Economic Network Modeling: A Graph-Theoretical Framework Linking Micro-interactions to Macro-dynamics

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Abstract

Traditional macroeconomic models often overlook the micro-level interactions through which shocks propagate and macroeconomic phenomena emerge. To address this limitation, this work introduces a novel graph-theoretical framework that formalizes the economy as a dynamical network of interconnected agents.
The methodology establishes an algebraic representation of the system, infers agent behavior from empirical data, and analyzes system convergence and shock diffusion within the network.
As a proof of concept, a computational simulation complemented by an interactive dashboard has been developed, enabling the conceptual exploration of hypothetical scenarios and policy interventions.
By moving beyond aggregate approaches, this framework offers a robust tool for macroeconomic analysis, monitoring, and scenario testing, providing a network-based paradigm for understanding economic complexity.

Keywords: economic networks, behavioral inference, shock propagation, visual analytics.

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Chapter 1

Introduction

1.1 Context and justification of the work

According to the first law of thermodynamics, energy cannot be created or destroyed, only transferred. This physical principle provides a compelling analogy for economics in which one agent's income corresponds to another's expenditure, illustrating monetary circulation. Although the analogy is not exact, since central banks can create money and individuals can burn bills, it still frames the economy as a dynamic system of interconnected agents whose actions are mutually influenced.

Traditional macroeconomic models often simplify this complexity by aggregating flows, overlooking explicit interactions and, consequently, limiting their capacity to analyze propagation effects. This work addresses these limitations by proposing a novel graph-theoretical framework that explicitly links micro-level interactions to macro-level dynamics, providing a richer foundation for understanding how individual behaviors collectively shape macroeconomic phenomena.

Therefore, the fundamental motivation of this thesis is to develop a unified framework to capture and study economic complexity.

1.2 Work objectives

The primary objectives of this research are to propose a new framework for modeling economic environments as a discrete dynamic graph and to design an interactive dashboard for visual analytics as a proof of concept. All this is done with the following specific objectives:

- Develop a graph-based model to represent monetary interactions and agent connectivity.
- Incorporate a novel behavioral inference method to calibrate agent interactions using empirical data.
- Formalize the system's evolution using discrete-time dynamical systems.
- Implement an interactive, real-time dashboard for scenario exploration and analysis.

Together, these objectives establish a cohesive framework that integrates theoretical modeling with practical tools for monitoring and simulating economic systems.

1.3 Impact on sustainability, ethics, and diversity

The proposed framework provides a substantial contribution to sustainable and inclusive economic analysis by explicitly modeling interactions among heterogeneous agents. This approach enables the identification of structural imbalances, contagion risks, and potential distributional inequalities, aligning with the objectives of the 2030 Agenda for Sustainable Development.
Its impact can be articulated across four interrelated dimensions:

- **Economic stability and innovation (SDG 8 & SDG 9).** The framework facilitates the design of policies that cultivate stable and resilient economic growth while introducing methodological innovations that refine decision-making within complex economic systems.
- **Social inclusion (SDG 10).** By representing detailed interactions among agents, the model enables a precise analysis of inequality dynamics and resource flows, supporting interventions that reduce systemic risks and enhance social equity across the population.
- **Ethical governance and accountability (SDG 16).** Complementing the social and economic dimensions, elucidating assumptions and tracing the propagation of shocks reinforce transparency and accountability in economic modeling, thus strengthening confidence in policy-making processes.
- **Diversity and sustainable participation (SDG 5 & SDG 12).** Incorporating heterogeneous agents captures the complexity of real-world economies, allowing the assessment of differentiated impacts and fostering inclusive participation. This strengthens gender equity and aligns with the guiding principle of *leaving no one behind*.

1.4 Focus and method followed

The research adopted an Agile-inspired framework to support iterative development and conceptual validation. Rather than following a linear workflow, the project evolved through iterative cycles consisting of:

- **Objective definition.** Each cycle began by specifying key goals, such as the algebraic modeling of economic networks or the dashboard design.
- **Implementation and validation.** This phase involved the development and preliminary testing of each module to ensure theoretical and computational consistency.
- **Refinement.** The cycle ended with the adjustment of intermediate outcomes based on analytical findings to improve the overall theoretical coherence.

This iterative and modular approach allowed each component to be developed independently, but cohesively, forming a unified analytical framework.
In summary, this Agile-inspired methodology ensured both flexibility and analytical rigor, facilitating the integration of theoretical modeling and computational experimentation.

