SIM4Action: An Interactive Platform for Social-Environmental Systems Mapping and Causal Analysis

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SIM4Action: An Interactive Platform for Social-Environmental Systems Mapping and Causal Analysis

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Abstract

SIM4Action is an open-source, browser-based platform for participatory analysis of complex socio-environmental systems through interactive causal network graphs. Existing systems mapping tools require practitioners to combine separate software for map construction, network analysis, and causal simulation; none provides an integrated workflow accessible to non-technical stakeholders. SIM4Action addresses this gap through a three-stage adaptive management workflow—Understand, Intervene, Monitor—implemented as dedicated analytical laboratories offering feedback loop detection, community detection, token-based causal diffusion simulation (probabilistic and deterministic modes with forward and backward propagation), multiple centrality metrics for leverage point identification, and a genetic algorithm optimiser for intervention resource allocation. Python's scientific stack runs in-browser via Pyodide/WebAssembly, enabling zero-installation deployment. A domain-agnostic, configuration-driven architecture serves multiple system maps, each defined by a Google Sheets data source and a JSON configuration file; core analytical libraries are independently importable for scripted research pipelines. Co-designed with stakeholders over six years across seven funded projects spanning Australia, Chile, Peru, Finland, and the Western Indian Ocean region, the platform currently hosts over ten deployed system maps spanning fisheries, water governance, lithium extraction, and social welfare domains. This growing, standardised collection of causal models lays the groundwork for a broader research programme: from domain-specific case studies through cross-system structural comparisons toward a *Systems Atlas*—a large-scale repository enabling comparative analysis of socio-environmental complexity across domains, geographies, and scales. A public version is hosted at `https://sim4action.io`.

Keywords: systems mapping, causal analysis, socio-environmental systems, network analysis, participatory modelling, adaptive management

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Metadata

1. Motivation and significance

Understanding complex socio-environmental systems requires tools that bridge the gap between qualitative systems thinking and quantitative network analysis. Researchers, policymakers, and communities increasingly use causal loop diagrams and systems maps to reason about the interconnected dynamics of ecological, economic, social, and governance factors [1, 2]. The systems and complexity sciences have been around since at least the mid-twentieth century, and interest in their application to real-world concerns has come in waves—with notable successes but also false dawns [16]. A persistent obstacle is that complexity science has historically offered one of three unsatisfying options: (i) highly technical 'black-box' modelling inaccessible to non-specialists, (ii) appealing metaphors and language that do not directly lead to action and are often misapplied, or (iii) overwhelming, paralysing complexity that exposes the full intricacy of a system without providing any means to navigate it [16]. In this landscape, causal systems mapping has emerged as a particularly useful "gateway" approach—one that can relatively quickly and straightforwardly capture multicausality, indirect effects, the uncertain boundaries of open systems, feedbacks, and multiple stakeholder perspectives [16]. Yet despite their promise as gateway tools, existing software platforms present significant limitations for applied participatory research, leaving practitioners without an integrated workflow that covers interactive visualisation, causal simulation, and structural network analysis in a single accessible platform.

SIM4Action (Social-Environmental Interactive Mapping Platform for Action) was developed to address this gap. The platform originated in 2020 as a Python/Streamlit application [3] for the ITLA Foundation in Finland, mapping systemic drivers of long-term social assistance use. Between 2020 and 2025, it was iteratively refined through participatory modelling workshops across Humboldt Current fisheries in Chile and Peru, coastal basin ecosystems in central Chile, the Western Indian Ocean, and Australian Commonwealth fisheries—with stakeholders directly shaping which features were built and how they work. During workshops in Chile and the Western Indian Ocean, participants expressed a need to explore and compare the downstream impacts of different intervention strategies on their system maps; this requirement gave rise to the token-based

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Nr.	Code metadata description	Metadata
C1	Current code version	v1.0.0
C2	Permanent link to code/repository	`https://github.com/Sim4Action-Labs/sim4action`
C3	Permanent link to Reproducible Capsule	
C4	Legal Code License	GNU Affero General Public License v3.0 (AGPL-3.0)
C5	Code versioning system used	git
C6	Software code languages, tools, and services used	Python 3, JavaScript (ES6+), HTML5, CSS3, D3.js, NetworkX, Pyodide, Chart.js, Graphology
C7	Compilation requirements, operating environments & dependencies	Python 3.8+; modern browser; NetworkX $\geq$3.0, pandas $\geq$2.0; internet connection
C8	Link to developer documentation/manual	`https://github.com/Sim4Action-Labs/sim4action/blob/main/README.md`
C9	Support email for questions	juan.castillarho@canberra.edu.au

Table 1: Code metadata (mandatory)

