Towards an Agent-based Model for the Analysis of Macroeconomic Signals

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Abstract. This work introduces an agent-based model for the analysis of macroeconomic signals. The Bottom-up Adaptive Model (BAM) deploys a closed Walrasian economy where three types of agents (households, firms and banks) interact in three markets (goods, labor and credit) producing some signals of interest, e.g., unemployment rate, GDP, inflation, wealth distribution, etc. Agents are bounded rational, i.e., their behavior is defined in terms of simple rules finitely searching for the best salary, the best price, and the lowest interest rate in the corresponding markets, under incomplete information. The markets define fixed protocols of interaction adopted by the agents. The observed signals are emergent properties of the whole system. All this contrasts with the traditional macroeconomic approach based on the general equilibrium model, where perfect rationality and/or full information availability are assumed. The model is defined following the Overview, Design concepts, and Details Protocol and implemented in NetLogo. BAM is promoted as a toolbox for studying the macroeconomic effects of the agent activities at the service of the elaboration of public policies.

Keywords: Agent-Based Model, Macroeconomic, ODD protocol

1 Introduction

Both in the natural and social sciences, there are complex processes that 1) consist of many agents which interact with each other 2) exhibit emergent global properties, and 3) lack a centralized control governing such properties [1]. Analyzing these systems as a whole is an extremely complicated task, so models are used to describe them. A model is an abstract representation of reality, in which only the relevant characteristics of the system are considered for the analysis.

In economics, the continuous relationship between various agents such as households, companies, banks and the government, generates a large number of macroeconomic signals, such as production, unemployment, inflation, interest rates, among others. In macroeconomics, two approaches are distinguished to model this phenomena, the classical approach (top-down) based on the theory of general equilibrium and a new approach (bottom-up) based on agents [2].

The top-down models rest on the theory of general equilibrium, whose central statement establishes that from the interaction between supply and demand derives a general equilibrium on all markets. An important characteristic of these models is the market clearing condition (Walrasian auctioneer), which is given by a central authority that proposes a set of prices, determines an excess of demand at these prices and adjusts them to their equilibrium values. The roots of this approach go back to the nineteenth century, when many economists tried to formulate a full general equilibrium model, but it was conceived until 1874 by Leon Walras, a French economist [3]. The most recent versions of this model incorporate dynamism (the economic variables consider the expectations of the future), and randomness (as a source of uncertainty) and are called Dynamic Stochastic General Equilibrium (DSGE) models. The solution in this type of models is found when solving systems of equations, e.g., households optimize a utility function subject to a budget constraint, while companies maximize their profit subject to the restriction of technological resources [4].

It is not difficult to notice that one of the main limitations of the model is the assumption of equilibrium, since it is a too simplistic supposition to collect the complexity of economic processes over time. By their conception, the equations of the DSGE models pick up small fluctuations around a stationary state and in this way analyze and predict the signals of the economy. So these models behave well when there are no disturbances. However, when risk and uncertainty come into play, which can alter the behavior of agents, the performance of this approach does not reach a sufficient predictive level that serves as a basis for policy decision making. Another disadvantage is that by the very nature of this approach, modeled through equations, agents are assumed homogeneous, i.e., they have the same information and worse, they have complete information of the system with which they determine their optimal plans. Finally, the Walrasian trial and error mechanism has no counterpart in the real market economy, and goes against the spirit of complex systems, where there is no centralized control.

On the other hand, the bottom-up models conceive complex systems as composed of autonomous interactive agents. Agents base their behavior on simple rules and interact with other agents, which in turn influences their behavior. Two important features of this type of models are that 1) each agent has its own attributes and behavior, i.e., heterogeneity 2) the effects of the diversity among agents can be observed in the behavior of the system as a whole, emergency [5]. Despite their simplicity, these models are not devoid of rationality [2], economic agents guide their behavior to achieve a utility, i.e., instead of coding a specific goal, a measure is defined, allowing the agent to decide what is better for them, e.g., higher salary offered by firms, lower interest rate of banks, better leverage of firms. Although always within the cognitive limitations of the agents.