1.5 Work schedule

			Year	2025															2026			
			Month	09		10				11				12					01			
Task	Start	End	Week	22	29	06	13	20	27	03	10	17	24	01	08	15	22	29	05	12	19	26
M1	25/09/25	12/10/25																				
Document structuring	25/09/25	26/09/25																				
Introduction writing	27/09/25	04/10/25																				
Bibliography review	05/10/25	12/10/25																				
M2	13/10/25	02/11/25																				
Conceptual framework	13/10/25	23/10/25																				
Literature review	24/10/25	29/10/25																				
Benchmarking analysis	30/10/25	02/11/25																				
M3	03/11/25	14/12/25																				
Graph-based modeling	03/11/25	11/11/25																				
Behavioral inference	12/11/25	19/11/25																				
Dynamical approach	20/11/25	30/11/25																				
Dashboard design	01/12/25	14/12/25																				
M4	15/12/25	06/01/26																				
Document draft	15/12/25	28/12/25																				
Audiovisual production	29/12/25	06/01/26																				
M5	07/01/26	30/01/26																				
Thesis submission	07/01/26	09/01/26																				
Defense rehearsal	10/01/26	30/01/26																				

Table 1.1: Gantt chart

1.6 Brief summary of products obtained

This work produces two main outcomes:

- An integrated graph-theoretical framework for economic modeling.
- A functional computational prototype for interactive, real-time visual analytics.

1.7 Brief description of document structure

The remainder of this document is structured as follows:

Chapter 2 reviews the related literature and presents the proposed graph-theoretical approach.

Chapter 3 designs the computational prototype as a proof of concept.

Chapter 4 summarizes key findings and outlines future research directions.

Chapter 5 defines essential technical terms.

Chapter 6 lists the references.

Chapter 7 acknowledges the use of AI-assisted tools throughout the research process.

Chapter 8 outlines three appendices that address individual decision-making, a simplified model, and a hierarchical application.

1.8 Risk assessment and mitigation strategies

The thesis may face certain risks that could affect its timely and successful completion. The most relevant are summarized below.

- **Technical implementation risk.** Compatibility issues between interdependent libraries may disrupt progress.

  The codebase is version-controlled and executed in an isolated virtual environment, with a `requirements.txt` file ensuring stability and reproducibility.

- **Time and schedule adherence risk.** Given the tight timeline defined in the work schedule, any delay could limit revision time.

  Careful planning, weekly milestones, and early completion of key tasks will help ensure on-time delivery.

- **Conceptual and communicative risk.** Translating complex theoretical constructs into an interpretable model may challenge both coherence and accessibility.

  Iterative tutor feedback and visual aids will help maintain conceptual consistency while keeping the content accessible for a non-expert audience.

Chapter 2

Materials and Methods

2.1 State of the art

In recent years, macroeconomic modeling has diversified substantially, giving rise to a variety of approaches that differ in their assumptions and analytical objectives.

To situate this thesis, a structured review of traditional modeling is conducted.

2.1.1 Conceptual framework

Macroeconomic models can be systematically analyzed along three key dimensions: **granularity**, **dynamics**, and **topology** (Jackson, 2008). Together, these dimensions define a conceptual space that enables coherent classification and comparison among modeling approaches.

Granularity refers to the level of disaggregation used to represent the economy:

- **Aggregate.** The economy is treated as a whole.
- **Representative.** Groups of similar agents are aggregated.
- **Individual.** Each agent is modeled explicitly (Gabaix, 2011).

Temporal evolution describes how the system evolves over time:

- **Static.** Equilibrium without explicit temporal evolution.
- **Discrete.** Stepwise evolution capturing short-run adjustments.
- **Continuous.** Smooth evolution over time.

Topology captures the pattern of interactions among agents:

- **Isolated.** Agents act independently.
- **Connected.** Agents influence one another through interactions (Battiston et al., 2016).

Mapping macroeconomic models into this conceptual framework reveals their methodological families, highlighting the mechanisms and scope of different modeling approaches.

2.1.2 Literature review

Building on this framework, the following overview maps canonical macroeconomic paradigms onto the conceptual space defined above, summarizing their core principles and methodological orientation.

Vector Auto-Regression (VAR) Models. VAR models capture empirical correlations between aggregate variables in discrete time. They lack explicit microfoundations or network structure, focusing instead on the statistical propagation of shocks (Sims, 1980).

Computable General Equilibrium (CGE) Models. CGE models simulate aggregated sectors linked by market-clearing conditions. They are typically static, used to assess comparative equilibria under external shocks through indirect interactions (Shoven and Whalley, 1984).

