Rigorous Agent-Based Modeling of Green Practice Diffusion: Analytical Approximations and Validation on Organizational Networks

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Abstract

Agent-based modeling (ABM) is increasingly used to manage pro-environmental behavior change, especially in energy-related contexts. A key advantage of ABM is its ability to model local consumer interactions, which play a crucial role in promoting pro-environmental behavior driven by peer pressure and social norms. However, ABM is often criticized for its lack of rigorous validation and sensitivity analysis. To address these challenges, we refine an existing ABM of green product and practice diffusion, applying Pair Approximation (PA) and Monte Carlo Simulations (MCS) to real-world organizational networks. This approach provides new insights into how well analytical methods can capture diffusion dynamics in social systems.

The model considers two main factors: (1) social interactions among agents, crucial for the spread of energy-related behaviors, and (2) the probability of engagement in a certain behavior. The original model assumed engagement following a logistic function. We propose a modified version where engagement probability is treated as an independent parameter not defined by any specific functional form. The new version can be seen as a general innovation diffusion model that extends beyond pairwise interactions.

The model simulates agents in a social network, where each agent has neighbors defined by the network structure. Interactions between agents allow social influence to shape their decisions. Each agent can either: 1) randomly decide to adopt or reject an innovation, or 2) respond to social influence by conforming to a unanimous group of neighbors or maintaining their previous state. The system evolves through random sequential updating, simulating continuous time. In each update, a randomly chosen agent changes its decision. This process continues until the system stabilizes and reaches a steady state.

We use two analytical methods to analyze the model: Mean-Field Approximation (MFA) and Pair Approximation (PA). These methods are compared with MCS applied to Watts-Strogatz (WS) graphs and organizational networks. The WS graph serves as a controlled environment, allowing us to verify the model implementation and examine how well PA captures diffusion dynamics across different graph parameters. We also validate the model on real organizational networks to examine actual diffusion patterns. By comparing PA and MCS results, we assess the accuracy of analytical methods in predicting adoption dynamics.

The results on the WS graph show that PA provides accurate results when the clustering coefficient is low, but overestimates adoption levels in highly clustered networks. In these cases, we cannot replace the ABM with the analytical approximation. Additionally, the time to reach steady-state adoption levels is longer in clustered networks, showing a "critical slowing-down" effect near phase transitions. This insight is crucial for policymakers and businesses aiming to accelerate green practice adoption within organizations. We also examine organizational networks, where properties such as clustering coefficient and degree distribution, along with global network parameters, help to explain the differences between PA predictions and MC results.

Our study highlights the need to evaluate ABM results with analytical methods and MCS, especially when using real-world data. While PA is useful in less clustered networks, MCS is necessary for accurate predictions in highly structured systems.

Keywords

Agent-based modeling (ABM), Pair approximation (PA), Monte carlo simulations (MCS), Organizational networks, Green practice diffusion

Current status of the research is: Work-in-progress