Macroeconomic Agent Based Modelling

Feyzi Can Eser

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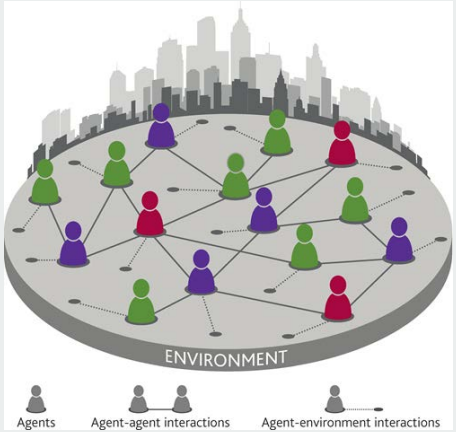
Supervisor: Salvador Navarro Martinez



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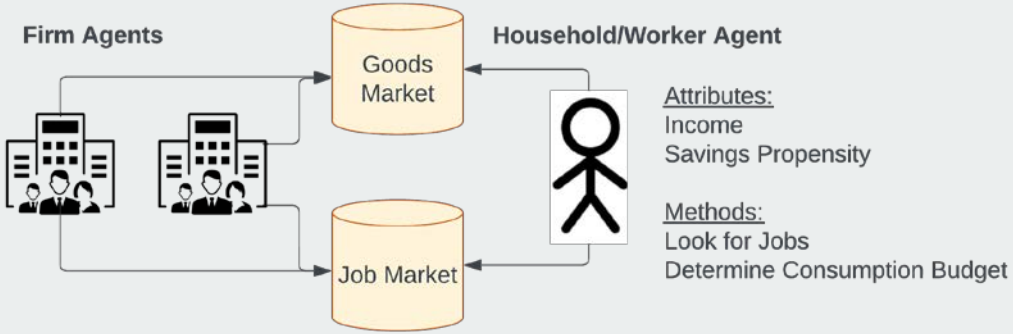
Motivation – Economic Modelling

- Economic Modelling: A computational representation of economic processes
  - Used for predicting effects of various economic policies to aid decision making.
- Why is it difficult?
  - No precise equations that definitively model economic activities
  - Humans have unpredictable behaviour and complex interactions
- What are Macroeconomic Agent Based Models (MABM)?
  - Computational method that simulates the actions and interactions of autonomous agents in order to build a digital economy that reproduces key stylized economic facts found in real life
- Alternatives to MABMs
  - Dynamic Stochastic General Equilibrium models: Model behaviour of a representative agent assuming perfect rationality and market equilibrium.

Background Information - Agents

What is an Agent?

- An autonomous entity that interacts with other agents through specific communication channels, i.e., markets.
- Characterized by attributes and decision making-rules
- In the context of Object-Oriented Programming, an agent is an instance of a class



Background Information – Agent Based Modelling

How are agents useful for Economic Modelling?

- MABMs include lots of heterogenous agents of various types. Their states evolve as they interact with each other. Aggregating individual agent's attributes allows us to observe economic phenomena.
  - E.g., Gross Domestic Product = Sum of spending of all firms, households and government

- Typical Agents: Households, Consumer Firms, Capital Firms, Banks
- Typical Markets: Consumer and Capital Goods Markets, Job Market, Financial and Credit Markets
- Typical Size: Several hundred to several million agents depending on the model

Project Objectives

Main Objectives

1. Develop and build a MABM in C++ that incorporates households, capital firms, consumer firms operating in different sectors, a bank, and the relevant markets for agent interactions, along with CO_2 emission metrics that affect consumer preferences.
2. Validate the model by testing it under various scenarios to show whether it can reproduce key stylised economic facts and whether changes in key economic parameters lead to sensible economic outcomes.

