedure is applied to terminal greenwashing densities and time-specific mean trajectories.

For Experiment 1, which has a single fixed network, the uncertainty intervals are computed across the 20 Monte Carlo replicates. These intervals describe replicate-level uncertainty conditional on the fixed network and should not be interpreted as capturing variation across independent network realizations.

For matched comparisons, the Friedman test is used to assess overall differences across experimental conditions. Where pairwise comparisons are conducted, Wilcoxon signed-rank tests are applied to matched network-level means, and the Holm procedure is used to adjust for multiple testing.

A simulation is classified as reaching a homogeneous absorbing state when all enterprises adopt the same strategy. Runs that do not reach a homogeneous absorbing state within the observation horizon are classified as nonabsorbed. Their observed durations are right-censored at the simulation horizon when interpreting the absorption times. Quasi-convergence is evaluated separately and is not considered to be equivalent to absorption.

Where displayed confidence limits fall outside [0, 1], they are truncated to the admissible density range for visualization; the untruncated values are retained in the numerical outputs.

A.5. Random seed management and code availability

A root seed of 42 is used as the reproducibility reference for the simulation experiments. Network generation, initial strategy allocation, and stochastic updating involve separate sources of randomness.

For exact reproducibility, the implementation records the random number generator's settings and the seeds associated with network realizations and Monte Carlo replicates.

The simulation scripts specify the random seeds used for network generation, strategy initialization, and stochastic updating. The exact seed-generating procedures are documented in the corresponding experimental implementations to support reproducibility.

The released materials identify the software versions, network generation parameters, node-labeling convention, hub identification procedure, initialization rules, payoff-sampling methods, and statistical analysis procedures.

The accompanying reproducibility materials contain the following components:

1. Python scripts implementing Experiments 1–6;
2. Baseline and experiment-specific parameter configurations;
3. Random seed records and software dependency information;
4. Replicate-level simulation outputs and network-level summaries;
5. Scripts or instructions for reproducing figures, tables, confidence intervals, and statistical comparisons.

The location and version of the released materials are specified in the Data and Code Availability statement of the manuscript.



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