An Agent-Based Decentralized Matching Macroeconomic Model

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Abstract

In this paper we present a basic but flexible macroeconomic framework with heterogeneous agents – households, firms, banks – which interact through a decentralized matching process presenting common features across four markets – goods, labour, credit and deposit. We study the dynamics of the model by means of computer simulation. Some macroeconomic properties emerge such as endogenous business cycles, nominal GDP growth, unemployment rate fluctuations, the Phillips curve, leverage cycles and credit constraints, bank defaults and financial instability, and the importance of government as an acyclical sector which stabilize the economy. Moreover, we perform some computational s on the parameters governing regulatory constraints on the banking sector. Repeated simulations show that if regulation is excessively tight then strong credit constraints emerge, causing high unemployment and a further weakness of economic and financial conditions in a vicious circle. By contrast, if regulatory rules are too loose then an excessive financial risk follows and this may result in bankruptcies avalanches of firms and banks.

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1 Introduction

Our aim is to develop a basic but flexible macroeconomic framework with heterogeneous agents that interact through a decentralized matching process presenting common features across markets. The framework is basic since we propose a minimal macroeconomic model and it is flexible because this baseline setup is thought to be enriched by adding new modules with different agents, markets, and institutions. Indeed, in this paper we propose an agent-based macroeconomic model in which there are three classes of computational agents - households, firms, banks - interacting in four markets - goods, labour, credit and deposit - according to a fully decentralized matching mechanism.

In recent years many economists have developed agent-based models to investigate the working of a macroeconomic system composed of heterogeneous interacting entities (Tesfatsion and Judd, 2006; LeBaron and Tesfatsion, 2008). In general, the idea is start from simple (adaptive) individual behavioral rules and interaction mechanisms in order to reproduce the emergence of aggregate regularities and endogenous crises. In a sense, this is a generative approach according to which we construct the macroeconomy from the "bottom up" (Epstein and Axtell, 1996).

Let's now propose a few examples about agent-based models which analyze a decentralized matching mechanism in one or more markets in order to reproduce some macroeconomic emergent features. Fagiolo et al. (2004) investigate labor market dynamics and the evolution of aggregate output. In particular, they model a decentralized matching process to describe the interaction between workers and firms in context characterized by endogenous price formation and stochastic technical progress. Russo et al. (2007) present an agent-based model in which bounded rational firms and workers interact on fully decentralized markets both for final goods and labor. The model is used to analyze the role of fiscal policy in promoting R&D investments that may increase economic growth. This model has been further developed by Gaffeo et al. (2008) through the introduction of a similar matching protocol for the credit market. Cincotti et al. (2010) investigate the interplay between monetary aggregates and the dynamics of output and prices by considering both the credit extended by commercial banks and the money supply created by the central bank. In particular, they study the effects of quantitative easing as a monetary policy. Building upon Dosi et al (2006, 2010), Dosi et al. (2012) analyze the interplay between income distribution and economic policies. They find that more unequal economies are exposed to more severe business cycles fluctuations, higher unemployment rates, and higher probability of crises. They also find that fiscal policies dampen business cycles, reduce unemployment and the likelihood of large crises, and may affect positively long-term growth.

The major innovations we introduce in the agent-based macroeconomic framework delineated in the literature are the following: (i) we apply a common matching mechanisms to all markets; (ii) we provide an explicit modeling for the deposit market in which banks receive households' saving; and, most importantly, (iii) we introduce a firms' financial structure derived from the Dynamic Trade-Off theory (Flannery and Rangan, 2006). According to this theory, we hypothesize that firms have a "target leverage", that is a desired ratio between debt and net worth, and they try to reach it by following an adaptive rule governing credit demand. This capital structure is already investigated in the agent-based model proposed by Riccetti et al. (2011) that builds upon the previous work by Delli Gatti et al. (2010) which is based on a firms' capital structure given by the Pecking Order theory (Donaldson, 1961; Myers and Majluf, 1984). The Dynamic Trade-Off theory has a relevant role in influencing the leverage cycle, with important consequences on macroeconomic dynamics. We propose a different modeling of banks' credit supply with respect to Riccetti et al. (2011), which allows us to explicitly analyze the effects of credit rationing on economic performance.

The paper is organized as follows. In Section 2 we explain the basic aspects of the modeling framework such as the sequence of events and the matching mechanism. Section 3 presents the working of the four markets which composes our economy. The evolution of agents' wealth is described in Section 4, while the behavior of policy makers is discussed in Section 5. Model dynamics are studied in Section 6 in which we report the simulation results about the baseline model. In Section 7 we perform a computational experiment to evaluate the role of the parameter that governs banks' credit portfolio concentration. Section 8 concludes.

2 Model setup

The macroeconomy is populated by households ($h = 1, 2, ..., H$), firms ($f = 1, 2, ..., F$), banks ($b = 1, 2, ..., B$), a central bank, and the government, which interact over a time span $t = 1, 2, ..., T$ in the following four markets:

- Credit market: firms and banks.
- Labor market: firms and households.
- Goods market: households and firms.
- Deposit market: banks and households.

Agents are boundedly rational and follow (relatively) simple rules of behaviour in an incomplete and asymmetric information context: households try to buy consumption goods from the cheapest supplier, they also try to work in the firm offering the highest wage; firms try to accumulate profits by selling their products to households (they set the price according to their individual excess demand) and hiring cheapest workers; workers update the asked wage according to their occupational status (upward if employed, downward if unemployed); households' saving goes into bank deposits; given the Basilea-like regulatory constraints, banks extend credit to finance firms' production; firms choose the banks offering lowest interest rates, while households deposit money in the banks offering the highest interest rates. The government hires public workers, taxes private agents and issues public debt. Finally, the central bank provides money to banks and the government given their requirements.

In the following subsections we firstly describe the sequence of events occurring in each period. Subsequently, we explain the working of the matching mechanism which characterizes the interaction structure of all markets.

2.1 Sequence of events

The sequence of events occurring in each period runs as follows:

1. At first firms ask for credit to banks given the demand deriving from their net worth and leverage target. In each period, the leverage level changes according to expected profits and inventories.

2. Banks set their credit supply depending on their net worth, deposits and the quantity of money provided by the central bank. Moreover, they must comply with some regulatory constraints.

3. Banks and firms interact in the credit market. At the end of the matching process, some banks may lend all the available credit supply while others may remain with some residual money; similarly, some firms may obtain the required credit while other may remain credit constrained.