Preliminary Objective

1. Conduct a Literature review on MABMs and gain the necessary expertise to develop the model in C++ with Object-Oriented Programming

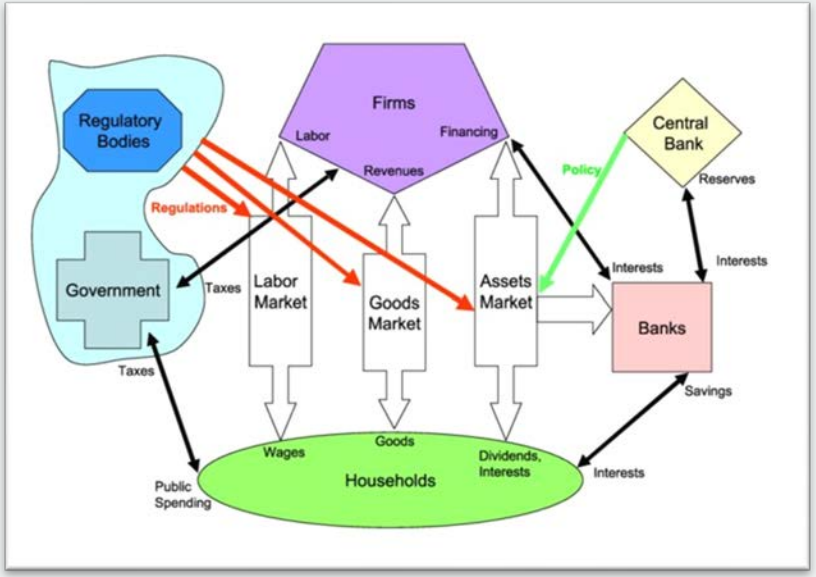
Existing Models in the Literature

EURACE: Model of the EU economy

- Geographical Structure: Agents interact with spatially close agents
- Stock market, Government, Regulators…
- Technological Developments, different production machines for different sectors

Lengnick's Baseline Model (Lengnick, 2013)

- Household and Consumer Firms only
- No technology, no banks, no capital goods/machines for production.



Schematic of the EURACE Model

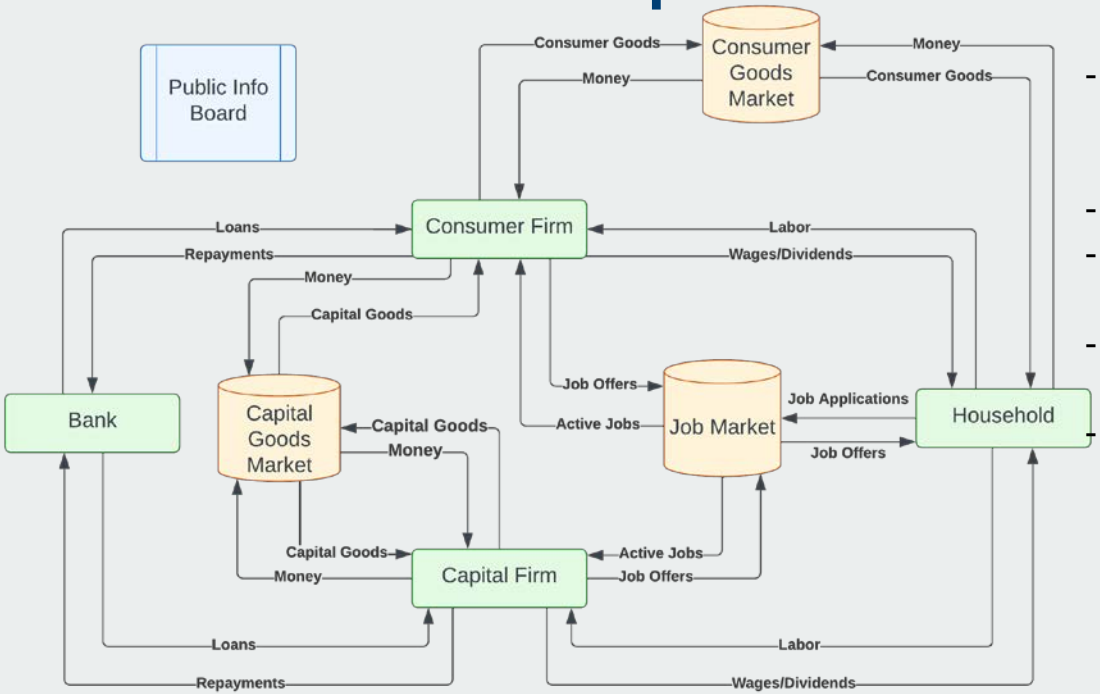
https://www.researchgate.net/publication/287587943_Large-Scale_Modeling_of_Economic_Systems/figures?lo=1