Nr.	(Executable) software metadata description	Metadata
S1	Current software version	1.0.0
S2	Permanent link to executables of this version	`https://github.com/Sim4Action-Labs/sim4action/releases/tag/v1.0.0`
S3	Permanent link to Reproducible Capsule	
S4	Legal Software License	AGPL-3.0
S5	Computing platforms/Operating Systems	Web-based (distributed); server runs on Linux, macOS, Microsoft Windows
S6	Installation requirements & dependencies	Python 3.8+, pip (for NetworkX, pandas); modern web browser; internet connection
S7	Link to user manual	`https://github.com/Sim4Action-Labs/sim4action/blob/main/README.md`
S8	Support email for questions	juan.castillarho@canberra.edu.au

Table 2: Software metadata (optional)

causal diffusion simulation that became the core of the Intervention Lab. The centrality-based Monitoring Lab emerged from collaboration with environmental regulators who needed structured approaches to monitoring programme design. In 2025, growing demands for richer interactive visualisation led to a complete re-implementation using web technologies (HTML5, JavaScript, D3.js, Pyodide), producing the current platform.

The software is grounded in the five broad functions that Barbrook-Johnson and Penn [16] identify as the core value proposition of systems mapping: (1) helping us *think* by making assumptions and mental models explicit; (2) helping us *orient* ourselves to a system by seeing positions, connections, and affected parties; (3) helping us *synthesise* disparate types of data, evidence, and stakeholder knowledge into a connected whole; (4) helping us *communicate* by creating shared representations that unearth and challenge assumptions through group discussion; and (5) helping us *extrapolate from assumptions to implications* by tracing the consequences of structural assumptions through formal analysis. A recurring challenge across all five functions is that large causal maps can become 'horrendograms'—overwhelming diagrams that show the full complexity of a system in an unfiltered manner and can paralyse rather than inform decision-making [16]. The core innovation of Participatory Systems Mapping (PSM) as articulated by Barbrook-Johnson and Penn is to address this problem by capturing the full complexity of a system but then using network analysis and the flow of causal chains to create focused submaps that make the complexity practical and actionable without compromising on depth [16]. SIM4Action computationally operationalises this philosophy. First, it enables non-technical stakeholders to interact with complex causal network visualisations through a browser-based interface that requires no installation, supporting the orientation and communication functions. Second, it provides causal simulation capabilities—forward and backward token-based diffusion with temporal delays—that allow users to explore intervention impacts and trace root causes within their system maps, operationalising the extrapolation function. Third, it applies graph-theoretic centrality metrics to inform monitoring programme design, identifying leverage points and sentinel indicators from the network structure—using 'system-suggested' factors (those that network analysis reveals to have interesting structural properties) to complement 'stakeholder-suggested' factors (those that participants identify as important), following the dual approach to analysis advocated by PSM [16].

Users interact with the platform through a three-stage workflow aligned with adaptive management [1]: *understand* the system (structural diagnostics), *design interventions* (causal diffusion simulation), and *monitor outcomes* (centrality-based indicator selection). This workflow was not derived from a theoretical model; it crystallised from repeated observation that workshop participants naturally follow this cognitive sequence—they need to *see* the system structure before they can reason about interventions, and they need to explore interventions before they can decide what to monitor. System maps are loaded from Google Sheets—a familiar interface for participatory workshop participants that gives stakeholders ownership of their data—and rendered as interactive force-directed networks. Each analysis stage is implemented as a dedicated laboratory within the platform.

Barbrook-Johnson and Penn [16] identify three categories of software for participatory systems mapping—general-purpose diagramming tools (e.g., diagrams.net, Miro), network visualisation and analysis software (e.g., Gephi, R/Python packages), and purpose-built platforms (e.g., Kumu, PRSM)—each with characteristic trade-offs. General-purpose diagramming tools are easy to use and produce human-readable maps, but offer no automated analysis; any structural investigation must be done manually, which is time-consuming and error-prone for maps with dozens of factors and hundreds of connections. Network analysis software enables formal computation but requires programming skills that exclude non-technical stakeholders and lacks the interactive, browser-based interfaces needed for participatory workshops. Purpose-built platforms offer appealing interfaces but tend to have limited or no analysis capabilities, and their stability and longevity can be uncertain [16]. In practice, practitioners often need to combine two or more tools—building maps in one, exporting data to another for analysis, and visualising results in a third—introducing friction, data loss, and barriers to real-time participatory use. Several tools support aspects of the analytical workflow required for participatory socio-environmental research, but none integrates the full set of capabilities. Mental Modeler [4] provides a web interface for constructing and running fuzzy cognitive maps via matrix multiplication, but lacks network-level structural analysis (feedback loop enumeration, community detection, centrality metrics) and temporal delay modelling. Kumu [5] offers rich network visualisation but no causal simulation engine or programmatic API, and its proprietary nature limits reproducibility. FCMpy [6] implements fuzzy cognitive map inference and learning algorithms as a Python library but provides no interactive visualisation or web interface, making it inaccessible to non-technical stakeholders in participatory settings. PRSM [7] supports real-time collaborative systems mapping through a web interface but focuses on the mapping process itself and does not include causal diffusion simulation, centrality analysis, or feedback loop detection. Table 3 summarises the key capability differences.