4. The government hires public workers. Moreover, it collects taxes (coming from previous period private incomes and wealth) and, given the wage expenditure for public workers, calculates its deficit (surplus), and updates the overall debt.

5. Banks buy government securities to employ excess liquidity. The central bank purchases the remaining securities.

6. Firms hire workers in the labor market. The labor demand depends on available funds, that is net worth and bank credit. After the labor matching some firms satisfy their labor demand, while others remain with residual cash; at the same time, some people may remain unemployed. Employed people pay income taxes to the government.

7. Firms produce consumption goods on the basis of hired workers. They put in the goods market their current period production and previous period inventories.

8. Households decide their desired consumption on the basis of their wages and wealth (net of taxes).

9. Households and firms interact in the goods market. As a result, some households satisfy their desired consumption, while others may remain with residual cash; on the other hand, some firms sell all the produced output, while others may accumulate inventories.

10. Households determine their savings to be deposited in banks. Banks can accept this money depending on their credit supply requirements.

11. Firms calculate profits and survival firms repay their debt to banks, pay taxes, and distribute dividends to households.

12. Banks calculate profits. Households lose (part of) deposited money in case of bank defaults. Survival banks pay taxes and distribute dividends to households.

13. Agents update their wealth, on which they pay capital levy.

14. Central bank decides the amount of money to be lent to banks in the following period according to credit demand/supply unbalance.

15. New entrants replace bankrupted agents (firms or banks) according to a one-to-one replacement. New agents enter the system with initial conditions we will define below. Moreover, the money needed to finance entrants is subtract from households' wealth. In the case private wealth is not enough, then government intervenes.

2.2 The matching mechanism

In each of the four markets composing our macroeconomy the following matching protocol is at work. In general, two classes of agents interact, that is the demand and the supply sides. One side observes a list of potential counterparts and chooses the most suitable partner according to some market-specific criteria.

At the beginning, a random list of agents in the demand side – firms in the credit market, firms in the labor market, households in the goods market, and banks in the deposit market – is set. Then, the first agent in the list observes a random subset of potential partners, whose size depends on a parameter $0 < \chi \leq 1$ (which proxies the degree of imperfect information), and chooses the cheapest one. For example, in the labor market, the first firm on the list, say the firm f_1 observes the asked wage of a subsample of workers and chooses the agent asking for the lowest one, say the worker h_1.

After that, the second agent on the list performs the same activity on a new random subset of the updated potential partner list. In the case of the labor market, the new list of potential workers to be hired no longer contains the worker h_1. The process iterates till the end of the demand side list (in our example, all the firms enter the matching process and have the possibility to employ one worker).

Then, a new random list of agents in the demand side is set and the whole matching mechanism goes on until either one side of the market (demand or supply) is empty or no further matchings are feasible because the highest *bid* (for example, the money till available to the richest firm) is lower than the lowest *ask* (for example, the lowest wage asked by till unemployed workers).

Given this matching protocol governing agents' interaction, now we describe the details of agents' behavior in the four markets.

3 Markets

3.1 Credit market

Firms and banks interact in this market: firms want to finance production and banks may provide credit to this end. Firm's f credit demand at time t depends on its net worth A_{ft} and the leverage target l_{ft}. Hence, required credit is:

$$B^d_{ft} = A_{ft} \cdot l_{ft} \tag{1}$$

The leverage target is set according to the following rule:

$$l_{ft} = \begin{cases} l_{ft-1} \cdot (1 + adj \cdot U(0,1)), & \text{if } \pi_{ft-1}/(A_{ft-1} + B_{ft-1}) > i_{ft-1} \text{ and } \hat{y}_{ft-1} < \psi \cdot y_{ft-1} \\ l_{ft-1}, & \text{if } \pi_{ft-1}/(A_{ft-1} + B_{ft-1}) = i_{ft-1} \text{ and } \hat{y}_{ft-1} < \psi \cdot y_{ft-1} \\ l_{ft-1} \cdot (1 - adj \cdot U(0,1)), & \text{if } \pi_{ft-1}/(A_{ft-1} + B_{ft-1}) < i_{ft-1} \text{ or } \hat{y}_{ft-1} \geq \psi \cdot y_{ft-1} \end{cases} \tag{2}$$

where $adj > 0$ is a parameter representing the maximum percentage change of the relevant variable (in this case the target leverage), $U(0,1)$ is a random number picked from a uniform distribution in the interval (0,1), π_{ft-1} is the gross profit (realized in the previous period), B_{ft-1} is the previous period effective debt, i_{ft-1} is the nominal interest rate paid on previous debts[1], $\hat{y}_{ft-1}$ represents inventories (that is, unsold goods), $0 \leq \psi \leq 1$ is a parameter representing a threshold for inventories based on previous period production y_{ft-1}.

On the other side, bank b offers a total amount of money B^d_{bt} depending on net worth A_{bt}, deposits D_{bt}, central bank credit m_{bt}, and some legal constraints (proxied by the parameters $reg1 > 0$ and $0 \leq reg2 \leq 1$ that represents respectively the maximum admissible leverage and maximum percentage of capital to be invested in lending activities):

$$B^d_{bt} = min(k1_{bt}, k2_{bt}) \tag{3}$$

where $k1 = reg1 \cdot A_{bt}$, $k2 = reg2 \cdot A_{bt} + D_{bt-1} + m_{bt}$. Moreover, in order to reduce risk concentration, banks lend to a single firm up to a maximum fraction β of the total amount of

[1] It is a mean interest rate calculated as the weighted average of interests paid to the lending banks

the credit B^d_{bt}. This behavioural parameter can be also interpreted as a regulatory constraint to avoid excessive concentration.

The interest rate charged by the bank b on the firm f at time t is given by:

$$i_{bft} = i_{CBt} + i1_{bt} + i2_{ft} \tag{4}$$

where i_{CBt} is the nominal interest rate set by the central bank at time t, $i1_{bt}$ is a bank-specific component, and $i2_{ft} = \rho^{l_{ft}}/100$ is a firm-specific component, that is a risk premium on firm target leverage.
The bank-specific component evolves as follows:

$$i1_{bt} = \begin{array}{ll} i1_{bt} \cdot (1 - adj \cdot U(0,1)), & \text{if } \hat{B}_{bt-1} > 0 \\ i1_{bt} \cdot (1 + adj \cdot U(0,1)), & \text{if } \hat{B}_{bt-1} = 0 \end{array} \tag{5}$$

where $\hat{B}_{bt-1}$ is the amount of money that the bank did not manage to lend to firms in the previous period.