Bottom-up models do not make assumptions about the efficiency of markets or the existence of an equilibrium, so they can absorb the tensions or disturbances generated in periods of crisis through the emerging behavior resulting from the interaction between agents, in such a way that the panic of agents eventually spreads to the whole system. Finally, these models are non-linear, which implies that the generated effects do not have to be proportional to their causes. This allows to identify the causes in areas that in principle are not related. In some models, the effects can be of a magnitude much greater than the causes that provoke them while in others the effects dissipate in a conventional manner.

The main contribution of the paper is offering a complete and concise, basic Bottom-up Adaptive Model (BAM) based on the work of Delli Gatti et al. [9]. The model is described adopting the Overview, Design concepts, and Details (ODD) protocol [6,7], for the sake of reproducibility. The resulting system is available at Github [4]. The paper is organized as follows: Section 2 introduces the BAM model conceptually, for then offering details accordingly to the ODD Protocol. Section 3 presents the implementation of the model in NetLogo. Section 4 presents results, as well as the empirical validation of the model by fulfilling some stylized facts used in economic theory. Finally, Section 5 presents our conclusions and future work.

2 The BAM model

Despite the criticism for its excessive abstraction, the Walrasian economic model has persisted as a fundamental paradigm [8]. Indeed, because of its simplicity, it is a good starting point for exploring both perfect and imperfect economic models.

The Bottom-up Adaptive Model (BAM) [9] adopted in this paper is Walrasian in nature. As shown in Fig. 1, it is composed by the following types of agents:

- **Households** representing the point of consumption and labor force.
- **Firms** representing the transformation of work in goods and / or services.
- **Banks** providing liquidity to firms if necessary.

A large number of autonomous households, producers and banks operate adaptively in three totally decentralized and interconnected markets:

- A **labor market**, in which each household offers an inelastic unit of work per period, while firms demand depending on their production plans;
- A perishable consumer **goods market**, in which households spend all or part of their wealth and firms offer goods at different prices; and

[4] `https://github.com/alexplatasl/BAMmodel/`

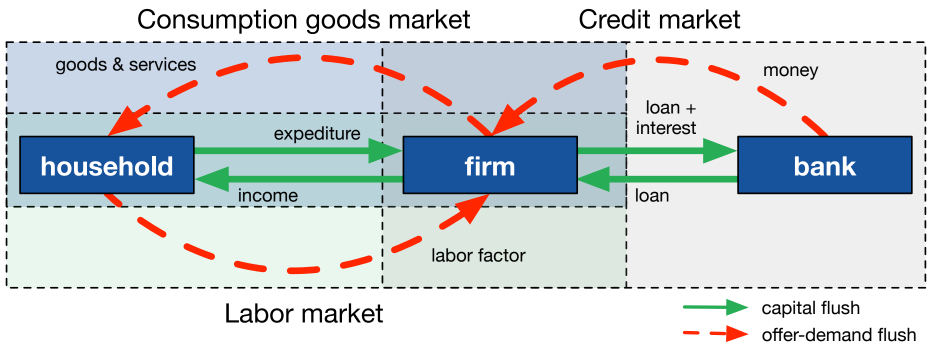

Fig. 1. The Bottom-up Adaptive Macroeconomics Model (BAM).

– A **credit market** in which firms demand money if their resources are insufficient to cover their production expenses, and banks offer money at different interest rates.

Opportunities for exchange in these markets are discovered through a sequential process characterized by optimization, namely, maximizing wages, minimizing the price of goods consumed and minimizing the price of money (interest rate). Firms can modify prices and quantities adaptively given the signals of the inventory and the market price.

BAM was adopted because the agents that intervene in the model are those necessary to model disturbances that are similar to those observed in a real world economy; while generating macroeconomic signals of interest, e.g., inflation, unemployment, wealth, production among others are generated.

