Micro-foundations of macroeconomic dynamics: the agent-based BAM model

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Abstract. This paper presents an open-source agent-based implementation of the BAM model, a micro-founded simulation of macroeconomic basic dynamics defined in the reference book *Macroeconomics from the Bottom-up*. By exploring the parameter space of our simulation we show that: i) BAM reproduces numerous stylized facts and its parameters influence the outputs plausibly; and ii) the effects of changing the size of markets and introducing shocks of different sizes are as expected. The outcomes are measured in terms of gross domestic product, inflation and unemployment rate, using monthly payments as time scale. These results confirm the fidelity and usability of our implementation, as well as the feasibility of the BAM model.

Keywords. Agent-Based Modelling, Simulation, Macroeconomics

1. Introduction

The complexity that emanates from economic processes requires appropriate conceptual and analytical tools. Refusing the Walrasian auctioneer, present in the classical approaches of macroeconomic analysis [1], implies that the results of the market must be derived from the interaction of a set of heterogeneous and adaptive individuals, instead of being deduced as equilibrium solutions from a system of differential equations. The process of removing externally imposed coordination devices induces a shift from the reductionist top-down perspective to a bottom-up approach. Approaches from Artificial Intelligence, such as Multi-Agent Systems, have proposed agent-based computational models [4,10,5,2,8,6] as a promising tool for analyzing macroeconomic dynamics with micro-foundations based on decentralized, heterogeneous and adaptive processes of individual decision-making.

Following the work by Delli Gatti et al. [7] on the Bottom-up Adaptive Macroeconomics (BAM) model, we have implemented a complete version [1] of this micro-founded model of macroeconomic dynamics in NetLogo [13]. To the authors' knowledge, this is the first open-source available implementation of this model. In this paper, we present an exploration of the parameter space of the BAM model showing how different stylized facts are reproduced and how some parameters influence the aggregate variables in a very plausible way. We also show that the effects of changing the size of markets and of introducing shocks of different sizes on wages, prices and interest rates produce also expected results. The outcomes are measured in terms of gross domestic product (GDP), inflation and the unemployment rate. Results confirm the fidelity and usability of our implementation, as well as the general feasibility of the BAM model.

The paper is organized as follows: Section 2 introduces the full definition of our implementation of the BAM model. Section 3 discusses experimental results regarding the effect of parameter variations on some macroeconomic variables of interest. Finally, Section 4 draws conclusions and future work.

2. The Bottom-up Adaptive Macroeconomics Model

The BAM model [7] adopted in this paper is of Walrasian nature. Despite the criticism for its excessive abstraction, the Walrasian economic model has persisted as a fundamental paradigm [11]. Indeed, because of its simplicity, it is a good starting point for exploring both perfect and imperfect economic models. As Figure 1 shows, it is composed of the following types of agents: **households** representing the point of consumption and labor force; **firms** transforming work in goods and/or services; and **banks** providing liquidity to firms if necessary.

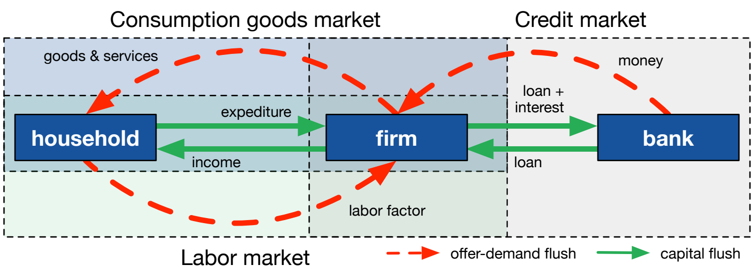

Figure 1. Overview of the Bottom-up Adaptive Macroeconomics (BAM) Model.

A large number of autonomous households (workers hereinafter), firms and banks operate in three totally decentralized and interconnected markets: a **labor market** where each worker offers a constant unit of work per period, while firms demand workers depending on their production plan; a **goods market** where workers spend all or part of their wealth and firms offer perishable goods at different prices; and a **credit market** where firms demand money if their resources are insufficient to cover their production expenses, and banks offer money at different interest rates.