Given this setting on credit supply and demand, firms and banks interact according to the matching mechanism. As a consequence, each firm ends up with a credit $B_{ft} \leq B^d_{ft}$ and each bank lends to firms an amount $B_{bt} \leq B^d_{bt}$. The difference between desired and effective credit is equal to $B^d_{ft} - B_{ft} = \hat{B}_{ft}$ and $B^d_{bt} - B_{bt} = \hat{B}_{bt}$, for firms and banks respectively. Moreover, we hypothesize that banks ask for an investment in government securities equal to $PD^d_{bt} = k2_{bt} - B_{bt}$. If the sum of desired government bonds exceeds the amount of outstanding public debt then the effective investment PD_{bt} is rescaled according to a factor $PD^d_{bt}/ \quad PD^d_{bt}$. Instead, if public debt exceeds the banks' desired amount, then the central bank buys the difference.

3.2 Labor market

In each period, the government hires a fraction pw of households. The remaining part is available for working in the firms. Firm's f labor demand depends on the total capital available: $A_{ft} + B_{ft}$. Each worker posts a wage w_{ht} which is updated according to the following rule:

$$w_{ht} = \begin{array}{ll} w_{ht-1} \cdot (1 + adj \cdot U(0,1)), & \text{if } h \text{ employed at time } t-1 \\ w_{ht-1} \cdot (1 - adj \cdot U(0,1)), & \text{if } h \text{ unemployed at time } t-1 \end{array} \tag{6}$$

However, the required wage has a minimum related to the price of a single good net of income tax.

Given this setting on labor supply and demand, firms and households interact according to the matching mechanism. As a consequence, each firm ends up with a number of workers

n_{ft} and a residual cash (insufficient to hire an additional worker). Obviously, a fraction of households may remain unemployed. The wage of unemployed people is set equal to zero.

3.3 Goods market

In this market households represent the demand side, while firms are the supply side. Households set the desired consumption as follows:

$$c^d_{ht} = c1 \cdot w_{ht} + c2 \cdot A_{ht} \tag{7}$$

where $0 < c1 \leq 1$ is the propensity to consume current income, $0 \leq c2 \leq 1$ is the propensity to consume the wealth A_{ht}. If the amount c^d_{ht} is smaller than the average price of one good $\bar{p}$ then $c^d_{ht} = min(\bar{p}\,, w_{ht} + A_{ht})$.

Firm f produces an amount of goods given by:

$$y_{ft} = \phi \cdot n_{ft} \tag{8}$$

where $\phi \geq 1$ is a productivity parameter.

The firm tries to sell this produced amount plus the inventories $\hat{y}_{ft-1}$. The selling price evolves according to this rule:

$$p_{ft} = \begin{cases} p_{ft-1} \cdot (1 + adj \cdot U(0,1))\,, & \text{if } \hat{y}_{ft-1} = 0 \text{ and } y_{ft-1} > 0 \\ p_{ft-1} \cdot (1 - adj \cdot U(0,1))\,, & \text{if } \hat{y}_{ft-1} > 0 \text{ or } y_{ft-1} = 0 \end{cases} \tag{9}$$

However, the minimum price is set such that it is at least equal to the average cost of production.

Given this setting on goods supply and demand, households and firms interact according to the matching mechanism. As a consequence, each household ends up with a residual cash, that is not enough to buy an additional good and that she will try to deposit in a bank. On the other hand, firms sell an amount $0 \leq \bar{y}_{ft} \leq y_{ft}$ and they may remain with unsold goods (that is, the inventories $\hat{y}_{ft} = y_{ft} - \bar{y}_{ft}$ that the firm will try to sell in the next period).

3.4 Deposit market

In the deposit market, banks represent the demand side (because they require capital to extend credit) and households are on the supply side. Banks offer an interest rate on deposits according to their funds requirement:

$$i^D_{bt} = \begin{cases} i^D_{bt-1} \cdot (1 - adj \cdot U(0,1))\,, & \text{if } k2_{bt} - B_{bt} - PD_{bt} > 0 \\ min\{i^D_{bt-1} \cdot (1 + adj \cdot U(0,1))\,, i_{CBt}\}, & \text{if } k2_{bt} - B_{bt} - PD_{bt} = 0 \end{cases} \tag{10}$$

where PD_{bt} is the amount of public debt bought by bank b at time t. Hence, the previous equation states that if a bank exhausts the credit supply by lending to private firms or government then it decides to increase the interest rate paid on deposits, so to attract new depositors, and viceversa. However, the interest rate on deposits can increase till a maximum given by the policy rate r_{CBt} which is both the rate at which banks could refinance from the central bank and the rate paid by the government on public bonds.

Households set the minimum interest rate they want to obtain on bank deposits as follows:

$$i^D_{ht} = \begin{cases} i^D_{ht-1} \cdot (1 - adj \cdot U(0,1)), & \text{if } D_{ht-1} = 0 \\ i^D_{ht-1} \cdot (1 + adj \cdot U(0,1)), & \text{if } D_{ht-1} > 0 \end{cases} \tag{11}$$

where D_{ht-1} is the household h's deposit in the previous period. This means that a household that found a bank paying an interest rate higher or equal to the desired one decides to ask for a higher remuneration. In the opposite case, she did not find a bank satisfying her requirements, thus she kept her money in cash and now she asks for a lower rate. We hypothesize that a household deposits all the available money in a single bank that offers an adequate interest rate. A household that decides to not deposit her money in a bank signals a preference for liquidity, because she does not accept to deposit her cash for an interest rate below the desired one.

4 Wealth evolution

4.1 Firms

According to the outcomes of the credit, labor and goods markets, the firm f's profit is equal to:

$$\pi_{ft} = p_{ft} \cdot \bar{y}_{ft} - wb_{ft} - int_{ft} \tag{12}$$

where wb_{ft} is the firm f's wage bill, that is the sum of wages paid to employed workers, and int_{ft} is the sum of interests paid on bank loans.
Firms pay a proportional tax τ on positive profits; negative profits will be subtracted from the next positive profits. We indicate net profits with $\bar{\pi}_{ft}$.
Finally, firms pay a percentage δ_{ft} as dividends on positive net profits. The fraction $0 \leq \delta_{ft} \leq 1$ evolves according to the following rule:

$$\delta_{ft} = \begin{cases} \delta_{ft-1} \cdot (1 - adj \cdot U(0,1)), & \text{if } \hat{y}_{ft} = 0 \text{ and } y_{ft} > 0 \\ \delta_{ft-1} \cdot (1 + adj \cdot U(0,1)), & \text{if } \hat{y}_{ft} > 0 \text{ or } y_{ft} = 0 \end{cases} \tag{13}$$

We indicate the profit net of taxes and dividends as $\hat{\pi}_{ft}$. Obviously, in case of negative profits $\hat{\pi}_{ft} = \pi_{ft}$.