Design Methodology

- Aim for a sufficiently complex model that incorporates some unique features for novelty
- Build a minimum viable model with Households + Firms, Labor and Goods Markets
- Iterate over the design to add complexity: Capital Firms, Consumer Sectors, Banks, Emissions
- *Make all simulation parameters that govern the initialization, main loop, and explicit randomness user customizable
- Run tests to validate model and observe interesting outcomes

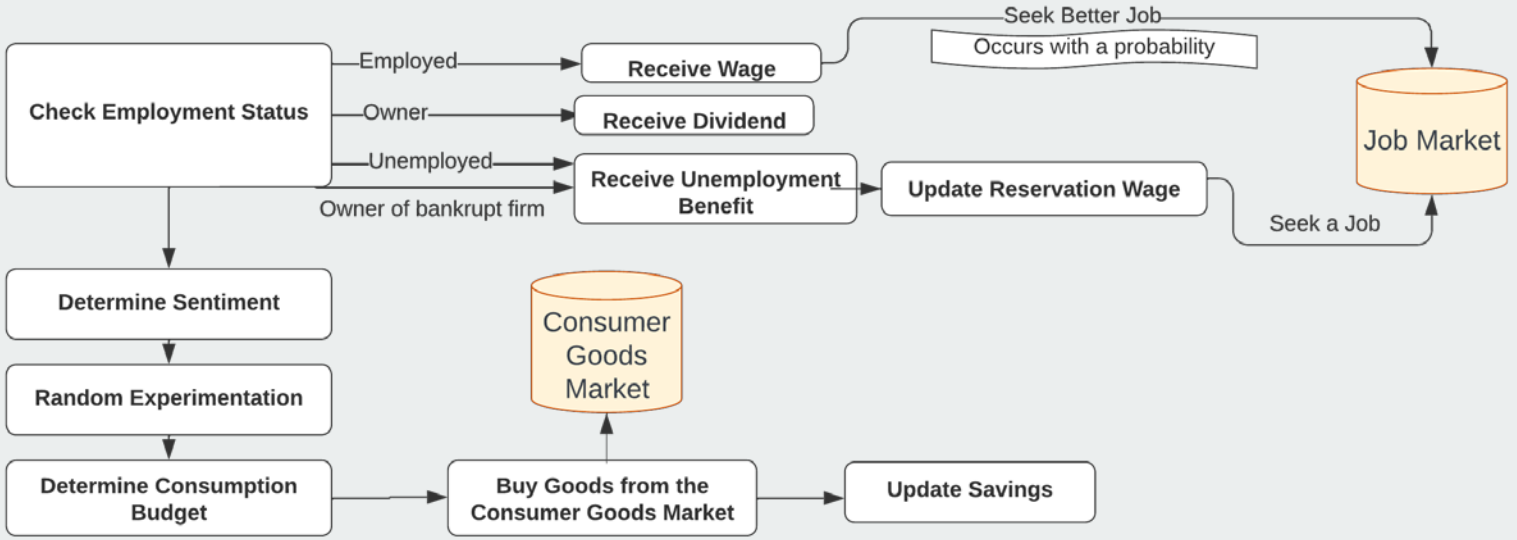
C++ is used as the memory management features allow efficient use of markets and agent interactions