As mentioned in the introduction, for the sake of reproducibility, the details of the model will be described following the ODD protocol, which is organized in three parts:

1. **Overview**. A general description of the model, including its purpose and its basic components: agents, variables describing them and the environment, and scales used in the model, e.g., time and space; as well as a processes overview and their scheduling.
2. **Design concepts**. A brief description of the basic principles underlying the model's design, e.g., rationality, emergence, adaptation, learning, etc.
3. **Details**. Full definitions of the involved submodels.

2.1 Overview

Purpose. Exploring the use of the bottom-up approach for the study of macroeconomic signals, particularly the effect of the agent's activities in such signals.

Entities, state variables, and scales.

- Agents: Firms, workers, and banks.
- Environment: Agents are situated in a grid environment which is meaningless with respect to the model. The environment is used exclusively as a visual aid for debugging.
- State variables: The attributes that characterize each agent are shown in Table 1.
- Scales: Time is discrete, e.g., each step represents a quarter.

Table 1. State variables by agent.

Agent	Attribute	Type	Agent	Attribute	Type
	who	Int		who	Integer
	production-Y	Int		employed?	Bool
	desired-production-Yd	Int		my-potential-firms	AgSet
	expected-demand-De	Int		my-firm	Ag
	desired-labor-force-Ld	Int		contract	Int
	my-employees	AgSet	Worker	income	Float
	current-numbers-employees-L0	Int		savings	Float
	number-of-vacancies-offered-V	Int		wealth	Float
	minimum-wage-W-hat	Float		propensity-to-consume-c	Float
Firm	wage-offered-Wb	Float		my-stores	AgSet
	net-worth-A	Float		my-large-store	Ag
	total-payroll-W	Float		who	Int
	loan-B	Float		total-amount-of-credit-C	Float
	my-potential-banks	AgSet		patrimonial-base-E	Float
	my-bank	AgSet	Bank	operational-interest-rate	Float
	inventory-S	Float		interest-rate-r	Float
	individual-price-P	Float		my-borrowing-firms	AgSet
	revenue-R	Float		bankrupt?	Bool
	retained-profits-pi	Float			

Process overview and scheduling. The main loop of the simulation is as follows:

1. Firms calculate production based on expected demand.
2. A decentralized labor market opens.
3. A decentralized credit market opens.
4. Firms produce.
5. Market for goods open.
6. Firms will pay loan and dividends.
7. Firms and banks will survive or die.
8. Replacing of bankrupt firms/banks.

2.2 Design concepts

Basic Principles. The model follows fundamental principles of neoclassical economics [16], since it gives great importance to money in economic processes and also the strategy for determining prices is given considering both supply and demand.

Emergence. The model generates adaptive behavior of the agents, without the imposition of an equation that governs their actions. Macroeconomic signals are also emergent properties of the system.

Adaptation. At each step, firms can adapt price or amount to supply (only one of the two strategies). Adaptation of each strategy depends on the condition of the firm (level of excessive supply / demand in the previous period) and/or the market environment (the difference between the individual price and the market price in the previous period).

Objectives. Agents do not explicitly have an objective, but implicitly they try to maximize a utility or attribute.

Learning. None for the moment.

Prediction. Firms predict the quantities to be produced or the price of the good produced based on the excess of supply/demand in the previous period and the differential of its price and the average price in the market.

Sensing.

- Firms perceive their own produced quantity, good's price, labor force, net value, profits, offered wages; as well as the average market price and the interest rate of randomly chosen banks.
- Workers perceive the size of firms visited in the previous period, prices published by the firms in actual period and wages offered by the firms.
- Banks perceive net value of potential borrowers in order to calculate interest rate.

Interaction. Interactions among agents are determined by the markets:

- In the labor market, firms post their vacancies at a certain offered wage. Then, unemployed workers contact a given number of randomly chosen firms to get a job, starting from the one that offers the highest wage. Firms have to pay the wage bill in order to start production. A worker whose contract has just expired applies first to his/her last employer.