SIM4Action was built because the required combination of capabilities—interactive web-based visualisation, participatory data collection via Google Sheets, two-mode causal diffusion simulation with temporal delays, structural network analysis (feedback loops, community detection, centrality metrics), and a domain-agnostic configuration-driven architecture—is absent from any single existing tool. Its core analytical libraries are standalone modules with zero browser dependencies, ensuring reuse in scripted research pipelines independent of the web interface. The platform includes a comprehensive built-in primer that walks users through systems thinking concepts and the full analytical workflow, lowering the knowledge barrier for non-specialist participants.

2. Software description

2.1. Software architecture

SIM4Action's architecture separates analytical computation from web presentation, enabling both interactive use by non-technical stakeholders and programmatic use in research pipelines. Figure 1 illustrates the platform's layered design and three-stage workflow.

The core computational modules—`browser_analysis.py` (centrality metrics, community detection via NetworkX [8]), `feedback_loops.py` (cycle enumeration and polarity classification), `networkx_loader.py` (graph construction from tabular data), and `diffusion.js` (both diffusion algorithms with delay pipelines)—have zero browser dependencies and are importable in any Python or Node.js environment. A test suite (45 Python + 18 Node.js tests) validates all libraries outside the browser.

Python's scientific stack (NetworkX, pandas) runs directly in the browser via Pyodide [9] and WebAssembly, eliminating server-side compute infrastructure. A single static file server is sufficient for deployment, making the platform viable in low-resource institutional contexts. Google Sheets serves as the data source, providing a familiar collaborative interface for workshop participants and avoiding database administration overhead.

The platform employs a configuration-driven, domain-agnostic architecture: a single codebase in `platform/` serves all system maps, each defined by a JSON configuration file and a Google Sheets data source under `systems/{id}/`. New system maps can be created by non-developers through the web interface. The frontend uses plain HTML5, CSS3, and ES6+ JavaScript with no build step, lowering the barrier for researcher-developers. D3.js [11] renders force-directed network visualisation, Graphology [10] provides client-side graph operations, and Chart.js powers analytical charts.

2.2. Software functionalities

The platform's analytical capabilities are organised into three laboratories corresponding to the adaptive management workflow.

Diagnostics Lab. A causal system map is represented as a directed weighted graph $G = (V, E)$ where nodes represent system factors and edges represent causal relationships carrying three properties: polarity (same-direction or opposite-direction influence), strength (strong, medium, weak), and temporal delay (days, months, years). The lab provides: (1) feedback loop detection via depth-first cycle enumeration with polarity classification (reinforcing vs. balancing loops); (2) community detection using both the Louvain [12] and Girvan-Newman [13] algorithms; and (3) interactive filtering by domain, polarity, strength, and temporal scale.

Intervention Lab. Perturbation propagation is modelled through a token-based causal diffusion framework with two complementary modes. *Probabilistic* (agent-based) diffusion injects discrete tokens at intervention nodes; each token independently selects outgoing edges via weighted random sampling, with polarity-aware charge flipping and configurable delay pipelines. Running N simulations produces Monte Carlo distributions. *Deterministic* (flow-based) diffusion splits continuous flow proportionally across outgoing edges, producing identical results for identical inputs. Both modes support forward propagation (cause→effect) and backward propagation (effect→cause) for root-cause analysis. An integrated genetic algorithm optimiser discovers optimal intervention resource allocations.

Monitoring Lab. The platform currently provides five centrality metrics—degree, betweenness [14], closeness, eigenvector, and Katz—and is extensible to any centrality measure available in the Python scientific stack (NetworkX). Each metric maps to a distinct practical role in monitoring programme design: degree centrality identifies hub variables, betweenness identifies

Capability	SIM4Action	Mental Modeler	Kumu	FCMpy	PRSM
Web interface	✓	✓	✓		✓
Causal simulation	✓	✓		✓	
Temporal delays	✓				
Feedback loop detection	✓				
Community detection	✓				
Centrality metrics	✓				
Forward + backward propagation	✓				
Open source	✓			✓	✓
Programmatic API	✓			✓	

Table 3: Comparison of SIM4Action with existing systems mapping and fuzzy cognitive map tools.

