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No man is an Island: The impact of heterogeneity and local interactions on macroeconomic dynamics

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ABSTRACT

We develop an agent-based model in which heterogeneous firms and households interact in labor and good markets according to centralized or decentralized search and matching protocols. As the model has a deterministic backbone and a full-employment equilibrium, it can be directly compared to Dynamic Stochastic General Equilibrium (DSGE) models. We study the effects of negative productivity shocks by way of impulse-response functions (IRF). Simulation results show that when search and matching are centralized, the economy is always able to return to the full-employment equilibrium and IRFs are similar to those generated by DSGE models. However, when search and matching are local, coordination failures emerge and the economy persistently deviates from full-employment. Moreover, agents display persistent heterogeneity. Our results suggest that macroeconomic models should explicitly account for agents' heterogeneity and direct interactions. Moreover, our results point to the role of quantity adjustments in determining the ability of the economy to return or not to full-employment.

1. Introduction

In this work, we develop a small-scale agent-based model to study the macroeconomic outcomes (e.g. full-employment, coordination failures, involuntary unemployment) emerging out of the interactions occurring between heterogeneous firms and households in good and labor markets.

Following the “New Classical” revolution, most macroeconomists have been developing micro-founded macroeconomic models where a fully rational, representative household or firm maximizes an intertemporal utility or profit function under some constraints. Such a methodological commitment has allowed the profession to circumvent the problems of existence and stability of the general equilibrium (Kirman, 1989). Nevertheless, the price paid for such a shortcut has not been cheap: agents' heterogeneity and local interactions have been disregarded (see Kirman, 1992, for a sharp critique of the representative agent assumption).

At the same time, since the seminal contribution of Leijonhufvud (1970), a contrasting research venture has been studying how coordination mechanisms in decentralized markets can possibly lead to full-employment equilibrium or to persistent disequilibria (see e.g. Solow and Stiglitz, 1968; Clower and Leijonhufvud, 1975). In the latter case, mismatches between demand and supply of goods and labor are the norm, coordination failures (Cooper and John, 1988) and involuntary unemployment can endogenously arise.

The natural outcome of such a program is to consider the economy as a *complex evolving system*, i.e. as an ecology populated by heterogeneous agents whose far-from-equilibrium interactions continuously change the structure of the system (Farmer and Foley, 2009; Kirman, 2010, 2016; Rosser, 2011; Dosi, 2012; Battiston et al., 2016). This is the methodological core of agent-based computational economics (ACE, Tesfatsion and Judd, 2006; LeBaron and Tesfatsion, 2008). Agent-based models (ABM) have “behavioral” microfoundations (Akerlof, 2002): in line with the micro-empirical evidence, agents (e.g. firms, workers, households) behave adaptively and employ heuristics in their decision and forecasting processes (see e.g. Tversky and Kahneman, 1986; Gigerenzer and Brighton, 2009; Camerer et al., 2011; Gigerenzer and Goldstein, 2011; Hommes, 2014).

Agent-based models have received increasing attention after the Great Recession, and policy makers have called for a plurality of methods (see e.g. Trichet, 2010; Haldane, 2016). According to the former president of the European Central Bank, Jean-Claude Trichet (2010):

> *The key lesson I would draw from our experience is the danger of relying on a single tool, methodology or paradigm. Policy-makers need to have input from various theoretical perspectives and from a*

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range of empirical approaches. Open debate and a diversity of views must be cultivated [...] First we need to deal better with heterogeneity across agents and the interaction among those heterogeneous agents. Agent-based modelling dispenses with the optimization assumption and allows for more complex interactions between agents. [...] Second, we may need to consider a richer characterization of expectation formation. Rational expectations theory has brought macroeconomic analysis a long way over the past four decades. But there is a clear need to re-examine this assumption [...] Third, we need to better integrate the crucial role played by the financial system into our macroeconomic models.

As agent-based models[1] have taken a different methodological and theoretical perspective with respect to DSGE models, a comparison between the two different approaches is needed.[2] This is the aim of the present work, where we develop a parsimonious[3] model which bridges the agent-based framework with the DSGE one (see Fagiolo and Roventini, 2012, 2017, for a comparison of the DSGE and ACE paradigms).