- Firm can access to a fully decentralized credit market if net worth are in short supply with respect to the wage bill. Borrowing firms contact a given number of randomly chosen banks to get a loan, starting from the one which charges the lowest interest rate. Each bank sorts the borrowers' applications for loans in descending order according to the financial soundness of firms, and satisfy them until all credit supply has been exhausted. The contractual interest rate is calculated applying a mark-up on an exogenously determined baseline interest rate. After the credit market is closed, if financial resources are not enough to pay for the wage bill of the population of workers, some workers remain unemployed or are fired.
- In goods market, firms post their offer price, and consumers contact a given number of randomly chosen firms to purchase goods, starting from the one which posts the lowest price.

Stochasticity. Elements that have random shocks are:

- Determination of wages when vacancies are offered (ξ).
- Determination of contractual interest rate offered by banks to firms (ϕ).
- The strategy to set prices (η).
- The strategy to determine the quantity to produce (ρ).

Collectives. Markets configure collectives of agents as described above. They include labor, goods, and credit markets. In addition, firms and consumers are categorized as rich and poor.

Observation. Along simulation are observed:

- Logarithm of real GDP.
- Unemployment rate.
- Annual inflation rate.
- Interest rate.

At end of simulation are computed:

- Philips curve (inflation / unemployment).
- Distribution of the size of firms.
- Distribution of wealth of households.
- Growth rate of real GDP.

2.3 Details

Initialization. The initialization parameters described in Delli Gatti [9] was adopted. For the values not provided in the text, they were obtained through experimentation. Table 2 shows the initial values of the model.

Table 2. Parameters initialization.

	Parameter	Value
I	Number of consumers	500
J	Number of producers	100
K	Number of banks	10
T	Number of steps	1000
C_P	Propensity to consume of poorest people	1
C_R	Propensity to consume of richest people	0.5
σ_P	R&D investment of poorest firms	0
σ_R	R&D investment of richest firms	0.1
h_ξ	Maximum growth rate of wages	0.05
H_η	Maximum growth rate of prices	0.1
H_ρ	Maximum growth rate of quantities	0.1
H_ϕ	Maximum amount of banks' costs	0.1
Z	Number of trials in the goods market	2
M	Number of trials in the labor market	4
H	Number of trials in the credit market	2
$\hat{w}$	Minimum wage (set by a mandatory law)	1
P_t	Aggregate price	1.5
δ	Fixed fraction to share dividends	0.15

Input data. None, although data from real economies might be used for validation.

Submodels.

1. Production with constant returns to scale and technological multiplier: $Y_{it} = \alpha_{it} L_{it}$, s.t., $\alpha_{it} > 0$.
2. Desired production level Y^d_{it} is equal to the expected demand D^d_{it}.
3. Desired labor force (employees) $L^d_{it} = Y^d_{it}/\alpha_{it}$.
4. Current number of employees L^0_{it} is the sum of employees with and without a valid contract.
5. Number of vacancies offered by firms $V_{it} = max(L^d_{it} - L^0_{it}, 0)$.
6. $\hat{w}_t$ is the minimum wage determined by law.
7. If there are no vacancies ($V_{it} = 0$), wage offered is $w^b_{it} = max(\hat{w}_t, w_{it-1})$.
8. If $V_{it} > 0$, wage offered is $w^b_{it} = max(\hat{w}_t, w_{it-1}(1 + \xi_{it}))$.
9. ξ_{it} is a random term evenly distributed between $(0, h_\xi)$.
10. At the beginning of each period, a firm has a net value A_{it}. If total payroll to be paid $W_{it} > A_{it}$, firm asks for loan $B_{it} = max(W_{it} - A_{it}, 0)$.
11. For the loan search costs, it must be met that $H < K$
12. In each period the k-th bank can distribute a total amount of credit C_k equivalent to a multiple of its patrimonial base $C_{kt} = E_{kt}/v$, where $0 < v < 1$ can be interpreted as the capital requirement coefficient. Therefore, the v reciprocal represents the maximum allowed leverage by the bank.
13. Bank offers credit C_k, with its respective interest rate r^k_{it} and contract for 1 period.