Thus, the firm f's net worth evolves as follows:

$$A_{ft} = (1 - \tau') \cdot [A_{ft-1} + \hat{\pi}_{ft}] \tag{14}$$

where τ' is the tax rate on wealth (applied only on wealth exceeding a threshold $\bar{tau}' \cdot \bar{p}$, that is a multiple of the average goods price).

If $A_{ft} \leq 0$ then the firm goes bankrupt and a new entrant takes its place. The initial net worth of the new entrant is a multiple of the average goods price, while the leverage is one. Moreover, the initial price is equal to the mean price of survival firms.

4.2 Banks

As a consequence of operations in the credit and the deposit markets, the bank b's profit is equal to:

$$\pi_{bt} = int_{bt} + i_t^{PD} \cdot PD_{bt} - i_{bt-1}^{D} \cdot D_{bt-1} - i_C B^t \cdot m_{bt} - bad_{bt} \tag{15}$$

where int_{bt} represents the interests gained on lending to non-defaulted firms, i_t^{PD} is the interest rate on government securities (PD_{bt}), and bad_{bt} is the amount of "bad debt" due to bankrupted firms, that is non performing loans. Bad debt is the loss given default of the total loan, that is a fraction $1 - (A_{ft} + B_{ft})/B_{ft}$ of the loan to defaulted firm f connected with bank b.

Banks pay a proportional tax τ on positive profits; negative profits will be subtracted from the next positive profits. We indicate net profits with $\bar{\pi}_{bt}$.

Finally, banks pay a percentage δ_{bt} as dividends on positive net profits. The fraction $0 \leq \delta_{bt} \leq 1$ evolves according to the following rule:

$$\delta_{bt} = \begin{cases} \delta_{bt-1} \cdot (1 - adj \cdot U(0,1)), & \text{if } B_{bt} > 0 \text{ and } \hat{B}_{bt} = 0 \\ \delta_{ft-1} \cdot (1 + adj \cdot U(0,1)), & \text{if } B_{bt} = 0 \text{ or } \hat{B}_{bt} > 0 \end{cases} \tag{16}$$

Indeed, if the bank does not manage to lend the desired supply of credit then it decides to distribute more dividends (because it does not need high reinvested profits), and viceversa.

We indicate the profit net of taxes and dividends as $\hat{\pi}_{bt}$. Obviously, in case of negative profits $\hat{\pi}_{bt} = \pi_{bt}$.

Thus, the bank b's net worth evolves as follows:

$$A_{bt} = (1 - \tau') \cdot [A_{bt-1} + \hat{\pi}_{bt}] \tag{17}$$

where τ' is the tax rate on wealth (applied only on wealth exceeding a threshold $\bar{tau}' \cdot \bar{p}$, that is a multiple of the average goods price).

If $A_{bt} \leq 0$ then the bank is in default and a new entrant takes its place. The initial net worth of the new entrant is a multiple of the average goods price. Moreover, the initial bank-specific component of the interest rate ($i1_{bt}$) is equal to the mean value across banks.

4.3 Households

According to the outcomes of the labor, goods, and deposit markets, the household h's wealth evolves as follows:

$$A_{ht} = (1 - \tau') \cdot [(A_{ht-1} + (1 - \tau) \cdot w_{ht} + div_{ht} + int^D_{ht} - c_{ht}] \tag{18}$$

where τ' is the tax rate on wealth (applied only on wealth exceeding a threshold $t\bar{au}' \cdot \bar{p}$, that is a multiple of the average goods price), τ is the tax rate on income, w_{ht} is the wage gained by employed workers, div_{ht} is the fraction (proportional to the household h's wealth compared to overall households' wealth) of dividends distributed by firms and banks net of the amount of resources needed to finance new entrants (hence, this value may be negative), int^D_{ht} represents interests on deposits, and $c_{ht} \leq c^d_{ht}$ is the effective consumption.

5 Government and central bank

On the one hand, the government's current expenditure is given by the sum of wages paid to public workers (PW_t), the interests paid on public debt to banks (PD_t), and an amount Ω_t which is normally zero but for extreme cases in which the government has to intervene to finance new entrants when private wealth is not enough. On the other hand, government collects taxes on incomes and wealth, and receives interests gained by the central bank. The difference between expenditures and revenues is the public deficit $PDEF_t$. Consequently, public debt is $PD_t = PD_{t-1} + PDEF_t$.

Central bank decides the policy rate i_{CBt} and put a quantity of money into the system in accordance with it. In order to do that, the central bank observes the aggregate excess supply or demand in the credit market and sets an amount of money M_t to reduce the gap in the following period.

6 Simulations

We run a baseline simulation for a time span of T =150 periods and analyse the results for the last 50 (so the first 100 are used to initialise the model). Table 1 shows the parameter setting of the baseline simulation. The initial agents' wealth is set as follows: $A_{f1} = max\{0.1, N(3, 1)\}$, $A_{b1} = max\{0.2, N(5, 1)\}$, $A_{h1} = max\{0.01, N(0.5, 0.01)\}$. The policy rate i_{CBt} is constant at 1%.

Table 1: Parameter setting

H	number of households	500
F	number of firms	80
B	number of banks	10
adj	adjustment parameter	0.05
χ	matching imperfect information	0.2
ψ	inventory threshold	0.1
$reg1$	max bank's leverage	10
$reg2$	max % of bank's invested capital in lending	0.5
β	max bank's lending to single firm	0.5
ρ	risk premium on firm's loan	2
$c1$	propensity to consume current income	0.8
$c2$	propensity to consume wealth	0.3
ϕ	firm's productivity	3
τ	tax rate on income	0.3
τ'	tax rate on wealth	0.05
$t\bar{a}u'$	threshold for tax on wealth	3
pw	% of public workers on population	0.33

Simulation results are displayed in Figure 1 and show that endogenous business cycles emerge as a consequence of the interaction between real and financial factors. When firms' profits are improving, they try to expand the production and, if banks extend the required credit, this results in more employment; the decrease of the unemployment rate leads to the rise of wages that, on the one hand, increases the aggregate demand, while on the other hand reduces firms' profits, and this may cause the inversion of the business cycle. Banks' capitalization plays a relevant role in determining credit conditions, so influencing firms' leverage and, in general, the macroeconomic evolution. The presence of an acyclical sector, here represented by the government, has a fundamental role in sustaining the aggregate demand and in mitigating output volatility.

