PiperABM: A Python Library for Resilience-Based Agent Modeling

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Summary

PiperABM is an open-source Python library for building agent-based simulations that couple human behavior with degrading infrastructure on real geospatial layouts. It provides lightweight primitives for agents with a customizable decision loop, infrastructure with spatial graphs whose effective travel costs evolve, and built-in analysis for accessibility to resources and travel distance, plus optional animation. Because it is implemented with familiar scientific tools like NumPy and NetworkX, researchers can inspect and extend models directly, integrate empirical data, and reuse standard workflows. PiperABM targets resilience questions where people's choices and infrastructure conditions co-evolve, and it aims to reduce the setup overhead typical of one-off models while remaining flexible enough for diverse hazards, places, and policies.

Statement of Need

Agent-based models (ABMs) represent systems "from the bottom up" via interacting, heterogeneous agents; macro-level patterns then emerge from local rules and interactions [Joshua M. Epstein (1999); Joshua M. Epstein & Axtell (1996); schelling_2006]. Over the past two decades, ABM has matured from theoretical demonstrations to a practical research method supported by accessible tooling and the scientific Python ecosystem (Hoeven et al., 2025). This paradigm is well-suited to **infrastructure and community resilience**, particularly within the Food–Energy–Water (FEW) nexus, where access to essential resources depends on both physical networks and human decisions, and where nonlinear feedbacks, thresholds, and cascades are common (Cansino-Loeza et al., 2022; Xue et al., 2024; Zhang et al., 2019).

Resilience studies pose several practical modeling needs that are not well served by ad hoc scripts or purely equation-based approaches:

- **Partial service levels and progressive degradation:** Models should represent graded performance (e.g., rougher roads increasing cost/time) rather than only binary failure, reflecting well-studied pavement deterioration processes and performance impacts, e.g., IRI-based assessments (Altarabsheh et al., 2021; Llopis-Castelló et al., 2024).
- **Two-way coupling of behavior and infrastructure:** People adapt routes, priorities, and exchanges as networks evolve; these adaptations, in turn, load and degrade networks. Coupled human–infrastructure ABMs have demonstrated such feedbacks in flood-risk systems and related reviews emphasize capturing co-evolution (Anshuka et al., 2022; Michaelis et al., 2020).
- **Real geospatial layouts for place-based analysis:** Integrating GIS data (maps/satellite-derived inputs) enables site-specific scenarios and stakeholder communication; recent work in the Python ABM ecosystem formalizes GIS ingestion and spatial operations for ABMs (Wang et al., 2022).

41   • **Ensemble experiments and reproducibility:** Parameter sweeps, stochastic replications,
42   and uncertainty and sensitivity analysis require clear, standardized reporting and careful
43   data handling; community guidelines for documenting agent-based models and recent
44   work on calibration and sensitivity analysis support replicable workflows (Grimm et al.,
45   2020; McCulloch et al., 2022; Razavi et al., 2021).
46   • **Custom metrics and analysis pipelines:** Exposing model state in familiar data structures
47   should facilitate domain metrics—e.g., spatio-temporal accessibility to resources under
48   disruption—as used in recent resilience studies (Enderami et al., 2024; Tariverdi et al.,
49   2023).

50 PiperABM is designed around these requirements. It provides **resilience-aware primitives** in
51 a pure-Python library: continuous degradation that inflates effective travel cost; a succinct,
52 pluggable OODA-style policy interface for agent decision-making; first-class **accessibility** and
53 **travel distance** metrics; and utilities for ingesting map/satellite-derived layouts. Results can
54 be recorded compactly with delta encoding to support large ensembles and reproducibility
55 (Noorghasemi & McComb, 2025). By centering behavior–infrastructure co-evolution while
56 remaining extensible, PiperABM enables researchers to formulate hypotheses, run comparative
57 scenarios, and analyze socio-technical feedbacks without rebuilding simulation scaffolding for
58 each new study.

Comparison to Existing Tools

60 We group related work into two domains: (1) general frameworks intended to be reusable
61 across problems, and (2) purpose-built models created for a single, specific study.

Domain 1: General frameworks (Python)

63 Mesa is a widely used general-purpose ABM framework that makes it easy to define agents,
64 schedule steps, collect data, and visualize models in the browser—ideal for rapid prototyping
65 and analysis (Hoeven et al., 2025). Trade-off: domain logic is do-it-yourself; researchers
66 typically hand-roll infrastructure degradation, accessibility metrics, and behavior–infrastructure
67 coupling. `InfraRisk` is an infrastructure-centric Python platform for interdependent networks
68 (power, water, transport) with hazard, cascade, recovery, and resilience modules—strong on
69 network physics and restoration (Balakrishnan & Cassottana, 2022). Human decision-making
70 and accessibility-driven behavior are typically added on top, so tight socio-technical feedbacks
71 can be awkward. `Repast4Py` is a Python interface to an HPC engine for distributed/parallel
72 ABMs; models can run across many cores or machines for large studies (Collier & Ozik, 2022).
73 It does not provide resilience-specific logic (e.g., continuous degradation, accessibility metrics),
74 which the modeler must supply.

75 Like Mesa and Repast4Py, PiperABM stays flexible and Pythonic, but it elevates resilience
76 features to first-class concepts: continuous infrastructure degradation (e.g., rougher roads
77 increasing travel cost), built-in accessibility/travel metrics, a lightweight OODA-style policy
78 interface, geospatial ingestion, and optional animation. Unlike InfraRisk's "network-first with
79 agents layered on," PiperABM starts from coupled behavior–infrastructure dynamics, making
80 socio-technical feedbacks straightforward to model and analyze.

Domain 2: Purpose-built, one-off models

82 Examples include multilayer post-disaster recovery (e.g., Hurricane Harvey) (Xue et al., 2024),
83 RecovUS for household recovery after Sandy (Moradi & Nejat, 2020), storm-induced power-
84 outage restoration with crew dispatch (Walsh et al., 2018), community resilience under tornado
85 hazards (Aghababaei & Koliou, 2023), and flood risk–insurance dynamics (Dubbelboer et
86 al., 2017). These models capture exactly what they need but are hard to reuse and often
87 re-implement similar scaffolding.

88 PiperABM offers the custom feel of bespoke models while reducing rework: degradation and
89 accessibility are built in; OODA-style decision logic [Brehmer (2005); Johnson02012023_ooda]
90 is plug-and-play; infrastructure and agents live on an inspectable NetworkX backend; and
91 results can be analyzed with standard Python tools. This makes it easier to adapt a single
92 codebase to new hazards, geographies, and policies—and to compare scenarios consistently.

Acknowledgements

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