14. If $A_{it+1} > 0$ the payment scheme is $B_{it}(1 + r^k_{it})$.
15. If $A_{it+1} \leq 0$, bank retrieves R_{it+1}.
16. Contractual interest rate offered by the bank k to the firm i is determined as a margin on a rate policy established by Central Monetary Authority $\bar{r}$, s.t., $R^k_{it} = \bar{r}(1 + \phi_{kt}\mu(\ell_{it}))$.
17. Margin is a function of the specificity of the bank as possible variations in its operating costs and captured by the uniform random variable ϕ_{kt} in the interval $(0, h_\phi)$.
18. Margin is also a function of the borrower's financial fragility, captured by the term $\mu(\ell_{it})$, $\mu' > 0$. Where $\ell_{it} = B_{it}/A_{it}$ is the leverage of borrower.
19. Demand for credit is divisible, i.e., if a single bank is not able to satisfy the requested credit, it can request in the remaining $H - 1$ randomly selected banks.
20. Each firm has an inventory of unsold goods S_{it}, where excess supply $S_{it} > 0$ or demand $S_{it} = 0$ is reflected.
21. Deviation of the individual price from the average market price during the previous period is represented as: $P_{it-1} - P_{t-1}$
22. If deviation is positive $P_{it-1} > P_{t-1}$, firm recognizes that its price is high compared to its competitors, and is induced to decrease the price or quantity to prevent a migration massive in favor of its rivals; and vice versa.
23. In case of adjusting price downward, this is bounded below P^l_{it} to not be less than your average costs:

$$P^l_{it} = \frac{W_{it} + \sum_k r_{kit} B_{kit}}{Y_{it}}$$

24. Aggregate price P_t is common knowledge, while inventory S_{it} and individual price P_{it} are private.
25. Only the price or quantity to be produced can be modified. In the case of price, we have the following rule:

$$P^s_{it} = \begin{cases} \max[P^l_{it}, P_{it-1}(1 + \eta_{it})] & \text{if } S_{it-1} = 0 \text{ and } P_{it-1} < P \\ \max[P^l_{it}, P_{it-1}(1 - \eta_{it})] & \text{if } S_{it-1} > 0 \text{ and } P_{it-1} \geq P \end{cases}$$

    where: η_{it} is a randomized term uniformly distributed in the range $(0, h_\eta)$ and P^l_{it} is the minimum price at which firm i can solve its minimal costs at time t (previously defined).
26. In the case of quantities, these are adjusted adaptively according to the following rule:

$$D^e_{it} = \begin{cases} Y_{it-1}(1 + \rho_{it}) & \text{if } S_{it-1} = 0 \text{ and } P_{it-1} \geq P \\ Y_{it-1}(1 - \rho_{it}) & \text{if } S_{it-1} > 0 \text{ and } P_{it-1} < P \end{cases}$$

    where ρ_{it} is a random term uniform distributed and bounded between $(0, h_\rho)$.
27. Total income of households is the sum of the payroll paid to the workers in t and the dividends distributed to the shareholders in $t - 1$.

28. Wealth is defined as the sum of labor income plus the sum of all savings SA of the past.
29. Marginal propensity to consume c is a decreasing function of the worker's total wealth (higher the wealth lower the proportion spent on consumption) defined as:

$$c_{jt} = \frac{1}{1 + \left[\tanh\left(\frac{SA_{jt}}{SAt}\right)\right]^{\beta}}$$

where SA_t is the average savings. SA_{jt} is the real saving of the j -th consumer.
30. The revenue R_{it} of a firm after the goods market closes is $R_{it} = P_{it}Y_{it}$.
31. At the end of t period, each firm computes benefits π_{it-1}.
32. If the benefits are positive, shareholders receive dividends $Div_{it-1} = \delta\pi_{it-1}$.
33. Residual, after discounting dividends, is added to net value from previous period A_{it-1}. Therefore, net worth of a profitable firm in t is:

$$A_{it} = A_{it-1} + \pi_{it-1} - Div_{it-1} \equiv A_{it-1} + (1-\delta)\pi_{it-1}$$