The nominal GDP grows along time as a consequence of price inflation (given that there is no productivity growth in the baseline model). The average inflation rate is 2.07% with a minimum of 1.12% and a maximum of 2.87%. The unemployment rate oscillates around 8.42% with a minimum of 4% and a maximum of 12.8%. Model simulation reproduces a Phillips curve, that is a negative relationship between wage inflation and unemployment rate (the correlation coefficient is -0.76). The average fraction of firms going bankrupt is 6.3%, with a minimum of zero and a maximum of 25%. The average fraction of bank defaults is 1.2%, with a minimum of zero and a maximum of 10%. Bank's leverage is inversely related

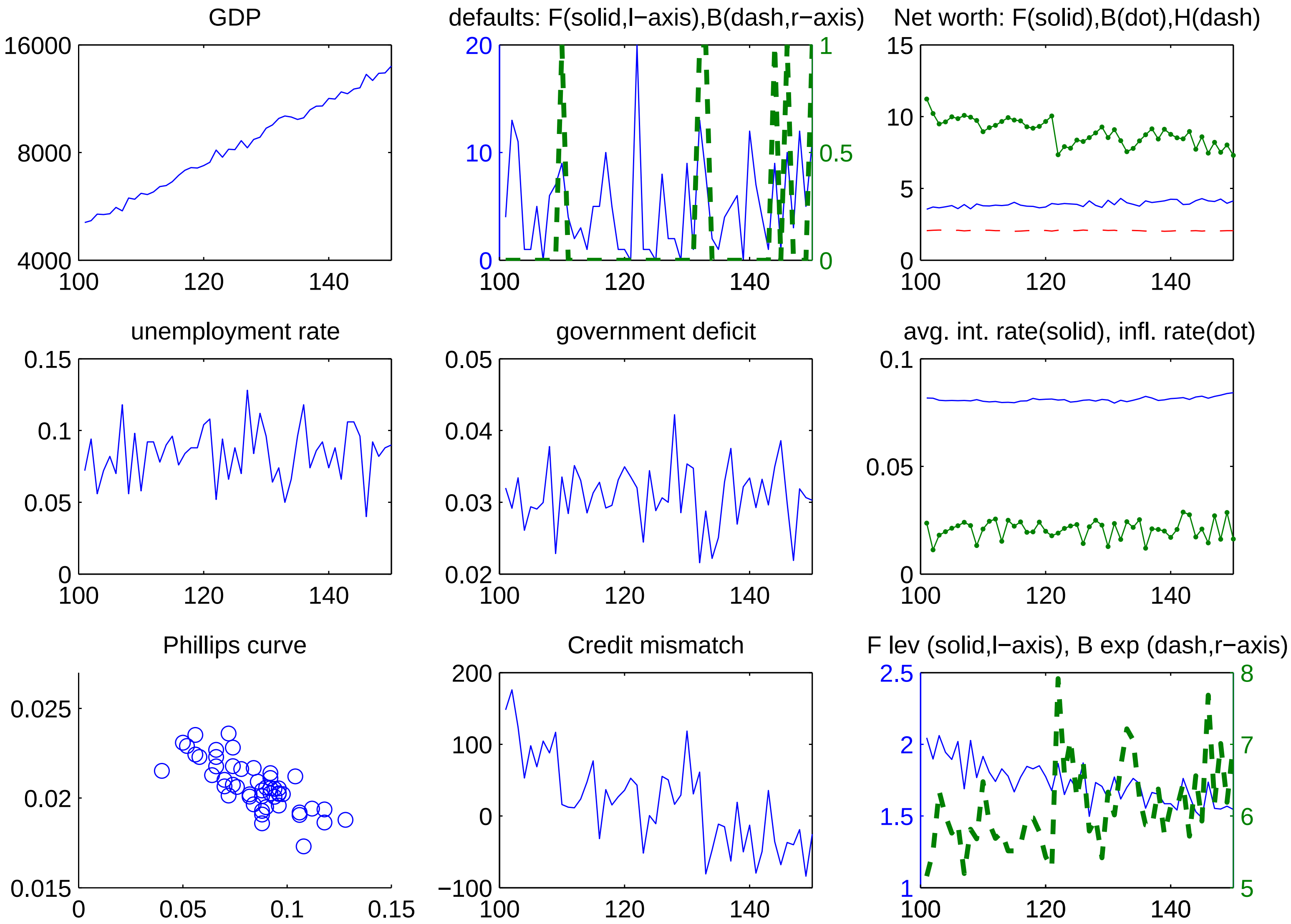

Figure 1: Baseline model: Simulation results

to bank's net worth. The per-capita average banks' net worth (in real terms) is 8.91 (min 7.30, max 11.23). Moreover, credit mismatch (that is the difference between banks' credit supply and firms' credit demand) tends to follow the cycle of banks' net worth: when banks are poorly capitalised this results in credit rationing for firms; in this case, the central bank intervenes providing credit to banks; on the contrary, when banks are well capitalised they are able to fulfill all credit demand. Accordingly, firms' mean leverage is influenced by credit availability. The mean interest rate charged by banks on firm loans is 8.11%. Per-capita households wealth (in real terms) is stable around 2.06 (min 2.01, max 2.10), while the same value for firms is equal to 3.91 (min 3.54, max 4.31). Finally, the average ratio between public deficit and GDP is equal to 3.09% (min 2.16%, max 4.22%). It is worth to note that the presence of the government, nevertheless the relatively low level of public deficit, allows for the nominal growth in the model. This outcome also depends on the working of the central bank that finances the government buying public securities charging a low interest rate.