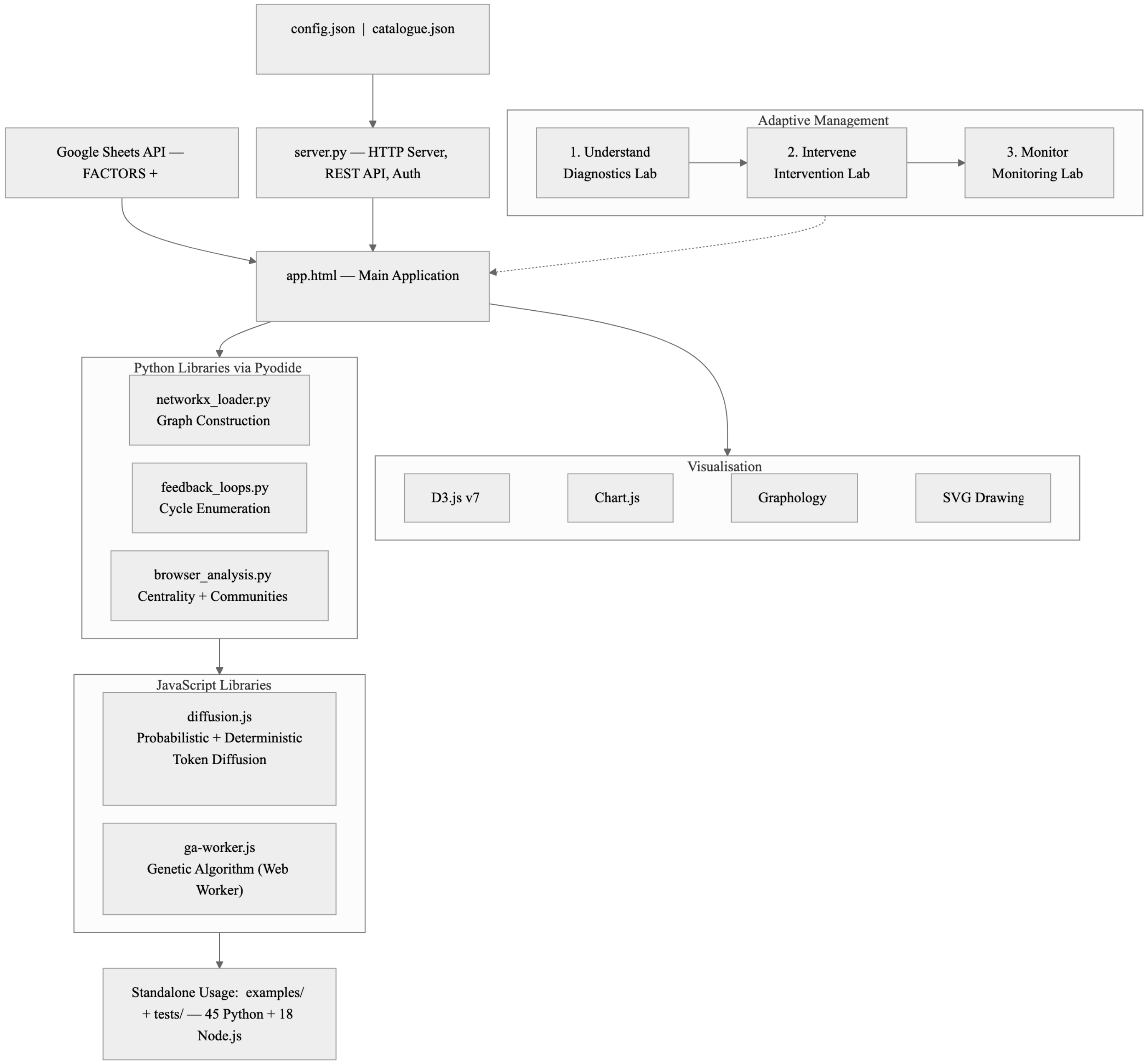

Figure 1: SIM4Action platform architecture. Data flows from Google Sheets and JSON configuration files (top) through the HTTP server to the main application (centre). The three-stage adaptive management workflow drives the interface. Core analytical libraries (bottom) have zero browser dependencies: Python modules run in-browser via Pyodide/WebAssembly; JavaScript diffusion runs natively with a Web Worker for genetic algorithm optimisation. All libraries are independently importable for scripted research pipelines and validated by an automated test suite.

bottleneck variables bridging subsystems, closeness identifies factors with rapid system-wide influence, eigenvector identifies factors connected to the most influential parts of the network, and Katz accounts for both direct and indirect influence with distance attenuation. Combining multiple metrics allows practitioners to distinguish leverage points (prime intervention targets), sentinel indicators (early warning signals), bridge variables (cross-subsystem monitors), and outcome variables (terminal nodes receiving but not propagating influence).

3. Illustrative examples

Consider a typical use case: a fisheries research team analysing the socio-environmental system around the Chilean octopus fishery using a causal map developed through participatory workshops with fishing communities. Figure 2 illustrates the platform interface through the complete workflow.

Stage 1: Understanding the system (Figure 2c–d**)**. The team loads the octopus fishery system map from the platform's catalogue. The force-directed network renders approximately 40 factors across ecological, economic, social, and governance domains. Using the Diagnostics Lab, they filter relationships by polarity to isolate reinforcing feedback loops—identifying, for example, a loop linking fishing effort, catch rates, income, and further investment in fishing effort. Community detection (Louvain algorithm) reveals four clusters corresponding to ecological health, economic viability, governance capacity, and social wellbeing, with bridge edges identifying the critical pathways connecting these subsystems.