[1] https://github.com/alexplatasl/BAMmodel/

Exchange trials are discovered in these markets through a sequential process characterized by optimization, i.e., maximizing wages, minimizing the price of goods consumed, and minimizing the price of money (interest rate). Firms can in turn adjust prices and goods on offer given their stock and the market price. In this way, the BAM model is able to reproduce disturbances that are similar to those observed in a real world economy while generating macroeconomic signals of interest such as inflation, unemployment, wealth or production, among others.

In what follows, for the benefit of replication, we describe the BAM model adhering to the Overview, Design concepts and Details (ODD) Protocol [9], a *de facto* standard for the description of agent-based models and simulations.

2.1. Overview

Purpose: Exploring the use of an agent-based approach for the study of macroeconomic signals. Particularly, we are interested in applying the BAM model to study the effect of agent behavior on such signals.

Entities, state variables and scales:

- Agents: Firms, workers and banks.
- Environment: A 2D grid is used as visual aid for debugging, but it is meaningless with respect to the model.
- State variables: The attributes that characterize each agent are shown in Table 1.
- Scales: Time is represented in discrete periods, each one represents a quarter.

Table 1. State variables for each agent, named as in code.

Agent	Variable	Type	Agent	Variable	Type
Firm	production-Y	Int	Worker	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		income	Float
	current-num-employees-L0	Int		savings	Float
	num-of-vacancies-offered-V	Int		wealth	Float
	minimum-wage-W-hat	Float		prop-to-consume-c	Float
	wage-offered-Wb	Float		my-stores	AgSet
	net-worth-A	Float		my-large-store	Ag
	total-payroll-W	Float	Bank	total-amount-of-credit-C	Float
	loan-B	Float		patrimonial-base-E	Float
	my-potential-banks	AgSet		operational-interest-rate	Float
	my-bank	AgSet		interest-rate-r	Float
	inventory-S	Float		my-borrowing-firms	AgSet
	individual-price-P	Float		bankrupt?	Bool
	revenue-R	Float			
	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. Unemployed workers look for a job.
3. A decentralized credit market opens. Banks will lend money to firms.
4. Firms produce.
5. A market for goods opens and workers buy.
6. Firms pay loans and dividends.
7. Firms and banks survive or go bankrupt.
8. Firms and banks that go bankrupt are replaced.

2.2. Design concepts

Basic Principles: The model follows fundamental principles of neoclassical economics [14], since it gives great importance to money in economic processes and also because the strategy for determining prices is given, considering both supply and demand.

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

Adaptation: Based on the evidence of survey data (See [7], p. 55), BAM assumes that the firms can adapt either the price or the amount of goods supplied, i.e., only one of them, at each step. Adaptation depends on the situation of the firm (supply-demand balance in the previous period) and the market (difference between the own and the market price).

Objectives: Agents do not have an explicit objective value but, implicitly, they try to improve a utility or attribute, e.g., workers always opt for the best known wage and price.

Learning: None for the moment, however, see the future work section for possible uses of learning in this model.

Prediction: Firms predict the quantity of goods to be produced based on the excess of supply-demand in the previous period and the difference between their own price and the average market price.

Sensing. Different for each kind of agent:

- Firms perceive their own quantity of goods produced, individual price, labor force, net worth, profits and 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, the prices published by firms in the actual period and the wages offered by firms.
- Banks perceive the net worth of potential borrowers to calculate interest rates.

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.

- Firms can access to a decentralized credit market if their net worth is in short supply for the wage bill. Borrowing firms contact a given number of randomly chosen banks and apply for a loan starting from the one charging the lowest interest rate. Banks sort applications 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 exogenous 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 the goods market, firms post their offer price, and workers contact a given number of randomly chosen firms to purchase goods, starting from the one which posts the lowest price.