6.1 Monte Carlo replication of the baseline model

In order to check the robustness of our findings, we performed 1000 Monte Carlo simulations of the baseline model. The first result of this computational experiment is that in some replications the economy completely crashes and the unemployment rate reaches very large values. To identify the worst case scenarios we set a threshold for the average unemployment rate equal to 20%. Then, we discard the five simulations with an average unemployment rate (computed over the time span 101-150) above the threshold. The statistics of the Monte Carlo experiment on the remaining 995 simulations are reported in Table 2. The results describe the average macroeconomic behaviour of the system, showing that mean variables values are quite stable across repeated simulations. The only two variables which are more unstable across simulations are: the credit constraint (that is, the fraction of firms' required credit not fulfilled by banks), and the bank exposure (calculated as the amount of credit lent to firms divided by net worth). The latter variable has a relevant procyclical impact on the economy, that is there is a significant negative correlation across between bank exposure and unemployment. In particular, the mean value across simulations is equal to -50.09% (with a standard deviation of 16.03%).

Let's now analyse in more detail the relationship between financial variables, like firm leverage and bank exposure, and the unemployment rate (which represents the main real variable in our macroeconomic framework).

Figure 2 shows that there is a negative non-linear relation between firm leverage and unemployment. It is worth to note that for relatively high levels of firm leverage the unemployment rate tends to be smaller and less volatile. However, for largest values of the firm leverage (above 2) the negative relation with the unemployment rate tends to disappear or rather it reverses (as shown by the cubic fit in the Figure).

Figure 2: Firm leverage and unemployment rate.

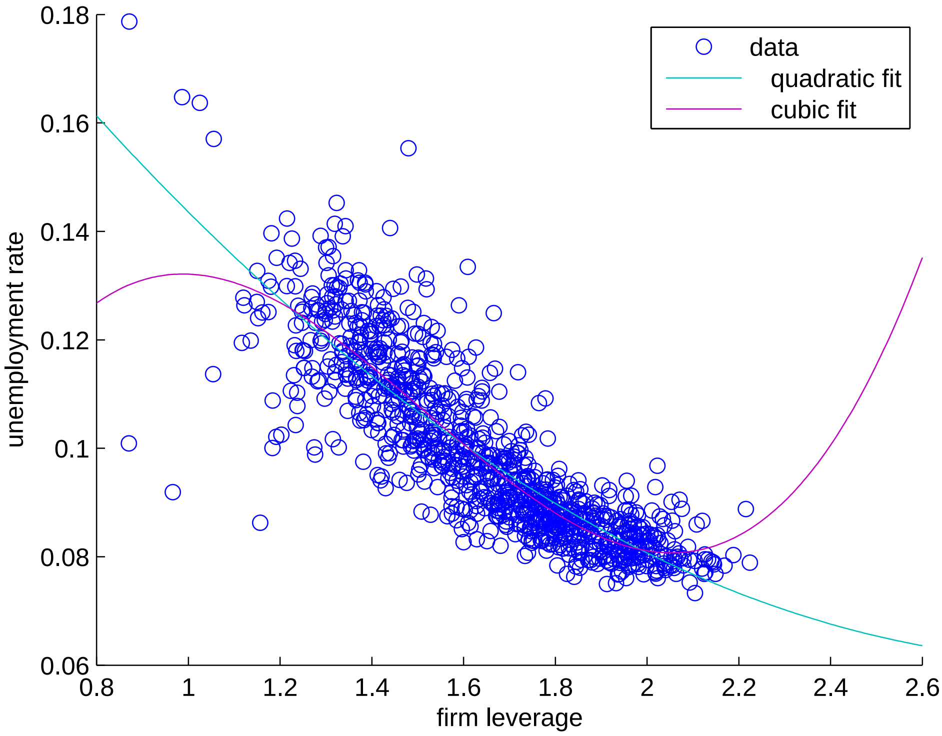

Figure 3: Bank exposure and unemployment rate.

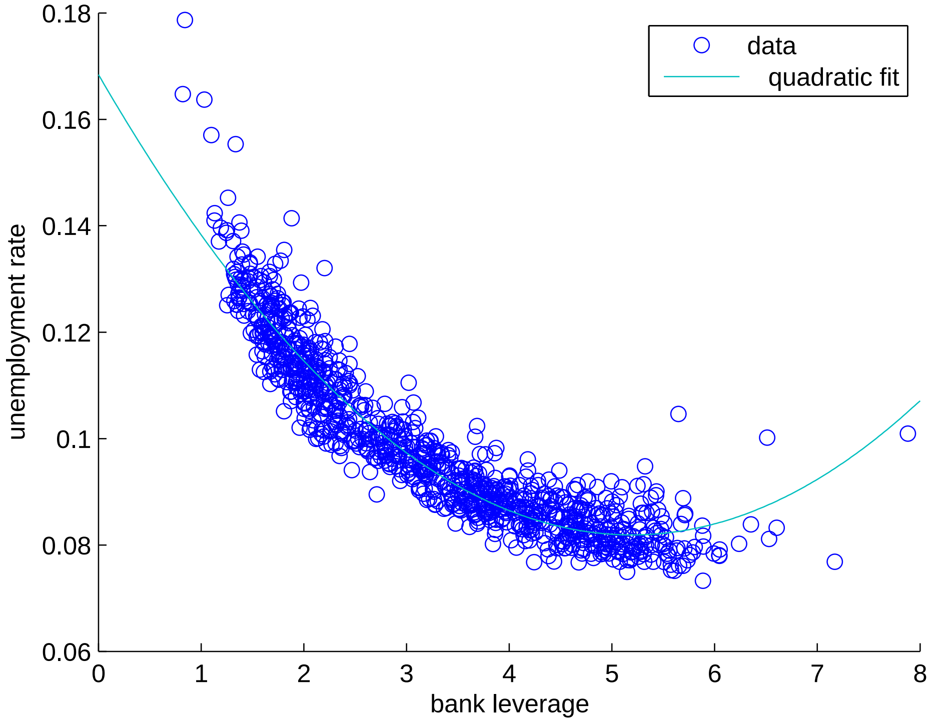

Table 2: Monte Carlo replications: mean values and corresponding standard deviation (calculated over the time span 101-150) of 995 simulations with average unemployment rate below 20%.