Final Model Description I- Overall Schematic



- **Public Info Board aggregates information** from agents and shares it as needed
- There is a **single Bank**
- No **financial markets** (households can't buy stocks or invest savings)
- **Households** can be **either workers or firm owners**
- **Firms can go bankrupt** and are removed from the simulation and their owners turn to workers

Final Model- Household Actions in each Timestep



Final Model Description II- Equations Used

- Agents' behavioural rules assume bounded rationality and are formed by studying real life data
- We use rules found in various models in the literature with some modifications
- Example Rules:
  - Household Consumption Budget: $C_t = (1-s)I_t + c_f S_{excess} + c_e I_{excess}$

    where C_t: Consumption I_t: Income s: saving propensity S_{excess}: Excess savings I_{excess}: Excess income c_f: propensity to consume excess wealth c_e: propensity to consume excess income

  - Firms' Price Updating Rule:

$$P_{t+1} = P_t\, U_{dist}[1, 1+n_p] \; if \; V < V_{desired} \; and \; P_t < P_{market}$$

$$P_{t+1} = P_t\, U_{dist}[1-n_p, 1] \; if \; V > V_{desired} \; and \; P_t > P_{market}$$

where P_{market} Average market price, P_t: Firm's price, n_p: Random price change upper limit V: inventory

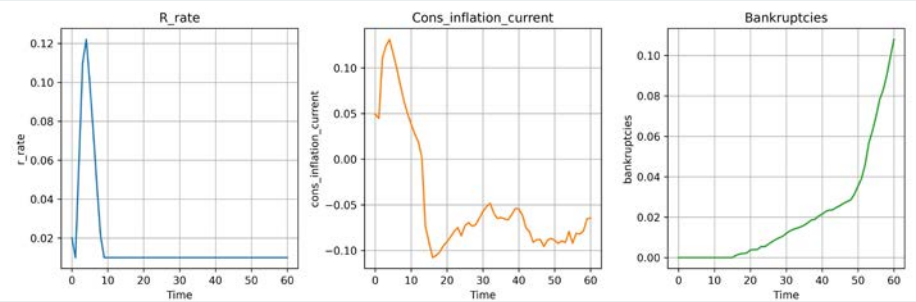
Testing

- We run simulations of various sizes:
  - Large simulations: ~100k agents
  - Medium Simulations: ~ 30k agents
  - Small simulations: ~5k agents

- And of various initialization types:
  - Randomized Simulations: Normally Distributed starting parameters for Agents
  - Uniform Simulations: All agents are created equal

- Some of the most interesting results from the simulatons are shown in the following slides

Validation Tests- Randomized Simulations



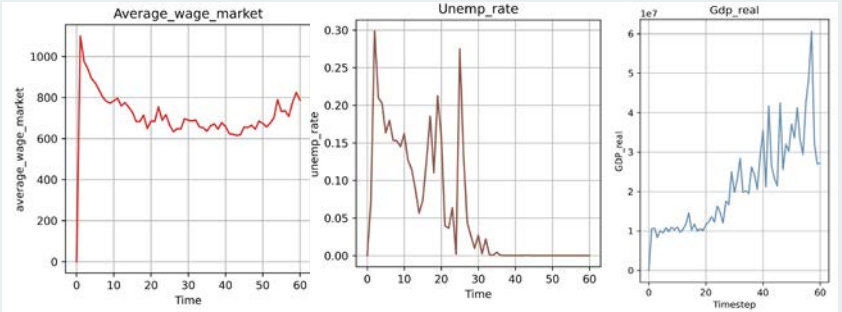
Endogenous business cycles
- Fluctuating but positive GDP growth
- Occasional downturns with GDP contractions
- Random spikes in unemployment

Wages decline as consumer prices decline
Thus real (inflation adjusted) consumer spending growing