34. If firm i accumulates a net value $A_{it} < 0$, it goes bankrupt.
35. Firms that go bankrupt are replaced with another one of size smaller than the average of incumbent firms.
36. Non-incumbent firms are those whose size is above and below 5%, the concept is used to calculate a more robust estimator of the average.
37. Bank's capital:

$$E_{kt} = E_{kt-1} + \sum_{i \in \Theta} r_{kit-1} B_{kit-1} - BD_{kt-1}$$

38. Θ is the bank's loan portfolio, BD_{kt-1} represents the portfolio of firms that go bankrupt.
39. Bankrupted banks are replaced with a copy of one of the surviving ones.

3 Implementation

The BAM model was implemented in Netlogo [10]. Fig. 2 shows the right side of the resulting GUI that allows the initialization of parameters and provides a view of the agents in a grid environment. As mentioned, the spacial issues in this view are meaningless, but the output is useful for debugging the system: Blue factories are the firms, red houses are the banks, green humans are employed workers while yellow ones are unemployed. Workers group around the firms where they work and shop. Factories display the number of employees.

4 Results

With the initial configuration of the parameters proposed by Delli Gatti et al. [9], the macroeconomic signals exemplified in Fig. 3 are produced. This output

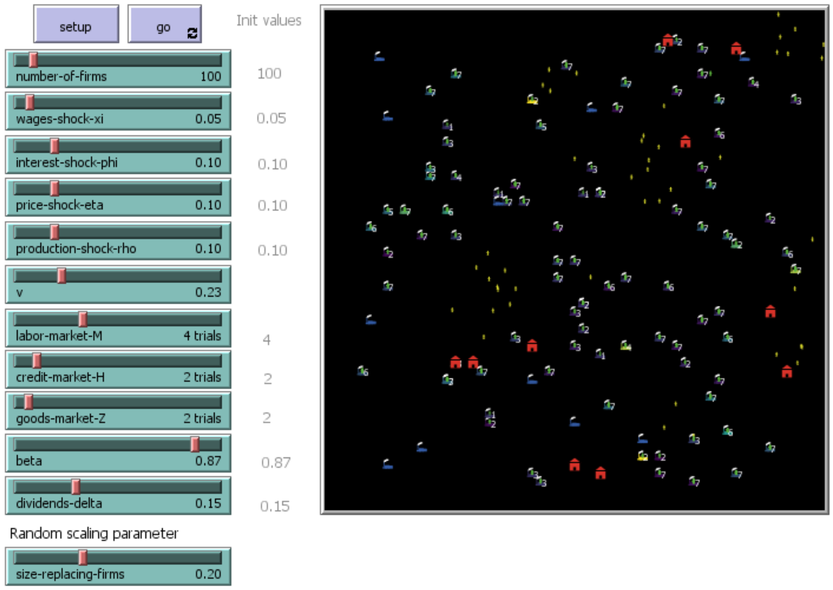

Fig. 2. The BAM model GUI: Parameters and view of the world.