Variable	Mean	St. Dev.
Unemployment rate	9.92%	1.63%
Unemployment volatility	2.05%	0.48%
Firm default rate	6.45%	2.10%
Bank default rate	0.57%	0.57%
Wage share	63.4%	0.53%
Public deficit	3.26%	0.19%
Interest rate	9.11%	1.93%
Inflation rate	1.99%	0.07%
Credit constraint	14.83%	8.23%
Firm mean leverage	1.65	0.24
Bank mean exposure	3.27	1.30
Firm leverage volatility	0.12	0.04
Bank exposure volatility	0.51	0.33

Figure 3 shows that a non-linear relation between bank exposure and unemployment emerges. In particular, for low levels, an increase of bank exposure reduces the rate of unemployment. Instead, for high levels of bank exposure (that is, above 5) a further increase makes the unemployment higher. In other words, if banks increase their exposure enlarging credit to firms, the latter hire more workers and the unemployment rate decreses. But, when the exposure of banks becomes "excessive" this leads to instability (more failures) and an increase of the unemployment rate follows.

7 A computational experiment

In this section we perform a computational experiment regarding the parameter β that governs banks' credit portfolio concentration. β can be interpreted both as a behavioural parameter (when it increases the bank is more prone to concentrate the credit risk and vice versa) or a regulatory constraint (according to which it is not allowed for banks to exceed a concentration threshold). We perform 1000 replications of the model organised as follows: 20 simulations for each values of β from 1% to 50% with step 1%, keeping unchanged all the other parameters.

Figure 4 shows that for very small values of β there is a relevant credit rationing which causes many firm defaults and high rate of unemployment, even though banks are safe and their default is very unlikely.

As the parameter grows, while remaining low, the credit mismatch reduces or disappears

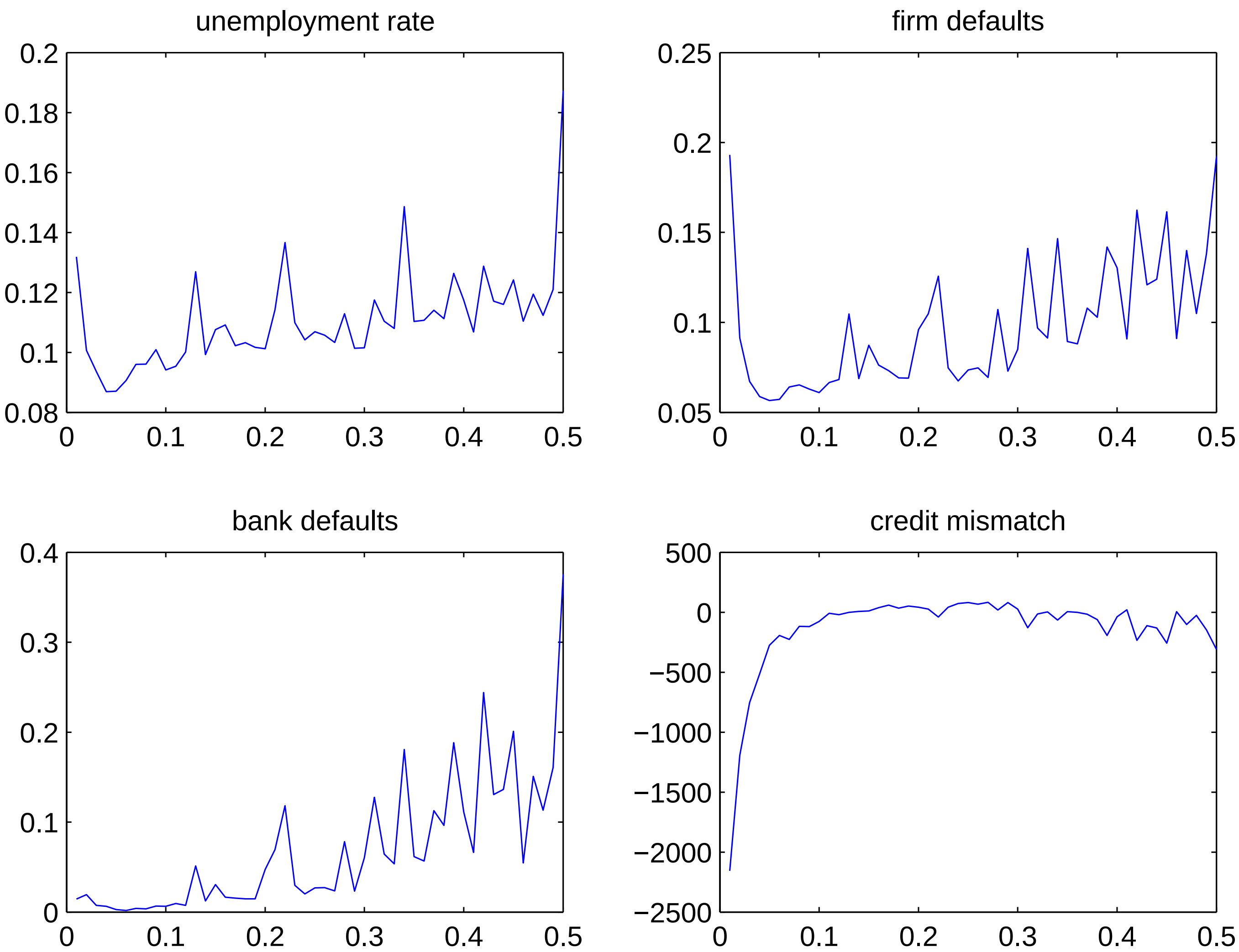

Figure 4: Bank lending concentration: from β=0.01 to β=0.5 with step 0.01.

and a reduction of firm defaults and unemployment follows. For increasing values of β, the riskiness of the financial system tends to increase, as shown by the growing number of bank defaults. This induces at first a slight increase of the mean rate of unemployment. Then, when the constraint becomes too loose, system's financial fragility is excessive and this can lead to large bankruptcy avalanches of firms and banks. As a consequence, banks' net worth collapses resulting in a strong credit constraint. At the same time, firms are not able to hire workers because their net worth also falls down and they do not receive enough credit from the banking system. Hence, credit crunches result in large unemployment rates.
Figure 4 is built on data from all the 1000 replications. However, the qualitative result continues to hold even if we consider only the simulations for which the average unemployment rate is below 20% (as already done in the previous Section). The simulations above this threshold are 24 out of 1000 and it is more likely to observe such a worst case scenarios when the level of β is high (see Table 3).

Table 3: Number of simulations with average unemployment rate above 20% for different values of β.