The first set of research questions we explore with our model are: (i) the extent to which DSGE and agent-based models are different and, related to that, (ii) the identification of the fundamental mechanisms that allow one to move from one perspective to the other. This is possible as our ABM is — similarly to DSGE models — characterized by the presence of a full-employment homogeneous-agents equilibrium, which can be considered as the reference point for the dynamics of the economic system. Moreover, as in a DSGE framework, the model sports a deterministic skeleton that can be hit by exogenous stochastic shocks. Such a structure allows one to directly compare the impulse-response functions (IRF) produced by both models and to assess the conditions (if any) under which the economy goes back to the full-employment equilibrium after a shock.

The second set of research questions that we explore relates to the understanding of: (i) the possible emergence of coordination failures out of the interactions of agents in the goods and labor markets, and (ii) the role of real wage flexibility as a coordination mechanism to restore the full-employment equilibrium.

In the model, market interactions among (possibly) heterogeneous firms and households occur according to two different protocols. Similarly to DSGE models, in the *centralized matching scenario*, a fictitious auctioneer solves any possible coordination problem among the agents. On the contrary, in the *decentralized matching scenario*, agents locally interact in the markets. In such a regime, matching frictions and agents' heterogeneity may lead to imperfect allocations of goods and labor.

In both scenarios, we study the response of the economy to negative productivity shocks. Simulation results show that in the fully centralized scenario, the economy always come back to the full-employment equilibrium, thus exhibiting a dynamics consistent with standard DSGE models. The presence of a “benevolent social planner” that organizes information efficiently works as a deus ex machina, thus solving any possible coordination issue among agents. On the contrary, in the fully decentralized regime, where information is dispersed and interactions are local, the economy fluctuates around an underemployment equilibrium characterized by persistent heterogeneity in firm and household populations. In addition, real wage movements are not able to drive the economy back to the full-employment equilibrium. The latter results depends on the interplay between demand feedbacks and matching frictions in a population of heterogeneous agents.

Our results suggest that macroeconomic models should seriously take into account agents' heterogeneity and decentralized market interactions. They also highlight the importance of quantity adjustment mechanisms (more than price adjustments) in determining the ability of the economy to keep full-employment.

The rest of the work is organized as follows. In Section 2, the model is introduced. Simulation results are presented in Section 3. Finally, Section 4 concludes.

2. The model

We consider a closed economy populated by F firms and H households. Firms produce a consumption good by using a linear technology that employs only labor. Households supply labor inelastically and consume the final good using the wage received by firms and their stock of liquid wealth. In the good and labor markets, firms and households are matched according to different protocols. The model is stock-flow consistent (SFC, see e.g. Godley and Lavoie, 2012): the transaction flow matrix is reported in Appendix A.

2.1. Timeline of events

In any given time period (t), the following microeconomic decisions take place in sequential order:

1. Financial state variables are updated. Firms update their net-worth and households update their wealth.
2. Firms set their offered wage, the selling price and determine their expected demand.
3. Households compute their desired consumption levels.
4. The labor market opens. Employers and employees are matched using different protocols (see Section 2.3.1 below). Production takes place. Households receive their wages.
5. The goods market opens. Firms and consumers are matched using different protocols (see Section 2.3.2 below). Firms compute their profits and distribute dividends to households.
6. Households calculate their consumption expenditure and their savings.
7. Bankrupted firms exit from the economy and are replaced by new ones on a one-to-one basis. The wealth of defaulted households is reset to a constant value.

At the end of each time step, aggregate variables (e.g. GDP, investment, employment) are computed summing over the corresponding microeconomic variables.

2.2. Consumption, production, prices and wages

Firms fix production as well as the price and wage they offer to the workers. At the same time, households set their desired consumption.

In line with the spirit of agent-based models and with microeconomic evidence, agents have adaptive behaviors and employ heuristics (see e.g. Tversky and Kahneman, 1986; Gigerenzer and Brighton, 2009; Camerer et al., 2011; Gigerenzer and Goldstein, 2011; Hommes, 2014), which usually boil down to linear decision rules. This also allows to keep the dimensionality of the parameter space as low as possible. Each decision rule is a linear combination of two effects: (i) a *within*' effect reflecting decisions based on the past levels of agent's state variables; (ii) a *network* effect accounting for the position of each agent with respect to its own peers. The latter effect allows to study how social interactions with neighbors (see Brock and Durlauf, 2001; Durlauf, 2004) influence the decisions of each agent.