Stochasticity: Random shocks are introduced in the setting of wages (ξ) and contractual interest rates (ϕ). Also in the strategies to set prices (η) and quantities to produce (ρ).

Collectives: Markets configure collectives of agents, they include labor, goods, and credit markets. In addition, firms and workers are categorized as rich and poor.

Observation: Gross Domestic Product (GDP), unemployment, inflation and interest rate are observed along the simulation. Distribution of firm sizes, workers' wealth and GDP growth rate are computed by the end of the simulation.

2.3. Details

Initialization: Table 2 shows the initialization parameters of the model, which are mainly taken from [7] or experimentally determined when not provided in the previous text.

Table 2. Initialization parameters.

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

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

Submodels: Agent behavior is defined as follows:

1. Production Y and technological productivity α: $Y_{it} = \alpha_{it}L_{it}$, s.t., $\alpha_{it} > 0$, where L is the labor factor of firm i at time t.
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. Number of vacancies offered by firms $V_{it} = max(L^d_{it} - L^0_{it}, 0)$.
5. Current number of employees L^0_{it} is the sum of employees with a valid contract.

6. If there are no vacancies ($V_{it} = 0$), wage offered is $w_{it}^b = max(\hat{w}_t, w_{it-1})$, where $\hat{w}_t$ is the minimum wage determined by law.
7. If $V_{it} > 0$, wage offered is $w_{it}^b = max(\hat{w}_t, w_{it-1}(1+\xi_{it}))$, where ξ_{it} is a random term evenly distributed between $(0, h_\xi)$.
8. At the beginning of each period, a firm has a net worth A_{it}. If total payroll to be paid $W_{it} > A_{it}$, firm asks for loan $B_{it} = max(W_{it} - A_{it}, 0)$.
9. Firms look for a limited number banks in the credit market $H < K$ since applying for a loan is considered an expensive task.
10. 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.
11. Bank offers credit C_k, with an interest rate r_{it}^k and contract for 1 period.
12. If $A_{it+1} > 0$ the payment scheme is $B_{it}(1 + r_{it}^k)$.
13. If $A_{it+1} \leq 0$, bank retrieves R_{it+1}.
14. Contractual interest rate offered by the bank k to the firm i is determined as a margin on a rate policy established by Central Bank $\bar{r}$, s.t., $R_{it}^k = \bar{r}(1 + \phi_{kt}\mu(\ell_{it}))$.
15. Margin is a function linked to each bank as possible variations in its operating costs and captured by the uniform random variable ϕ_{kt} in the interval $(0, h_\phi)$.
16. 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.
17. 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.
18. Each firm has a stock of unsold goods S_{it}, where excess supply $S_{it} > 0$ or demand $S_{it} = 0$ is reflected.
19. Deviation of the individual price from the average market price during the previous period is represented as: $P_{it-1} - P_{t-1}$
20. 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.
21. In case of adjusting price downward, this is bounded below P_{it}^l to not be less than your average costs:

$$P_{it}^l = (W_{it} + \sum_k r_{kit} B_{kit})/Y_{it}$$

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

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

where: η_{it} is a randomized term uniformly distributed in the range $(0, h_\eta)$ and P_{it}^l is the minimum price at which firm i can solve its minimal costs at time t.

24. In the case of quantities, these are adjusted according to:

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

where ρ_{it} is a random term uniform distributed and bounded between $(0, h_\rho)$.
25. Total income of workers is the sum of the payroll paid to the workers in t and the dividends distributed to the shareholders in $t-1$.
26. Wealth is defined as the sum of wage plus the sum of all savings SA of the past.
27. Marginal propensity to consume c is a decreasing function of the worker's total wealth (the higher the wealth the lower the proportion spent on consumption):

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

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

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

32. If firm i accumulates a net worth $A_{it} < 0$, it goes bankrupt.
33. Firms that go bankrupt are replaced with another one of size smaller than the average of incumbent firms. Non-incumbent firms' size is above and below 5%.
34. Bank's capital:

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

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

3. Results

Parameters proposed in Table 2 generate a fictitious stable economy with unemployment rate around 10% and moderate inflation in the range of 1% to 6%. According to data from the World Bank [15,16] during the period 2014 - 2018, average unemployment among countries is 8.22%, while the average annual inflation is 4.43%. The model shows a good sensitivity to the parameters and is, generally, very responsive to them. In particular, we observe that short and medium term dynamics of standard macroeconomic indexes, e.g., GDP or unemployment rate, correspond to those that we would expect empirically.