Input-Output (IO) Models. IO models depict a static network of production sectors connected by fixed technical coefficients (Leontief, 1936). They quantify proportional interdependencies and the immediate impact of sectoral shocks.

Stock-Flow Consistent (SFC) Models. SFC models describe aggregated institutional sectors linked by accounting identities in discrete time. Their interconnected balance sheets capture the propagation of monetary and real flows across the system (Godley and Lavoie, 2007).

Overlapping Generations (OLG) Models. OLG models represent successive cohorts of representative agents interacting through capital and labor markets. They evolve discretely, enabling the analysis of intergenerational and long-term policy dynamics (Diamond, 1965).

Dynamic Stochastic General Equilibrium (DSGE) Models. DSGE models build on the intertemporal optimization framework introduced by (Ramsey, 1928), evolving continuously through stochastic shocks with interactions mediated indirectly by market-clearing prices (Woodford, 2003).

Agent-Based Models (ABM). ABMs simulate heterogeneous agents interacting directly within network structures (Epstein and Axtell, 1996). They evolve discretely, generating aggregate outcomes from adaptive, bottom-up behaviors (Simon, 1955; Assenza et al., 2020), which often rely on ad-hoc rules and suffer from computational opacity.

Model	Granularity	Temporal evolution	Topology
VAR	Aggregate	Discrete	Isolated
CGE	Representative	Static	Connected
IO	Representative	Static	Connected
SFC	Representative	Discrete	Connected
OLG	Representative	Discrete	Connected
DSGE	Representative	Continuous	Connected
ABM	Individual	Discrete	Connected
Proposed framework	Individual	Discrete	Connected

Table 2.1: Canonical macroeconomic models within the conceptual framework

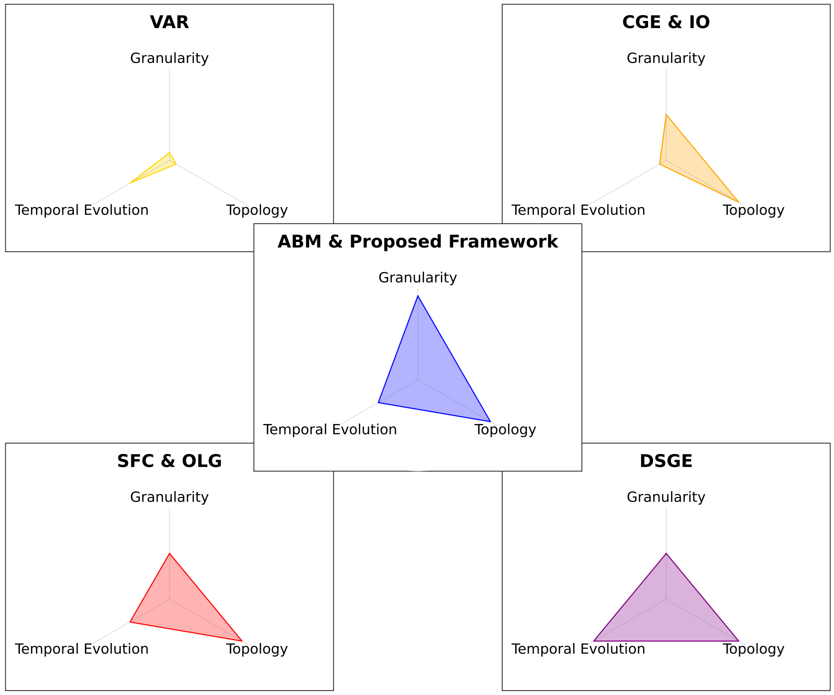


Figure 2.1: Conceptual mapping of macroeconomic canonical models

2.1.3 Proposed framework benchmarking against canonical models

The reviewed paradigms show key limitations, ranging from over-aggregation in traditional models to methodological opacity in canonical ABMs.
To highlight the native applications of the proposed framework relative to canonical macroeconomic models, a benchmarking exercise is conducted across seven key dimensions.

Micro-representation. Modeling macro-dynamics in terms of low-level interactions between heterogeneous individual agents (Gabaix, 2011).

Dynamic study. Analyzing steady states, equilibrium convergence, and scenario simulations using dynamic systems (Elaydi, 2005).

Behavioral inference. Deriving agent behavior from observed empirical data, linking theoretical optimality with empirical measurability.

Visual analytics. Integrating a dynamic, real-time visualization interface for monitoring network topology and monetary flows (Munzner, 2014).

Traceability. Enabling full and consistent traceability that rigorously links aggregate outcomes back to explicit algebraic decision rules and observed behavioral parameters.