[1] The number of macroeconomic agent-based model is increasing fast and an exhaustive list is beyond the scope of this work. For germane macro ABMs, see Russo et al. (2007), Dosi et al. (2010, 2013, 2015, 2016), Lamperti et al. (2016), Delli Gatti et al. (2010), Ashraf et al. (2011), Dawid et al. (2014), Riccetti et al. (2015), Assenza et al. (2015), Popoyan et al. (2015), Seppecher and Salle (2015). See also Fagiolo and Roventini (2012, 2017) for a survey of macro agent-based models.

[2] Other works have instead tried to introduce bytes of heterogeneity in standard DSGE models, see e.g. De Grauwe (2012), De Grauwe and Macchiarelli (2015), Assenza et al. (2014), Guerini (2013), Violante et al. (2015), Dilaver et al. (2016) and Agliari et al. (2017).

[3] Our model has a leaner structure than other macroeconomic agent-based models and most medium-scale DSGE models, as it contains a relatively low number of equations and parameters. In addition, it allows the direct computation of one equilibrium (the full-employment one) which enhances comparison with the DSGE frameworks.

The wage of a typical firm f is set as:

$$W_{f,t} = W_{f,t-1} + \gamma \Delta P_{f,t-1} + \alpha z^{lab}_{f,t-1} + \beta(\overline{W}_{f,t-1} - W_{f,t-1}),$$
$$\gamma > 0, \alpha > 0, \beta > 0, \tag{1}$$

where $\Delta P_{f,t-1} = P_{f,t-1} - P_{f,t-2}$ relates price growth to wage dynamics (as in Solow and Stiglitz (1968)). The term $z^{lab}_{f,t-1} = n^d_{f,t-1} - n^s_{f,t-1}$ represents the firm excess demand for labor and implies that a gap between open and filled vacancies will lead to an increase in the wage offered by the firm, thus reflecting the attempts of the latter to become more competitive in attracting workers (see e.g. Mortensen and Pissarides, 1999; Diamond, 1982). The third term captures social interaction effects, measuring the deviations of firm wage with respect to the average wage set by its N_f neighbors in the previous period, i.e. $\overline{W}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} W_{j,t-1}$. We assume that the network is complete so that $N_f = N - 1$ for any firm f and that, in the computation of the average wage, each firm f randomly assigns heterogeneous weights $\omega_{f,j}$ to its neighbors.[4]

In a similar way, firms fix price in an imperfect competition framework according to the linear rule:

$$P_{f,t} = P_{f,t-1} + \gamma \Delta W_{f,t-1} + \alpha z^{good}_{f,t-1} + \beta(\overline{P}_{f,t-1} - P_{f,t-1}),.$$
$$\gamma > 0, \alpha > 0, \beta > 0. \tag{2}$$

The first term indexes price to wage growth. Notice that in the model, wage and price setting rules are linked one with the other, reflecting dynamic wage-indexation to prices and mark-up pricing in the spirit of Solow and Stiglitz (1968). Moreover, in line with "customer market" models (Phelps and Winter, 1970; Diamond, 1971; Greenwald and Stiglitz, 2003), firms increase their price in presence of positive excess demand $z^{good}_{f,t-1} = q^d_{f,t-1} - q^s_{f,t-1}$ to exploit market power. Finally, the latter term in Eq. (2) captures the distance between the firm's price and the average one of its neighbors in the previous period ($\overline{P}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} P_{j,t-1}$). Again, we assume that the firms network is complete, i.e. $N_f = N - 1, \forall f$.

The production of the consumption good takes place by means of a linear production process employing only labor ($n_{f,t}$):

$$q^s_{f,t} = a_{f,t} n_{f,t}, \tag{3}$$

where $a_{f,t}$ is the firm-specific labor productivity. Output is perishable and cannot be stored for the next period. Firms set desired production ($\hat{q}_{f,t}$) using a rule accounting for both within and network effects:

$$\hat{q}_{f,t} = \tilde{q}_f + \alpha z^{good}_{f,t-1} + \beta(\overline{q}_{f,t-1} - q_{f,t-1}). \quad \alpha > 0, \beta > 0. \tag{4}$$

The term $\tilde{q}_f$ captures reference production level, in line with the insights from behavioral economics about reference-dependence and the role of status quo biases in decision-making (see e.g. Kahneman et al., 1991; Koszegi and Rabin, 2009). The above rule implies that deviations from the reference level of production are due to past excess demand $z^{good}_{f,t-1}$ and to the relative position of the firm vis-á-vis its neighbors $q_{f,t-1} - \overline{q}_{f,t-1}$, with $\overline{q}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} q_{j,t-1}$ being the average production level set by firm f's neighbors in the previous period.