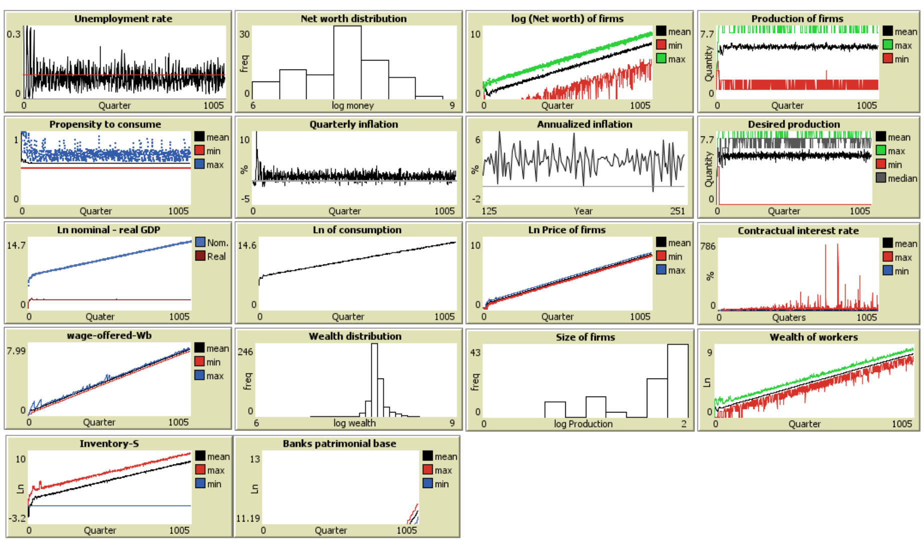

Fig. 3. The BAM model GUI: Macroeconomic signals.

reflects a stable fictitious economy, with unemployment rate close to 10% and moderate inflation in the range of 1 to 6%. In the next subsection, some stylized facts that theoretically should show these signals will be tested.

At the micro level, validation consists of verifying the existence of stylized facts concerning statistical distributions of state variables at an individual level [9]. Wealth and net worth in our case are characterized by a positive skew, which implies that there are few agents that become rich (Figure 4).

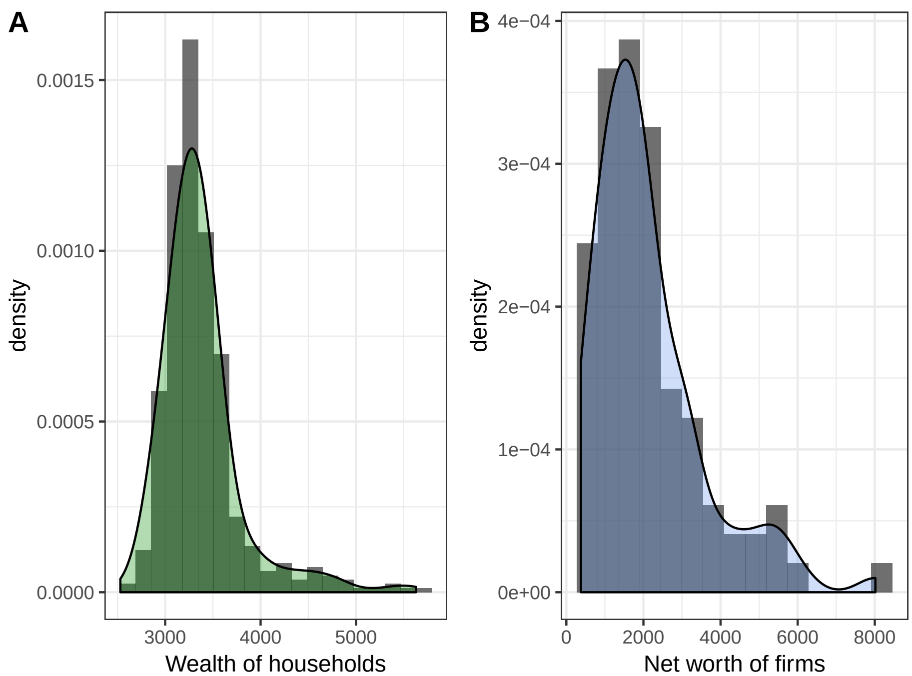

Fig. 4. Examples of our distribution of wealth (A) and net value (B) of a selected run.