Institutional applicability. Designing the framework as an institutional analysis tool and support for decision-making by monetary and supervisory authorities (Battiston et al., 2016).

Computational efficiency. Balancing the complexity of the theoretical formulation with efficient practical implementation.

Dimension	VAR	CGE	IO	SFC	OLG	DSGE	ABM	Proposed framework
Micro-representation	-	-	-	-	-	-	+	+
Dynamic study	+	-	-	+	+	+	+	+
Behavioral inference	-	-	-	-	-	-	-	+
Visual analytics	-	-	-	-	-	-	-	+
Traceability	-	+	+	+	+	+	-	+
Institutional applicability	+	+	+	+	+	+	-	+
Computational efficiency	+	+	+	+	+	+	-	-

Table 2.2: Benchmarking relative to canonical models

Legend: "-" = non-native application; "+" = native application.

Although the proposed framework is conceptually rooted in the ABM paradigm (Table 2.1), the benchmark analysis highlights critical departures from canonical applications. Specifically, the thesis incorporates three key innovations to address traditional ABMs' limitations.

Behavioral inference. Replacing the programming of ad hoc heuristic rules (Simon, 1955) with an inductive inference process grounded in observed empirical data.

Traceability. Solving the computational opacity with an algebraic formulation (Elaydi, 2005).

Visual analytics. Integrating a native visualization interface for real-time monitoring (Munzner, 2014).

Together, these innovations establish the framework as a transparent and auditable policy tool, enhancing its institutional applicability (Battiston et al., 2016).

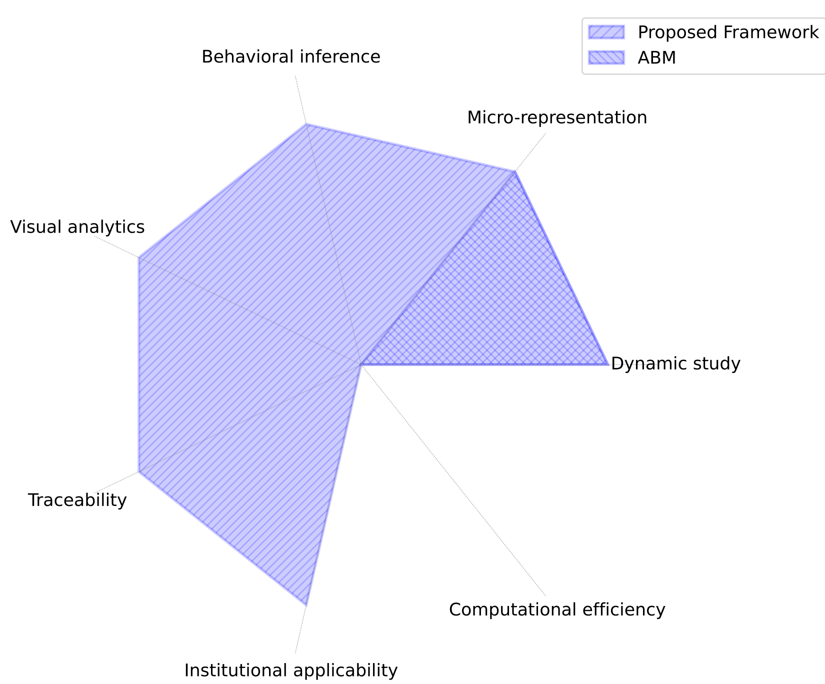


Figure 2.2: Proposed framework innovations over ABMs

2.2 Theoretical framework

2.2.1 Graph-based modeling

Algebraic formulation

An economic network is modeled as a **temporal positive-weighted reflexive complete directed graph** $G(A)$, where:

- $A := \{a_1, a_2, \ldots, a_n\}$ is the set of n agents.
- $A \times A$ is the set of n^2 possible directed edges.

The system is represented algebraically by the time-dependent flow matrix

$$S_t := \left[s_t^{a_i,a_j}\right]_{a_i,a_j \in A} \in \mathbb{R}_{\geq 0}^{n \times n} \quad \forall t \in \mathbb{N},$$

where $s_t^{a_i,a_j}$ denotes the monetary flow from a_i to a_j at time t and diagonal entries $s_t^{a_k,a_k}$ capture the intertemporal savings of $a_k \in A$.