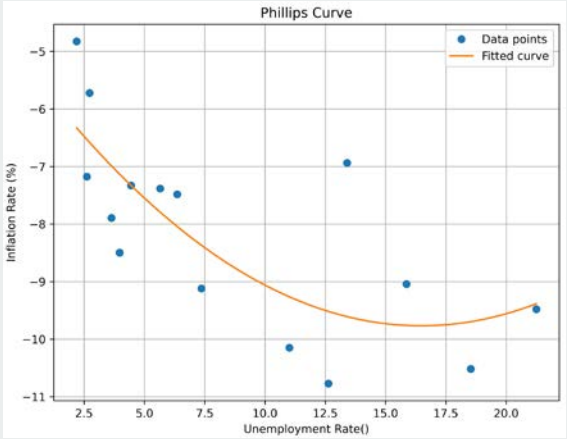
Interest rates zero after inflation turns into deflation

Unemployment settles to zero and is affected by bankruptcies as vacancies always exceed labor supply

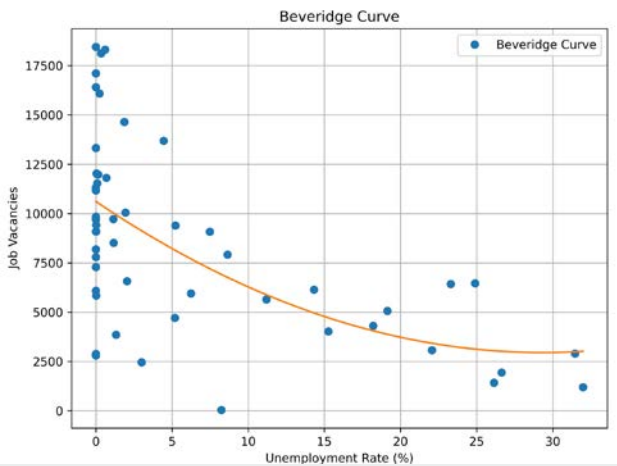
Overall picture similar in regardless of simulation size



Validation Tests - Randomized Simulations

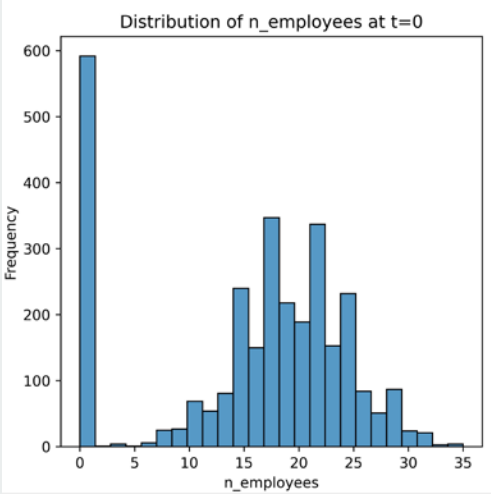


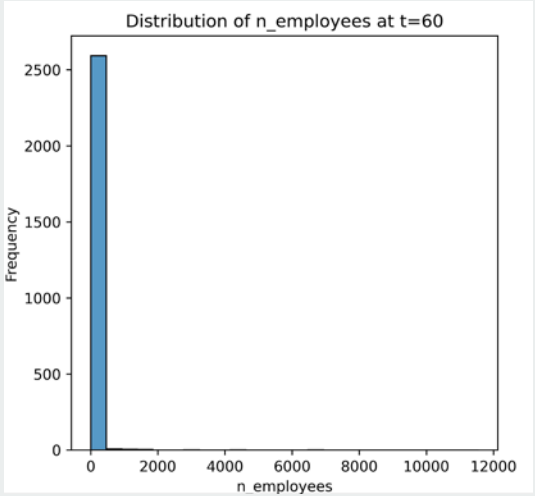
Inverse relationship between unemployment and inflation observed in major deflationary periods
(We look at deflationary periods here as initial positive inflation corresponds to labor market settling in after t=0)



Inverse relationship between job vacancies and unemployment observed
Relationship muddied by the constant zero unemployment at later timesteps