To prove that the distributions of wealth of 100 independent runs have a positive skew (Figure 5), level of skew was calculated with the method described by Joanes and Gill [11]:

$$b_1 = \frac{m_3}{s^3} = \left(\frac{n-1}{n}\right)^{3/2} \frac{m_3}{m_2^{3/2}} \ . \tag{1}$$

where,

$$m_r = \frac{1}{n} \Sigma (x_i - \bar{x})^r \ . \tag{2}$$

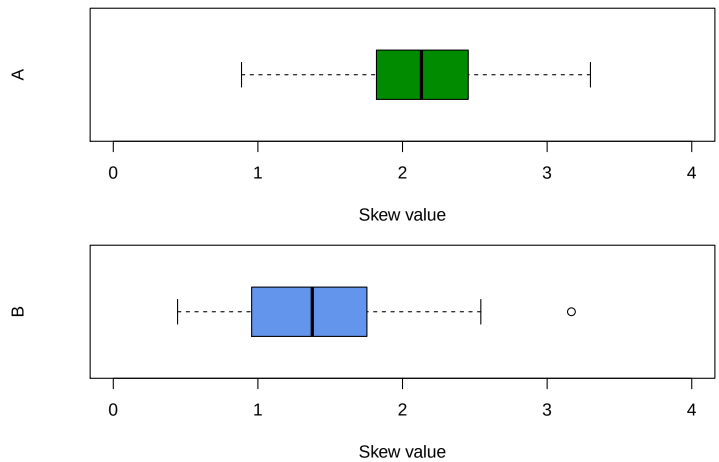

Fig. 5. Skewness values obtained over 100 independent runs of wealth distribution (A) and net worth (B). It is considered that values greater than 1 correspond to highly positively skewed distributions

At the macro level it is assumed that a economy is characterized in the long run by balanced growth, so this assumption implies for example that growth rate of GDP is mean stationary [12], in other words, series do not have time-dependent structure. There are a number of non-stationary tests and the Augmented Dickey-Fuller may be one of the more widely used. It uses an autoregressive model and optimizes an information criterion across multiple different lag values [13].

Applying the test without trend and zero lags on annual series of GDP growth of 100 independent runs, with an α value of 0.05, it is possible to reject the null hypothesis of non-stationarity, so this stylized fact is fulfilled.

Table 3. Basic statistics of the p-values resulting from the Dickey-Fuller test without trend and Lags = 0, applied to the 100 growth series of independent runs. It is appreciated that for the 100 runs the value of p is extremely small, even for the maximum value.

Min.	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max.**
0.000e+00	0.000e+00	4.500e-21	1.073e-17	1.336e-19	7.765e-16

5 Conclusion and future work

The main contribution of this work is the complete definition of the BAM model and an open-source, full implementation of the model in NetLogo. The tests performed in this papers suggest that BAM is well suited for studying macroeconomic signals resulting from agent's activities and affected by external shocks, e.g., variation in the reference interest rate of the central bank.

Future work includes exploring the parameter space of BAM in order to get a better understanding of the behavior of the model, particularly for answering what-if questions, e.g., What happens to GDP if the reference interest rate change? Such exploration is also useful for validating other stylized facts.

BAM will be used to study the macroeconomic effects of extortion racket systems [14], e.g., with a certain probability, unemployed workers become extorters. They search for victims among their known companies that have not been already being extorted by another criminal. An extorted firm must take a decision about refusing to pay the extortion or paying; while extorters must decide to punish or not when the firms refused to pay. Such decisions depends on the probability of being punished, the probability of being captured by law, etc. What is the impact of extortion in the observed macroeconomic signals? Well, BAM can be used to compare such signals in the presence and absence of extortion.

Computational intelligence might be very useful for calibrating BAM for adjusting it to the behavior of a real particular economy. Data can be used to train models implementing the decisions of some of the agents in the model, e.g, the firms. Data can also be used to initialize the states variables of some agents, e.g., the workers. An study of modeling unemployment in Veracruz, Mexico based on Bayesian Networks [15], has followed this approach. Evolutionary computation might also be explored as a tool for parameter calibration, e.g., finding the parameter values that minimize unemployment.

The current state of BAM is very encouraging for continuing with these lines of research. Open-sourcing it is also important for the validation of the model and to observe its applicability in other projects.

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