Accounting constraints, roles, and net monetary flow

The accounting constraint is defined as the monetary restriction including both inter-agent and intertemporal transfers for each agent at time t

$$R_t^{a_k} := \sum_{\substack{a_i \in A \\ a_i \neq a_k}} \left[s_t^{a_k,a_i} - s_t^{a_i,a_k}\right] + s_t^{a_k,a_k} - s_{t-1}^{a_k,a_k} \quad \forall a_k \in A, t \in \mathbb{N}.$$

To move beyond the pure conservation of the thermodynamic analogy and model real economic phenomena, agents are classified by the role function $\text{role} : A \to \{\text{destroyer}, \text{neutral}, \text{creator}\}$

$$\text{role}(a_k) = \begin{cases} \text{destroyer} & \text{if} \quad R_t^{a_k} \leq 0, \\ \text{neutral} & \text{if} \quad R_t^{a_k} = 0, \\ \text{creator} & \text{if} \quad R_t^{a_k} \geq 0, \end{cases}$$

embedding their capacity to be either creators or destroyers of money into the model's core.

Building on the agents' individual constraints, the system's net monetary flow is computed as the sum of all their restrictions

$$\Delta S_t := \sum_{a_k \in A} \left[R_t^{a_k}\right] \quad \forall t \in \mathbb{N},$$

quantifying the system's aggregate monetary imbalance according to the agents' roles at each time step.

2.2.2 Behavioral inference

Behavioral inference provides the micro-foundations for the economic network by formalizing agent decision-making processes from empirical data.

Based on continuous flow observation, the analysis of a monitored environment enables the direct deduction of the underlying behavioral parameters and hence the dynamical properties of the system. The inference process is structured in two essential steps.

Discretionary flows identification

Discretionary flows refer to monetary transfers that enter explicitly into the agent's utility function, reflecting decisions driven by individual preferences.
In the absence of a standardized identification procedure in the literature, discretionary flows are recognized through a combination of economic reasoning and institutional context.

The analysis is restricted to the simplified case where each agent has two discretionary flows

$$s_t^{a_k} := \{p_t^{a_k}, q_t^{a_k}\},$$

allowing Euler's equations (EE) to be reformulated in terms of the agents' propensity factor.

Relating via propensity factors

EE determine the optimal ratio between the discretionary flows of each agent

$$EE_t^{a_k} := \frac{p_t^{a_k}}{q_t^{a_k}}, \quad \forall a_k \in A, t \in \mathbb{N}.$$

By economic intuition, the propensity factor, which reflects agents' preferences, can be expressed relative to net income

$$\Omega_t^{a_k} := \frac{p_t^{a_k}}{I_t^{a_k}} \quad \forall a_k \in A,\ t \in \mathbb{N}.$$

From the accounting constraint and the thermodynamic principle of monetary circulation, each agent's net income becomes exactly the sum of its discretionary flows

$$I_t^{a_k} = p_t^{a_k} + q_t^{a_k} \quad \forall a_k \in A, t \in \mathbb{N}.$$

Hence, the propensity factor can be expressed as

$$\Omega_t^{a_k} = \left(1 + \frac{q_t^{a_k}}{p_t^{a_k}}\right)^{-1} \quad \forall a_k \in A, t \in \mathbb{N}$$

and consequently, EE is transformed into

$$q_t^{a_k} = \left(\frac{1}{\Omega_t^{a_k}} - 1\right) p_t^{a_k} \quad \forall a_k \in A, t \in \mathbb{N},$$

characterizing each agent's behavior in terms of its exogenous but observable propensity factor.

2.2.3 Networks as dynamical systems

The dynamical systems approach formalizes the macro-dynamics of the economic network, revealing the patterns emerging from micro-interactions propagation.

Modeling the economy as a dynamical network provides a fundamental analytical basis for examining both the existence and convergence of steady states, as well as the propagation of exogenous shocks through propensity factors.

The propensity factors, inferred from individual agent behavior, are the sole parameters governing the network's evolution, naturally leading to its representation as a discrete-time linear system.

Let the network be represented as a discrete-time linear system

$$x_t = M(\Omega_t)\, x_{t-1} \quad \text{with} \quad M(\Omega_t) := V(\Omega_t)J(\Omega_t)V^{-1}(\Omega_t) \quad \forall t \in \mathbb{N},$$

where x_t denotes the state vector comprising $2 \times n$ agents discretionary flows, V is the matrix of eigenvectors, and J is the Jordan canonical form.