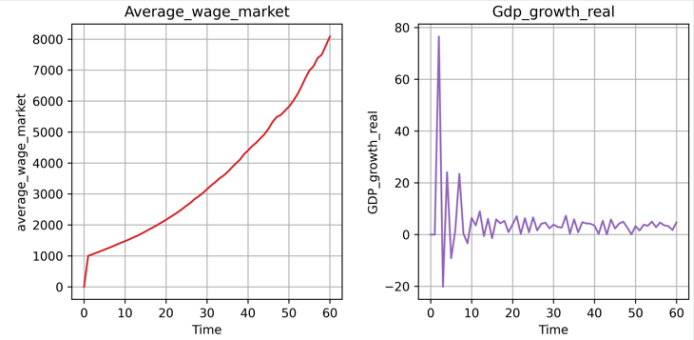
Validation Tests - Randomized Simulation





- Almost all firms end up with a few employees.
- A few large firms emerge (indiscernible in plot)
- Consistent with real life where small firms dominate in number

Validation Tests - Uniform Simulations



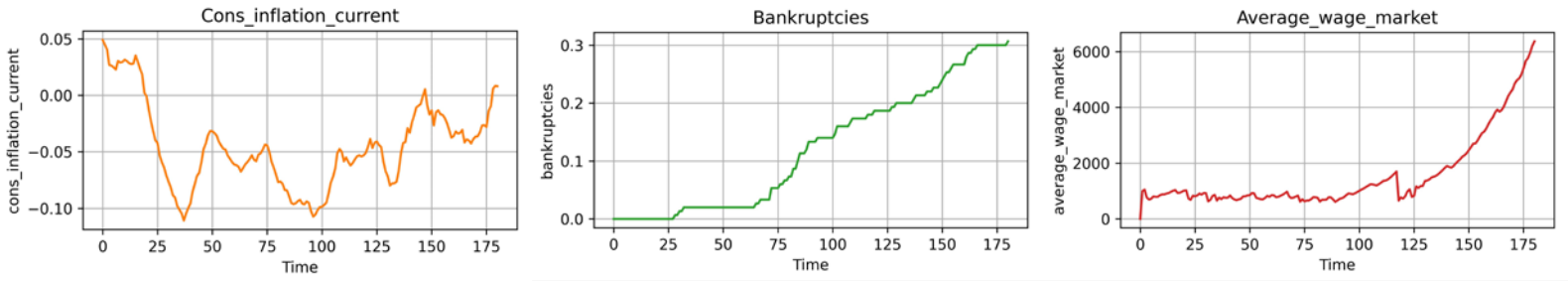
Outcomes are similar to those for the Randomized Simulations except for the Large-scale Uniform Simulation:

- Experiences a huge wage rise spiral
- Nonetheless every other economic indicator behaves very sensibly

Income inequality again forms as some households take better paying jobs by pure change

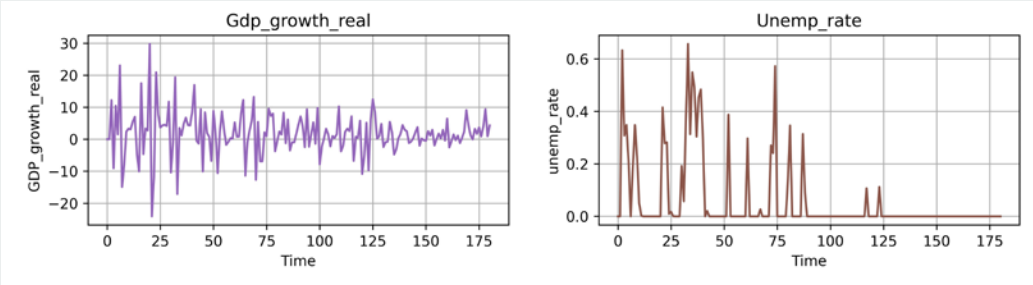
Firm size distribution same as for the Randomized Simulations

Validation Tests - To infinity and beyond?