Stylized facts are an indirect calibration approach to show the capability of the model to reproduce empirical evidence. At micro level, validation consists in verifying the presence of stylized facts in the distribution of agent's state variables. For instance, we follow the method described by Joanes and Gill [3] to calculate skewness of wealth distribution and net worth in our simulations. Both of them are characterized by a positive skew > 1, as shown in Figure 2, which implies, as expected, there are few agents becoming rich.

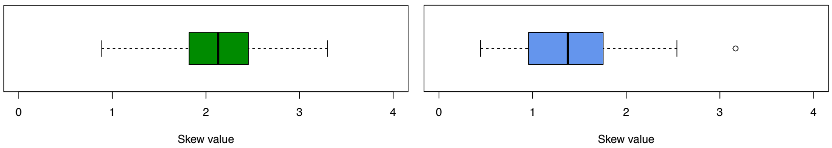

Figure 2. Skewness of wealth (left) and net worth (right) distribution over $n = 100$ independent runs. Values greater than 1 correspond to highly positively skewed distributions

The effect of shocks was tested varying wages (ξ), prices (η), and interest rates (ϕ) with values in $\{0.05, 0.1\}$. We also vary the propensity of consumption $\beta \in \{0.5, 0.85\}$. Replications of 20 runs for each combination of parameters were performed. A correlation between the presence of shocks and the dynamics of macroeconomic variables was observed, although it is less clear how the presence of shocks may be affected by the size of the markets, defined in terms of trials, i.e., the number of possible encounters among participant agents ($M, H, Z \in \{2, 4\}$). The small values for all these parameters were adopted from Delli Gatti et al. [7] while large values, although arbitrary, represent acceptable big increments with respect to the small values.

Figure 3 shows the effect of varying the size of shocks when updating wages (Submodel 7) on markets with two different sizes. As expected from theory, wage shocks lead to an increase in the GDP that is less evident in large markets (right) than in smaller ones (left). Similarly, as expected in macroeconomics, wage shocks produce a fluctuation in the unemployment rate that is less marked in large markets, as shown in Figure 4.

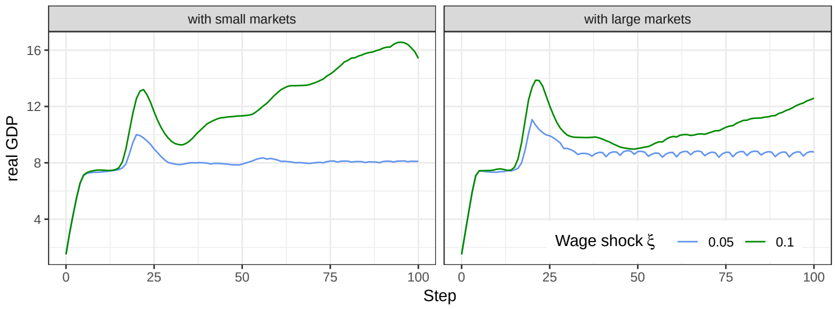

Figure 3. Dynamics of GDP under wage shocks of different size in small ($M = H = Z = 2$) and large ($M = H = Z = 4$) markets.

Figure 5 shows the effect of price shocks (Submodel 23). It is appreciated that the shock of the salary produces higher inflation in small markets than in large markets, which is even more evident with large-sized wage shocks. This result was expected, since the fact that agents have more market trials reduces the pressure on prices.