Steady-state existence and convergence

A steady-state is defined as a configuration that remains invariant over time in the absence of exogenous shocks

$$x^* := x_{t-1} = x_t \quad \forall t \in \mathbb{N}$$

and its stability properties are determined by the spectral radius of the system matrix

$$\rho(J) := \max_{\lambda \in \sigma(J)} |\lambda|.$$

From this perspective, different steady states correspond to different qualitative regimes of the economy.
Every linear dynamical system possesses at least the trivial steady-state ($x^* = 0$), the economic collapse. However, if J has at least one diagonal element equal to one, the system also admits a non-trivial steady-state ($x^* \neq 0$), a suitable economic stabilization.

After an exogenous shock, the economic convergence behavior depends critically on its spectral radius:

- If $\rho(J) < 1$, the economy is asymptotically convergent to its collapse $x^* = 0$.
- If $\rho(J) = 1$ with associated Jordan blocks of size one, the economy is non-convergent and does not return to its previous steady-state. Instead, the system transitions towards a new equilibrium.
- Otherwise, the economy becomes unstable.

Therefore, the spectral radius $\rho(J)$ determines the economic network's resilience to shocks, serving as a threshold separating asymptotically contractive, adaptive and unstable while simultaneously establishing the foundation for shock propagation analysis.

Shock Response

The propagation of exogenous shocks through the economic network is analyzed by examining their impact on the system's fundamental propensity factors. This analysis proceeds through the infinitesimal sensitivity of the state vector, enabling the characterization of both local and global transmission mechanisms.

The sensitivity of the state vector to changes in agents' propensity factors is given by its derivative

$$\frac{\partial x_t}{\partial \Omega_t^{a_k}} = \frac{\partial M(\Omega_t)}{\partial \Omega_t^{a_k}} x_{t-1} \quad \forall a_k \in A, t \in \mathbb{N},$$

which yields a first-order approximation for shock propagation

$$x_t\left(\Omega_t + \Delta\Omega_t^{a_k}\right) \approx x_t\left(\Omega_t\right) + \frac{\partial x_t}{\partial \Omega_t^{a_k}} \Delta\Omega_t^{a_k} \quad \forall a_k \in A, t \in \mathbb{N}.$$

and captures the initial and most direct phase of shock diffusion before nonlinear feedback effects emerge.

Beyond local approximations, the full nonlinear response to a finite shock is captured by comparing the perturbed and baseline trajectories.

Building upon this local formulation, the analysis can be extended to evaluate the system's economic behavior across different time horizons.
The overall effect is quantified through two temporal perspectives:

- **Short-term analysis** with a finite horizon impact

$$\Delta x_t = x_t\left(\tilde{\Omega}_t\right) - x_t\left(\Omega_t\right) \quad \forall t \in \mathbb{N}.$$

- **Long-term analysis** with an infinite horizon impact

$$\Delta x_\infty = \lim_{t\to\infty} \left[x_t\left(\tilde{\Omega}_t\right) - x_t\left(\Omega_t\right)\right].$$

As shown before, the eigenstructure of the economic network matrix $M(\Omega_t)$ determines its temporal propagation patterns.
Short-term dynamics are governed by eigenvectors associated with $|\lambda| > 0$, while long-term outcomes are dominated by persistent modes ($|\lambda| \geq 1$).
This decomposition reveals the economic architecture of shock propagation, distinguishing transient disturbances from enduring shifts.

From a policy perspective, this framework offers precise targeting. Short-term interventions should address flows associated with non-zeros modes ($|\lambda| > 0$) for immediate stabilization, while long-term reforms should adjust the persistent modes ($|\lambda| \geq 1$) for resilience.

Collectively, this framework establishes a unified analytical basis for quantifying shock propagation, from initial local transmission to ultimate deep economic consequences.

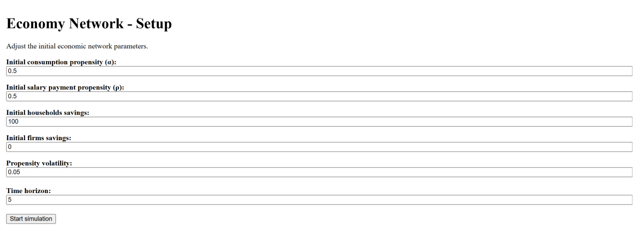
Chapter 3

Results

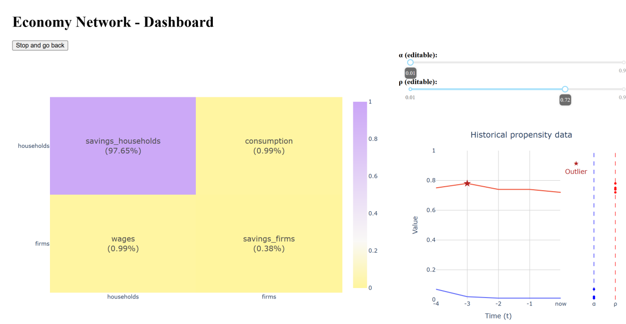
This chapter operationalizes the theoretical framework developed in Chapter 2 by implementing a controlled simulation and a minimal interactive dashboard.