The system never settles!

Random spikes in unemployment, wage rise spirals, economic recessions : all can arise out of the blue

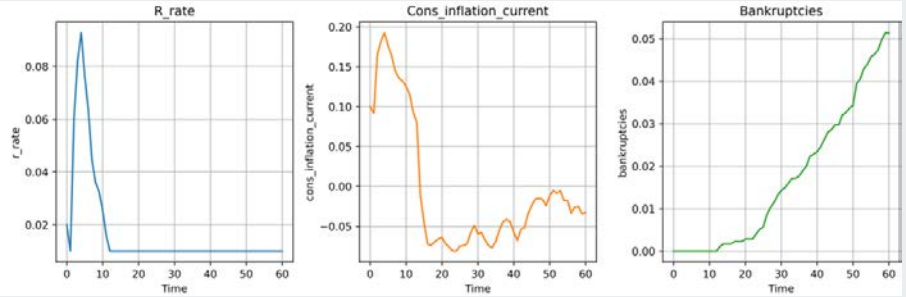


Validation Tests – Effects of Monetary Policy

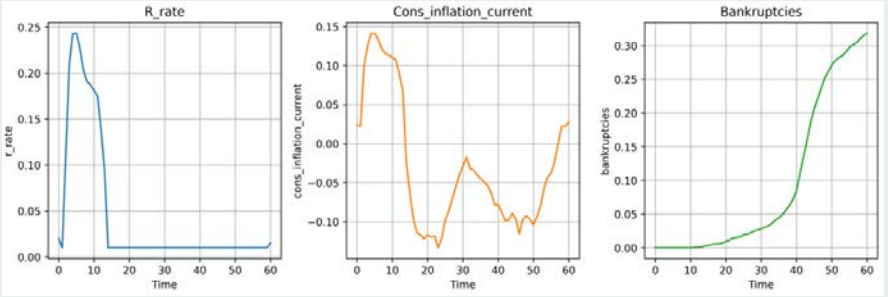
- Monetary Policy: Interest rates, lending criteria, etc.
- How is monetary policy present in the simulation?
  - Bank sets interest rates based on inflation target
  - Interest rate affects firm's loan repayments
  - Lending criteria affects whether risky firms get loans, how much risk premium they pay

- Two Simulations: Lax Policy and Tight Policy
- In the Tight Policy Simulation:
  - Bank has a lower inflation target
  - Responds to inflation more quickly and fiercely
  - Charges more risk premium on loans, and cuts off loans earlier

Validation Tests – Effects of Monetary Policy



Lax Policy



Tight Policy

Tighter policy leads to:

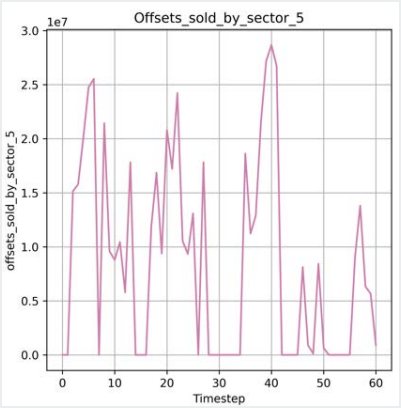
- Bank raising rates higher and faster
- Peak inflation being lower, peak deflation being higher
- Increased Bankruptcies
- Lower vacancies - though unemployment is unchanged due to vacancies till being too high

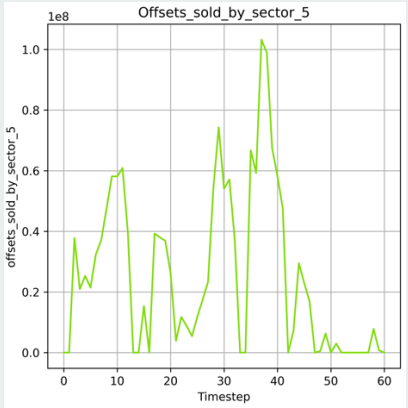
Validation Tests – Effects of Emission Policy