Stage 2: Designing interventions (Figure 2e–f**)**. The team uses the Intervention Lab to simulate the downstream effects of strengthening fisheries enforcement. They inject tokens at the "enforcement capacity" node using deterministic mode and observe how increased enforcement propagates through reduced illegal catch, improved stock biomass, and ultimately higher legal catch rates—with temporal delays of months to years visible in the time-series output. Switching to backward propagation from the "stock biomass" node reveals the full set of upstream factors that influence recovery, informing where additional interventions could reinforce the desired outcome. The genetic algorithm optimiser is then used to find the optimal allocation of limited resources across three candidate intervention points to maximise impact on stock recovery.

Stage 3: Monitoring outcomes (Figure 2g–h**)**. The Monitoring Lab applies centrality analysis to recommend which factors to monitor. High-betweenness nodes (e.g., "market access") are identified as critical bridge variables whose disruption would fragment subsystem interactions. High-eigenvector nodes connected to the most influential parts of the network are recommended as sentinel indicators for early detection of systemic shifts.

This three-stage workflow has been applied across all deployed system maps. In the water compliance domain (New South Wales, Australia), the same workflow was used to identify governance bottlenecks: community detection revealed that regulatory and compliance factors formed a distinct cluster weakly connected to on-ground environmental outcomes, while backward diffusion from water quality indicators exposed the upstream governance factors with the strongest causal influence. The consistency of the workflow across domains as different as artisanal fisheries and water regulation supports the platform's domain-agnostic design intent.

4. Impact

SIM4Action's impact extends beyond the code itself: the platform embodies a conceptual framework for operationalising adaptive management through causal network analysis in participatory settings, iteratively refined through six years of real-world deployment (2020–2026) across Australia, Chile, Peru, Finland, and the Western Indian Ocean region. Barbrook-Johnson and Penn [16] note that value from systems mapping can come from both the process of building a map and from the analysis and use of its outputs, and that one must be clear about which source of value one is pursuing. SIM4Action is designed to maximise both simultaneously: the interactive platform generates value *during* workshops (through the discussions, assumption surfacing, and mutual understanding that arise from live exploration) and *after* them (through the persistent, analysable, and re-usable map artefacts it produces).

Enabling new research questions. The platform enables questions that were previously impractical without an integrated tool. Researchers can now ask: "What are the most effective combinations of intervention points to maximise systemic impact given limited resources?" (via the genetic algorithm optimiser), "What upstream factors most strongly drive a target outcome across temporal scales?" (via backward diffusion), and "Which monitoring indicators will provide the earliest warning of systemic change?" (via multi-metric centrality analysis). These capabilities directly address what Barbrook-Johnson and Penn [16] identify as the fifth core function of systems mapping: helping us extrapolate from the assumptions embedded in system maps to their practical implications—following through from the structural and causal beliefs we have encoded to see how they play out. The authors note that people sometimes think of systems mapping as inherently static and unable to do this; indeed, they identify the inability to explore dynamics as "probably the single biggest weakness" of Participatory Systems Mapping [16]. SIM4Action's token-based causal diffusion engine directly addresses this acknowledged limitation: rather than requiring the transition to full System Dynamics modelling (which demands extensive quantitative data and specialist skills), it provides a lighter-weight simulation that traces causal pathways through a participatory map to reveal how structural assumptions propagate to distal outcomes—preserving the accessibility and transparency valued by PSM while adding the dynamic, scenario-exploration capability that PSM on its own cannot offer.

Improving pursuit of existing research questions. In fisheries management, where causal loop diagrams have long been used qualitatively [1], SIM4Action adds quantitative simulation and structural analysis to what was previously a purely visual exercise. Barbrook-Johnson and Penn [16] observe