Figure 6 shows how propensity to consume (Sub-model 27) interacts with the dynamics of prices. Changes in the β parameter do not have evident effects, which is consistent with the observed wealth distribution, since having a positive skew indicates the existence of few rich people, i.e., homogeneity in the propensity to consume that therefore do not induce rising prices.

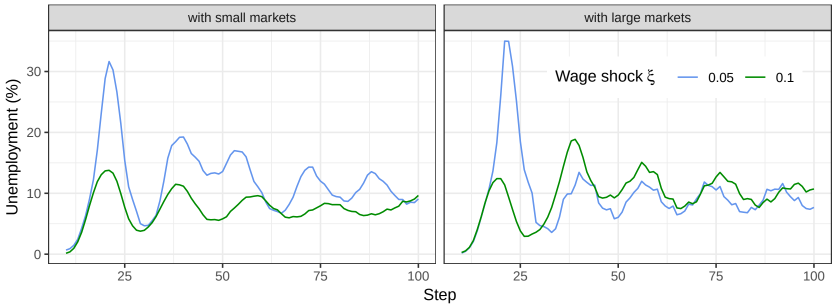

Figure 4. Dynamics of unemployment rate under wage shock in small and large markets.

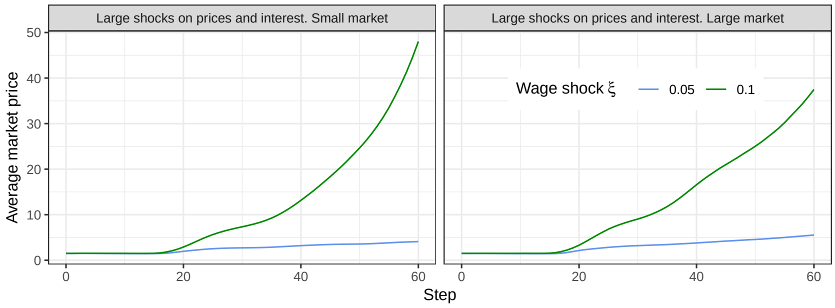

Figure 5. Dynamics average market price on small and large markets.

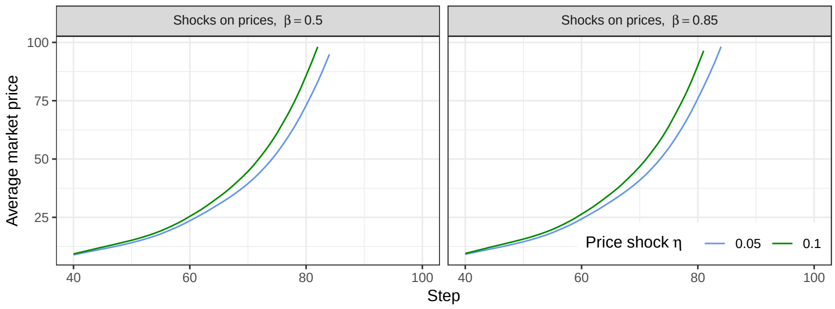

Figure 6. Dynamics of average market price when varying propensity to consume β.

4. Conclusions and Future Work

We provide a concise and complete description of the BAM model that adheres to the ODD protocol, which is argued to be relevant for reproducing results. Our implementation of the BAM model behaves correctly under stable conditions, i.e., those induced by its default configuration, as well as when introducing shocks, varying the propensity to consume, and the size of markets. These results contribute to validate the feasibility of the BAM model along with the fidelity and applicability of our implementation. This allows the use of the BAM model to investigate phenomena that are difficult to represent analytically, e.g., the dynamics of GDP as a function of shocks and size of markets, particularly when the scenario is composed by heterogeneous agents.

As part of our future work, we are currently using the presented BAM implementation to test the effects of extortion in macroeconomic signals [12]. Agent behaviours can be modified so that some unemployed workers become extorters and affect the activity of the firms. The output of these simulations can then be compared with the one produced by the original BAM model, in order to study the changes on the macroeconomic signals produced by such an activity. Of course, such a method of comparison would only work if the BAM model behaves correctly, as evidenced here.

Acknowledgements

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