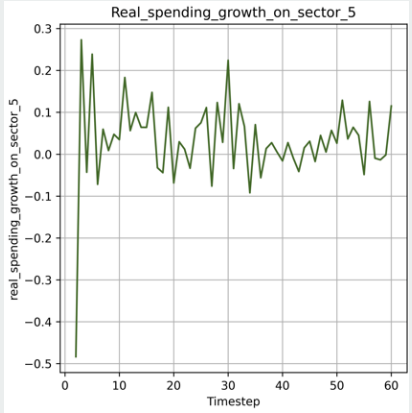
- Emission system in the model works as follows:
  - Each consumer sector has a specific unit production emission
  - Each firm is given an emission allowance in proportion to their past sales
  - Households have emission sensitivities for each sector
  - Households rank goods by emission adjusted prices
  - Firms with high inventories, low prices, and high emissions buy offsets

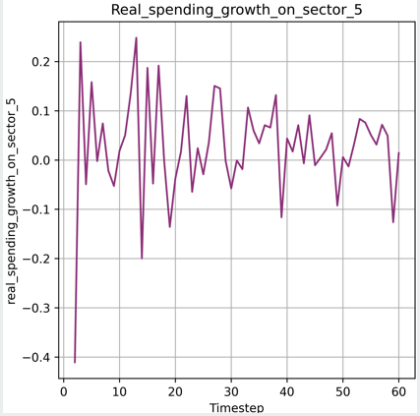
- Two simulations:
  - Uniform Policy Simulation: All consumer sectors face equal unit emissions and sensitivity
  - Non-Uniform Policy Simulation: Some sectors face tighter or laxer criteria

Economic Test 2 – Emission Policy Test









Less Emission Sensitive

More Emission Sensitive

Less Emission Sensitive

More Emission Sensitive

Firms buy more offsets when consumers are more sensitive to their emissions and when their unit emissions are higher

Performance between sectors largely unaffected

- Price growth, bankruptcies, spending growth all show mixed results for different sectors

Discussion

- The model successfully reproduces key stylized economic facts, which are broadly accepted patterns observed in economic data
  - Endogenous business cycles
  - Long run economic growth with fluctuations and downturns
  - Income and Wealth Inequality
  - Fat tailed firm size distributions (Mostly small, very few large firms)
  - Monetary Policy’s effects feed into the system

- Model flexibility via user defined parameters a key feature that increases the model’s potential as a macroeconomic laboratory

Discussion

- Shortfalls:
  - Unemployment settling at zero, whereas it should be 3%-5%
    - Labor market is inherently imbalanced, likely due to imperfect calibration of productivities etc
  - Emission penalties too low to make an impact on sector performances and on the overall economy
  - Lack clear explanations for how significant changes occur (a problem for most MABMs)

- Chaotic System
  - Very sensitive to Parameter Changes
  - Not always size-invariant

Future Work

- Calibration
  - Extensive testing to make simulation as size invariant as real economies, reduce labor demand
  - Deduce rules for how other parameters should change when some other parameter is changed
- Validation
  - Quantitative validation methods for MABMs lacking due to their nature
  - More in depth and systematic testing - Change one parameter at a time, run batch tests, repeat with many simulations
- Emission Features
  - Emission Features were devised based on general research into consumer behaviors as no relevant MABM was found in the literature
  - Additional research needed to find realistic behavioral rules and calibrate values

Future Work

- Additional features to improve model
  - Restrict agent interactions: A worker realistically can’t see all job postings or all goods on market. May make them view random subset, or make past purchases affect future ones
    - Introduces Slack to Markets (Non-zero Unemployment)
  - Technological Development: Firms invest excess profits in increasing future productivity
    - Allow profitable firms to differentiate themselves
    - Crucial for long run simulations
  - Differentiated Workers: Households become more productive in a sector as they work there
    - Income will not be a function of pure chance