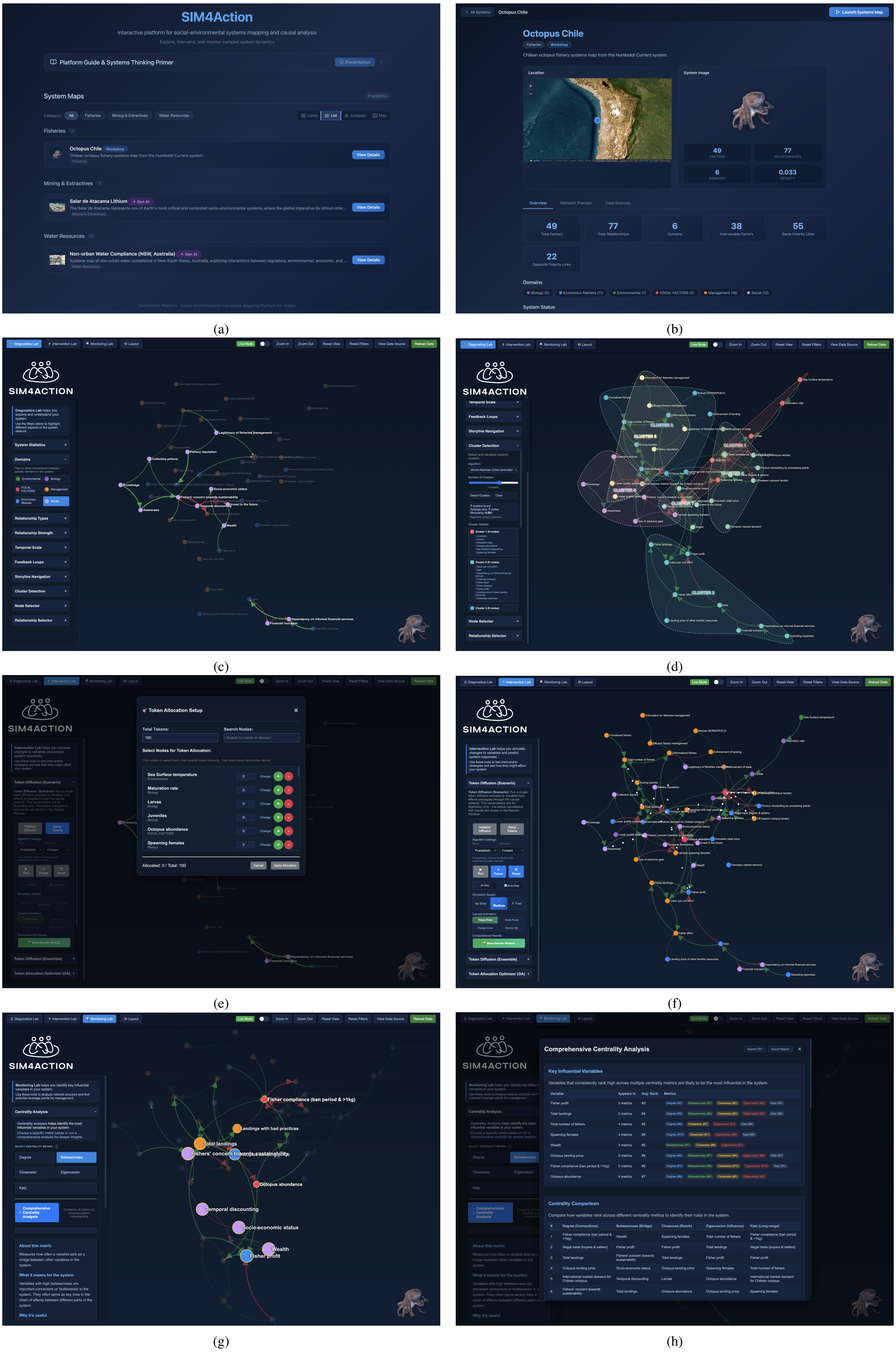

Figure 2: SIM4Action walkthrough: Chilean octopus fishery. (a) Platform catalogue with deployed system maps organised by domain, showing provenance tags (workshop or AI-generated). (b) System detail page: geographic context, structural statistics (49 factors, 77 relationships, 6 domains, density 0.033). (c) Diagnostics Lab: force-directed network with domain colour coding and filter controls for relationship type, strength, temporal scale, and feedback loops. (d) Community detection (Girvan-Newman) partitions the network into seven clusters; biological factors (sea surface temperature, larvae, spawning females) form a distinct subsystem. (e) Intervention Lab: token allocation dialogue for configuring causal diffusion scenarios across candidate intervention nodes. (f) Probabilistic diffusion in progress: tokens propagate via polarity-aware weighted random walks, visualising causal pathways in real time. (g) Monitoring Lab: betweenness centrality with node sizing; high-betweenness factors (e.g., “Total landings”, “Fishers’ concern towards sustainability”) identify bottleneck variables. (h) Comprehensive centrality analysis comparing degree, betweenness, closeness, eigenvector, and Katz metrics across top-ranked factors for leverage point and sentinel indicator identification.

that even when feedback loops are noticed, understood, and discussed in CLDs, it can be difficult to turn this dynamical view of a system into something usable or ‘actionable’—organisational problem-solving cultures that revolve around instrumental ‘button-pushing’ mindsets struggle to translate systemic understanding into concrete decisions. SIM4Action bridges this gap by converting abstract causal structure into tangible scenario outputs: the two diffusion modes address distinct stakeholder needs—probabilistic simulation produces uncertainty bounds familiar to communities accustomed to stochastic natural systems, while deterministic simulation enables the reproducible comparisons required for policy briefing documents. The genetic algorithm optimiser further operationalises the transition from understanding to action by discovering optimal resource allocations across candidate intervention points, directly answering the ‘what should we do?’ question that systems maps alone leave open.