β (%)	# simulations
1-5	0
6-10	0
11-15	1
16-20	0
21-25	3
26-30	0
31-35	2
36-40	4
41-45	4
46-50	10

To further check the robustness of this result, we perform two additional Monte Carlo experiments on a longer time span, that is 500 periods. In particular, the first experiment keeps the value of the parameter β as in the baseline model (0.1); in the second we set the parameter equal to 0.5. For each values we run 100 simulations and collect statistics for the period 101-500. When β is equal to 0.1, the mean value across the 100 average unemployment rates is equal to 10.03% and only in two cases the average unemployment rate exceeds the 20% threshold. Instead, when the parameter is set to 0.5, the mean value is 17.32% and we observe 22 worst cases. Moreover, we compute some conditional statistics: when $\beta = 0.1$ the mean value of unemployment in the two worst cases is 24.74%, while this is equal to 9.73% in the remaining 98 simulations; when $\beta = 0.5$ the mean unemplyment in the 22 worst cases is 41.12%, while it is equal to 10.61% in the other 78 simulations. On the one hand, the main difference between the two parameter settings depends on the frequency of observing large and extended crises (which is significantly higher with $\beta = 0.5$). On the other hand, the levels of the unemployment rate are not largely different in the two settings when we discard the worst cases.

8 Concluding remarks and future research

We present an agent-based macroeconomic model in which heterogeneous agents (households, firms and banks) interact according to a fully decentralized matching mechanism. The matching protocol is common to all markets (goods, labor, credit, deposits) and represents a best partner choice in a context of imperfect information.

Model simulation shows that decentralized interactions among heterogeneous entities give rise to emergent macroeconomic properties like the growth of nominal GDP, the fluctuation of the unemployment rate, the presence of the Phillips curve, the relevance of leverage cycles and credit constraints on economic performance, the presence of bank defaults and the role of financial instability, and the importance of government in providing a fraction of the aggregate demand and then as an acyclical sector which stabilize the economy.

Monte Carlo simulations show that model findings are quite robust. A particularly relevant result is that a non-linear relation between firm leverage and unemployment emerges: for relatively high levels of firm leverage the unemployment rate tends to be smaller and less volatile. However, for largest values of the firm leverage the negative relation with the unemployment rate tends to reverse. Also bank exposure and unemployment are non-lineraly related: for low levels, an increase of bank exposure reduces the rate of unemployment; instead, for high levels of bank exposure a further increase makes the unemployment higher. In other words, if banks increase their exposure enlarging credit to firms, the latter hire more workers and the unemployment rate decreses. But, when the exposure of banks becomes "excessive" this leads to instability (more failures) and an increase of the unemployment rate follows. All in all, firm leverage and bank exposure may support the working of the economy (reducing the unemployment rate), but when the levels of both leverage or exposure turn to be excessive, the economy becomes too financially fragile (and unemployment may rise).

Our modeling framework can be useful to understand the effects of some policy or institutional changes. As an example, we perform a computational experiment on the role of the parameter governing banks' credit portfolio concentration. This behavioural parameter can be also interpreted as a regulatory constraint. Repeated simulations show that if regulation is excessively tight then strong credit constraints emerge causing high unemployment and a further weakness of economic and financial conditions in a vicious circle. By contrast, if the regulatory constraint is too loose then an excessive financial risk follows and this may result in bankruptcies avalanches of firms and banks and large unemployment.

In future developments we will analyse the role of other parameters, so to investigate the effect of fiscal and monetary policies, labor market rigidity, heterogeneous consumption behavior, etc. Moreover, the baseline model presented in this paper will be enriched by adding modules as the interbank market, the stock and bond markets (allowing agents to decide their portfolio allocation), and long-run growth factors (heterogeneous workers' skills, R&D investments, etc.).

References

[1] Cincotti S., Raberto M., Teglio A. (2010), "Credit money and macroeconomic instability in the agent-based model and simulator Eurace", *Economics - The Open-Access, Open-Assessment E-Journal*, Kiel Institute for the World Economy, 4(26): 1-32.

[2] Delli Gatti D., Gallegati M., Greenwald B., Russo A., Stiglitz J.E. (2010), "The financial accelerator in an evolving credit network", *Journal of Economic Dynamics and Control*, 34(9): 1627-1650.

[3] Donaldson G. (1961), "Corporate debt capacity: a study of corporate debt policy and the determination of corporate debt capacity", Harvard Business School, Harvard University.

[4] Dosi G., Fagiolo G., Roventini A. (2006), "An Evolutionary Model of Endogenous Business Cycles", *Computational Economics*, 27(1): 3-34.

[5] Dosi G., Fagiolo G., Roventini A. (2010), "Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles", *Journal of Economic Dynamics and Control*, 34(9): 1748-1767.

[6] Dosi G., Fagiolo G., Napoletano M., Roventini A. (2012), "Income Distribution, Credit and Fiscal Policies in an Agent-Based Keynesian Model", *LEM Papers Series* 2012/03, Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy.

[7] Epstein J.M., Axtell R.L. (1996), *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press.

[8] Fagiolo G., Dosi G., Gabriele R. (2004), "Matching, Bargaining, And Wage Setting In An Evolutionary Model Of Labor Market And Output Dynamics", *Advances in Complex Systems*, 7(2): 157-186.

[9] Flannery M.J., Rangan K.P. (2006), "Partial adjustment toward target capital structures", *Journal of Financial Economics*, 79(3): 469-506.

[10] Gaffeo G., Delli Gatti D., Desiderio S., Gallegati M. (2008), "Adaptive Microfoundations for Emergent Macroeconomics", *Eastern Economic Journal*, 34(4): 441-463.

[11] LeBaron B., Tesfatsion L.S. (2008), "Modeling Macroeconomies as Open-Ended Dynamic Systems of Interacting Agents", *American Economic Review*, 98(2): 246-250.

[12] Myers S.C., Majluf N.S. (1984), "Corporate Financing and Investment Decisions When Firms Have Information that Investors Do Not Have", *Journal of Financial Economics*, 13: 87-224.

[13] Riccetti L., Russo A., Gallegati M. (2011), "Leveraged Network-Based Financial Accelerator", *Quaderno di Ricerca* 371, Department of Economics and Social Sciences, Università Politecnica delle Marche.

[14] Russo A., Catalano M., Gaffeo E., Gallegati M., Napoletano M. (2007), "Industrial dynamics, fiscal policy and R&D: Evidence from a computational experiment", *Journal of Economic Behavior & Organization*, 64(3-4): 426-447.

[15] Tesfatsion L.S., Judd K.L. (2006), *Handbook of Computational Economics: Agent-Based Computational Economics*, Vol. 2, North-Holland.