As a proof of concept, an interactive dashboard simulates and monitors a closed economy comprising households and firms. For more details, visit the GitHub repository: `https://github.com/efarran0/Economic_Network/`.

The dashboard features two complementary views: a configuration panel for setting simulation parameters and a monitoring interface that enables real-time observation and intervention during simulation execution.



(a) Setup screen



(b) Visualization screen

Figure 3.1: Dashboard screens

3.1 Model simulation

The simulation implements the theoretical model by assigning each agent a time-varying propensity factor sampled and by initializing the system with a savings vector at $t = 0$.
Discretionary flows are computed according to the behavioral equations derived in section 2.2.2.

$$p_t^{a_k} = \Omega_t^{a_k} I_t^{a_k} \quad \forall a_k \in A,\ t \in \mathbb{N}$$

$$q_t^{a_k} = \left(1 - \Omega_t^{a_k}\right) I_t^{a_k} \quad \forall a_k \in A,\ t \in \mathbb{N},$$

guaranteeing consistency with the accounting constraint derived in section 2.2.1 and ensuring that discretionary flows remain compatible with the algebraic structure of the model.

3.2 Dashboard design

The dashboard provides a minimal yet interpretable interface for real-time economic monitoring, offering three core analytical capabilities:

- Normalized flow visualization for examining monetary circulation patterns.
- Historical time series for propensity factors tracking.
- Interactive controls for scenario testing.

This design enables systematic monitoring of monetary flows, facilitating the detection of economic shocks and emergent network dynamics.

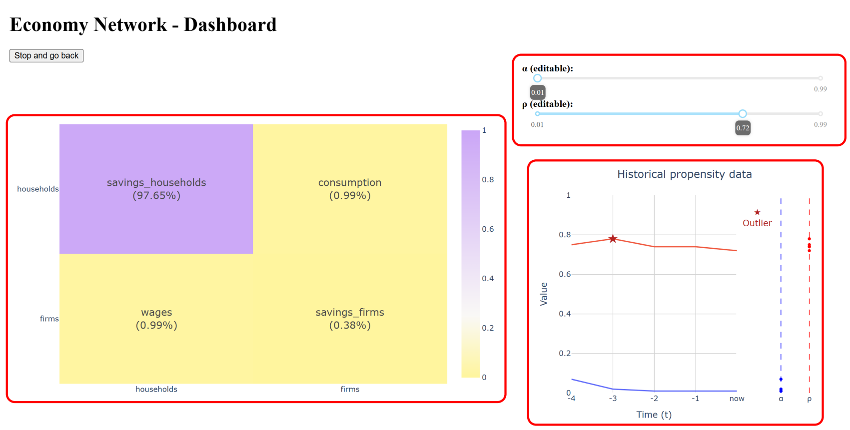


Figure 3.2: Dashboard visualization components

3.2.1 Heatmap

For consistent and interpretable visualization the flow matrix normalizes as

$$\bar{S}_t = \frac{1}{Z_t} s_t^{a_i,a_j} \in \mathbb{R}_{\geq 0}^{n\times n} \quad \forall a_i, a_j \in A,\ t \in \mathbb{N},$$

where the normalization factor $Z_t = \sum_{a_i \in A} \sum_{a_j \in A} \left[s_t^{a_i,a_j} \right]$ bounds all values within $[0, 1]$, enabling automated real-time monitoring within a consistent scale.

The heatmap enables immediate identification of patterns within the economic network, where the chosen color scheme effectively visualizes two key economic behaviors:

- **Monopolistic transit patterns**. Characterized by certain agents channeling disproportionate monetary volumes through the network
- **Hoarder behavior**. Identified through persistent savings accumulation that reduces monetary circulation

These patterns follow naturally from the constraint structure introduced in section 2.2.1.