Changing daily practice. The platform has the potential to change how participatory modelling workshops are conducted. Barbrook-Johnson and Penn [16] highlight that one of the biggest headwinds facing systems mapping is the increasingly fast-paced nature of policy work and the shrinking attention windows of stakeholders—where practitioners may have only a half-day, often virtual, rather than the multi-day workshops of earlier decades. This puts immense pressure on methods to deliver value quickly and efficiently. SIM4Action directly addresses this pressure: rather than producing static causal maps as workshop outputs that require post-hoc analysis by researchers, facilitators use the platform during workshops to immediately explore the implications of the maps that participants build—running simulations, identifying feedback loops, and discussing centrality-based monitoring strategies in real time. This matters because, as Barbrook-Johnson and Penn observe, the process of mapping with others unearths a multitude of assumptions that can then be challenged and unpicked; the richness and depth of discussion, while maintaining structure and focus, is often a surprise to first-time participants [16]. SIM4Action amplifies this assumption-surfacing function: when a participant proposes an intervention, the diffusion engine instantly reveals its downstream consequences, making implicit causal beliefs explicit and testable in the moment rather than in a post-workshop report. The SVG drawing layer supports collaborative annotation during facilitated sessions. Workshop participants—including fishers, NGOs, government regulators, and researchers—can interact directly with the network visualisation, testing their intuitions about system behaviour against the simulation results. This immediate analytical feedback can transform workshops from data collection exercises into collaborative analytical sessions where stakeholders co-produce actionable insights.

Deployment breadth. SIM4Action currently hosts over ten causal system maps spanning: Humboldt Current fisheries (octopus, southern hake) in Chile and Peru; Australian Commonwealth fisheries (Southern and Eastern Scalefish and Shark Fishery, Northern Prawn Fishery, Northwest Shelf Trap Fishery) under the Blue Economy CRC Seafood Futures programme; coastal basin ecosystems in central Chile; water resource compliance in New South Wales, Australia; lithium brine extraction from the Salar de Atacama, Chile; and long-term social assistance systems in Finland. The successful application of the same framework across domains as different as artisanal fisheries and lithium mining suggests the generalisability of the underlying conceptual model.

Funded research projects. Development has been supported by seven internationally funded projects: the ITLA Foundation (Finland, 2020); the Walton Foundation through Advanced Conservation Strategies (Chile and Peru, 2021–2024); the Minderoo Foundation and WIOMSA under the HIF-ID Blue programme (Western Indian Ocean, 2023–2025); CSIRO and the Blue Economy CRC with Austral (Australia, 2024–2026); the Natural Resources Access Regulator and UNSW (New South Wales); and Proyecto Anillo through Pontificia Universidad Católica de Chile.

Reuse and extensibility. Barbrook-Johnson and Penn [16] advocate treating system maps as “living documents”—repositories of collective knowledge that can be accessed again and again, updated as understanding evolves, and re-used across projects—and urge practitioners to build in a legacy plan for how maps will be maintained after a project ends. SIM4Action’s architecture embodies this principle structurally. Because system maps are stored in Google Sheets—a familiar, cloud-hosted interface that stakeholder communities already know how to use—maps remain editable by their creators long after a workshop concludes. The configuration-driven design means new system maps can be added without code changes: a non-developer provides a Google Sheets URL and basic metadata through the web interface, and the platform automatically generates the corresponding analytical environment. The standalone analytical libraries (`browser_analysis.py`, `feedback_loops.py`, `diffusion.js`) can be imported into scripted research pipelines independent of the web interface, as demonstrated by working examples in the `examples/` directory and validated by an automated test suite (45 Python + 18 Node.js tests). The platform distinguishes map provenance (`workshop` vs. `gen_ai` source types), supporting emerging hybrid approaches where AI-drafted causal maps are validated through participatory workshops.

Community-driven development. A central tenet of Participatory Systems Mapping is that maps should be ‘owned’ by the stakeholders who create them, rather than by researchers [16]. Barbrook-Johnson and Penn further distinguish between value derived from the *process* of mapping (the discussions, mutual understanding, and knowledge generated during construction) and value from the *outputs* (the map itself and the insights it produces), noting that practitioners often underestimate how much participants gain from the reflective process [16]. SIM4Action was designed with both sources of value in mind. Its features were co-designed with stakeholders who shaped the platform through participatory workshops across seven projects—the three-stage workflow itself emerged from the practical cognitive sequence that workshop participants naturally follow, rather than from a purely theoretical design process. The repository includes contribution guidelines, issue templates, and a public discussion forum to support community engagement beyond the original project teams, ensuring that the platform's evolution remains responsive to practitioner needs.