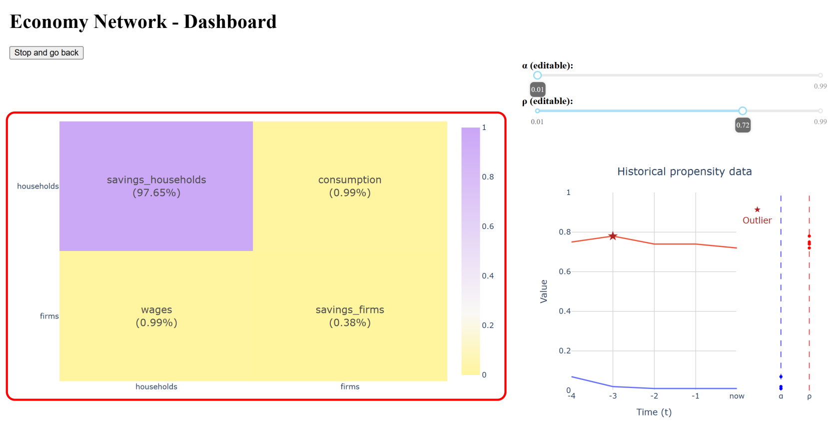


Figure 3.3: Dashboard visualization components: heatmap

Note: The scene illustrates both monopolistic and hoarder patterns in households' savings.

3.2.2 Historical time series

To support behavioral analysis and outlier detection, the dashboard incorporates historical time series visualization of propensity factors.

The implementation employs time series decomposition to isolate trend and stationary components, followed by an interquartile range test at 95% confidence over residuals to identify significant behavioral deviations.

This approach suits economic phenomena where behavioral patterns emerge from calendar events and periodic cycles, enabling distinction between normal fluctuations and significant deviations.

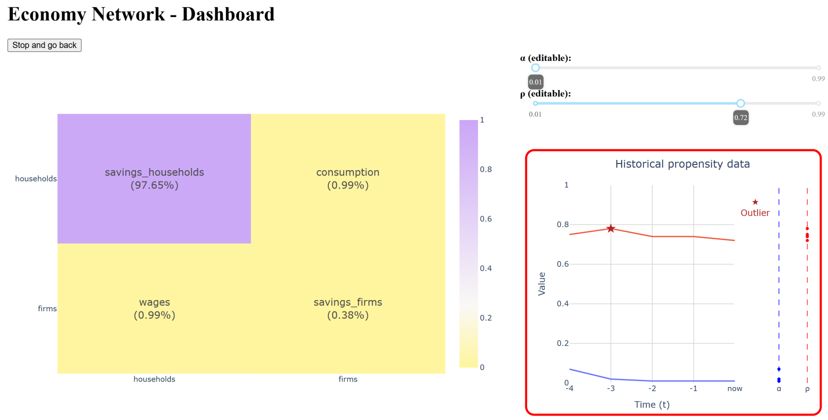


Figure 3.4: Dashboard visualization components: historical time series

3.2.3 Interactive components

Scenario testing enables the interactive adjustment of agent propensity factors through sliders. This component provides an intuitive interface for exploring how micro-level perturbations propagate through the network, complementing the dynamical insights discussed in section 2.2.3.

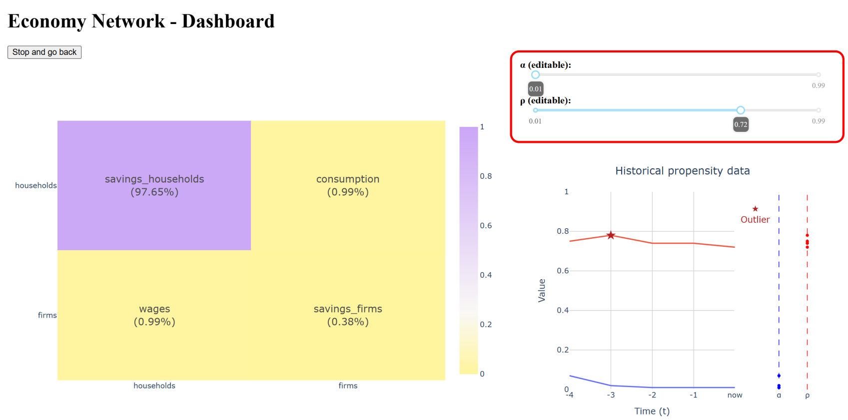


Figure 3.5: Dashboard visualization components: slide-bars

Overall, the results demonstrate that the proposed framework is not only theoretically consistent but also computationally implementable, providing a solid foundation for further theoretical development and future empirical extensions.

Chapter 4

Conclusions and Future Work

4.1 Limitations

4.2 Future work

Chapter 5

Glossary

Chapter 6

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Chapter 7

Acknowledgment of Artificial Intelligence Use

Generative Artificial Intelligence tools were employed to assist the research process, improving efficiency and consistency while preserving scientific integrity. Their use primarily encompassed:

- Academic writing.
- Literature review.

Chapter 8

Appendices