5. Conclusions

SIM4Action provides an integrated, open-source platform for participatory socio-environmental systems analysis, combining interactive network visualisation, causal diffusion simulation, and graph-theoretic monitoring analysis in a single browser-based tool. Barbrook-Johnson and Penn [16] argue that the philosophy underpinning systems mapping is one of deeply participatory, holistic, and humble engagement with complex adaptive systems—accepting that we cannot force or control these systems, but can work with them to steer and nurture desired change. They observe that current interest in complexity science represents a moment of great opportunity, but also a point at which failure to move beyond previous high-water marks may see interest decline rapidly; what is needed are tools that give these ideas and their practitioners "a foothold on the beach" so that they are not dragged back when the wave of interest inevitably recedes [16]. SIM4Action is designed to be one such tool. Its three-stage adaptive management workflow (Understand, Intervene, Monitor) was co-designed with stakeholders across seven funded projects in Australia, Chile, Peru, Finland, and the Western Indian Ocean over six years, aiming to ensure that the analytical capabilities address real practitioner needs rather than theoretical convenience. The domain-agnostic, configuration-driven architecture has been applied across fisheries, water governance, lithium extraction, and social welfare domains, with over ten deployed system maps. The separation of standalone analytical libraries from the web presentation layer ensures that the computational core is reusable, testable, and scriptable.

By providing a platform where stakeholders can move fluidly from structural understanding through intervention design to monitoring, SIM4Action offers a practical response to the long-standing challenge of making complexity science actionable in real-world participatory settings. It aims to address the three historic pitfalls identified by Barbrook-Johnson and Penn [16]—black-box inaccessibility, metaphorical vagueness, and paralysing complexity—by embedding formal network analysis and causal simulation within an interface designed for non-technical participants, producing outputs that are intended to be simultaneously rigorous and legible. Ongoing development is integrating AI-assisted causal map generation from scientific literature, with early results already showing promising potential to compress the time required to develop baseline causal maps from years to weeks. These AI-drafted maps are validated and refined through participatory workshops, accelerating the initial mapping phase while preserving the community engagement that gives these maps their legitimacy and local relevance.

Beyond map construction, a natural next frontier is embedding AI agents directly into each analytical laboratory. Consider a fisheries management workshop where a facilitator has just loaded a 60-node causal map of an artisanal octopus fishery. In the Diagnostics Lab, an AI agent could examine the network structure and surface observations that human analysts might overlook—flagging, for instance, that two reinforcing feedback loops share a single bottleneck node whose removal would fragment a critical subsystem, or that an isolated cluster of governance factors has no causal pathway to the ecological outcomes it is meant to protect. In the Intervention Lab, the agent could act as an analytical co-pilot: after a stakeholder proposes injecting resources at "enforcement capacity," the agent might note that backward diffusion from the desired outcome reveals three upstream nodes with stronger aggregate influence, suggest an alternative allocation, and explain the trade-offs in plain language—translating network-theoretic results into the decision vocabulary of the room. In the Monitoring Lab, the agent could synthesise centrality results across multiple metrics and recommend a parsimonious set of sentinel indicators, explaining why each was chosen and what early-warning signal it would provide. Critically, such agents would not replace the participatory process but augment it: they would lower the analytical expertise required to extract insight from complex maps, enabling smaller teams and shorter workshops to achieve the depth of analysis that currently demands specialist facilitation. The platform's architecture—with its standalone analytical libraries, structured data model, and browser-based execution environment—provides a ready foundation for this integration, positioning SIM4Action not only as a current analytical tool but as an extensible platform for the emerging generation of AI-augmented participatory systems research.

This paper represents the foundational layer of a broader research programme organised around the platform. The next phase involves detailed, domain-specific case studies—applying the full three-stage workflow to individual socio-environmental systems and evaluating the analytical insights it produces against domain expertise and empirical outcomes. Candidate systems include non-urban water compliance governance in New South Wales (Australia), Humboldt Current artisanal fisheries in Chile and Peru, and lithium brine extraction in the Atacama. Each case study would contribute a rigorously documented system map to a growing, standardised collection. As this collection expands, a third research tier becomes possible: cross-system structural comparisons. With dozens of causal maps expressed in a common graph format and analysed through identical metrics, questions that are currently beyond reach begin to open up. Do certain feedback loop archetypes—reinforcing poverty traps, balancing regulatory cycles—recur across unrelated domains? Are there universal structural signatures in network topology that predict system resilience or fragility? Do governance subsystems consistently exhibit weak causal coupling to the environmental or social outcomes they are designed to influence, regardless of the domain? Does the ratio of reinforcing to balancing loops correlate with a system's susceptibility to regime shifts? The long-term ambition is to develop what we term a *Systems Atlas*: a large-scale, openly accessible repository of participatory causal system models that enables comparative analysis across domains, geographies, and scales—moving from individual system understanding toward a structural science of socio-environmental complexity.

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Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author used Anthropic Claude Opus 4.6 in order to assist with software architecture analysis, manuscript drafting, literature synthesis, and code development. The Perplexity API was used for AI-assisted extraction of causal maps from scientific literature that are included in the public version of the platform. After using these tools, the author reviewed and edited all content thoroughly and takes full responsibility for the content of the published article.

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