Similarly to firms, households have a reference level for consumption, $\tilde{c}_h$. In addition, consumption is determined by the real value of wealth growth ($\Delta A_{h,t}/P_{t-1}$) to take into account the empirically relevant effect of wealth variation on consumption (see Sousa, 2009; Jawadi and Sousa, 2014). Moreover, household consumption is affected by social interaction effects, captured by the average level of past consumption across neighbors, $\overline{c}_{h,t-1} = \sum_{j=1}^{N_h} \omega_{h,j} c_{j,t-1}$. Such an effect allows one to account for external habits (see Abel, 1990; Duesenberry, 1949). To sum up, desired consumption is fixed according to:

$$\hat{c}_{h,t} = \tilde{c}_h + \alpha \frac{\Delta A_{h,t}}{P_{t-1}} + \beta(\overline{c}_{h,t-1} - c_{h,t-1}), \quad \alpha > 0, \beta > 0. \tag{5}$$

2.3. Search and matching

In both goods and labor markets, there are two alternative matching scenarios. In the *centralized matching* scenarios, the presence of a fictitious auctioneer allows to avoid possible coordination issues among agents in the market. On the contrary, in the *decentralized matching* scenario, firms and workers interact locally in both the goods and labor market (in line with an increasing literature in agent-based models, see e.g. Ashraf et al., 2011; Riccetti et al., 2015; Assenza et al., 2015; Popoyan et al., 2015; Seppecher and Salle, 2015; Dosi et al., 2016). Such a scenario allows us to study the relevance of heterogeneity and interactions and the possible emergence of coordination failures in a fully decentralized economy subject to shocks (more in Section 3 below).

2.3.1. The labor market

Firms demand labor to fulfill their production plans. Workers supply labor inelastically and have a zero reservation wage. Labor is measured in working hours terms.

Centralized matching regime. An "auctioneer" collects vacancies posted by firms and allocate workers to firms in proportion to their relative wage offers. Given the total number of households (H) and firms (F), the amount of labor supply allocated to each firm f is:

$$n^s_{f,t} = \frac{H}{F}\left(\frac{W_{f,t}}{\overline{W}_t}\right). \tag{6}$$

where $W_{f,t}$ is the firm wage and $\overline{W}_t$ is market average wage. The labor demand of each firm is

$$n^d_{f,t} = \left(\frac{\hat{q}_{f,t}}{a_{f,t-1}}\right)\left(\frac{W_{f,t}}{P_{f,t}}\right)^{-\varphi}. \tag{7}$$

The first component in the labor demand equation accounts for genuine "Keynesian" effects related to expectations in the demand for goods. The second one links labor demand to the real wage.

The effective number of hours worked at the firm level is determined by the short side of the market:

$$n_{f,t} = \min\{n^s_{f,t}, n^d_{f,t}\}. \tag{8}$$

It follows that if the demand constraint is binding, i.e. $n^d_{f,t} > n^s_{f,t}$, the firm is not able to cover all the opened vacancies, and it will produce $q_{f,t} < \hat{q}_{f,t}$. On the contrary if the supply constraint is binding, unemployment arises. In the centralized matching scenario, there is no frictional unemployment, and disequilibria at the micro-level can emerge only if total labor demand is higher or lower than total labor supply.

Decentralized matching regime. The matching between firms and workers is local. Firms post their vacancies and wage quotes. Workers decide to queue up or not for the job opened by a firm with a probability increasing in the offered wage. Labor demand is determined as in (7), but workers will search for open vacancies and will queue-up ($\Phi_{h,t} = 1$) or not ($\Phi_{h,t} = 0$) for a job according to the following Bernoulli trial:

$$\Phi^{LM}_{h,t} = \begin{cases} 0 & \textit{with probability } p^{LM}_{f,t} \\ 1 & \textit{with probability } 1 - p^{LM}_{f,t}. \end{cases} \tag{9}$$

A worker can queue up for one job only, and she inelastically supplies one unit of labor. The probability of queuing ($1 - p^{LM}_{f,t}$) is proportional to the wage offered by the firm relative to the market-average one:

$$1 - p^{LM}_{f,t} = 1 - \frac{1}{\rho^{LM}}\left[1 - \left(\frac{W_{f,t} - \overline{W}_t}{\overline{W}_t}\right)\right], \tag{10}$$

where $\overline{W}_t$ is the market average wage and $\rho^{LM} \in (1, \infty)$ is a parameter

[4] In order to generate the random graph we have adopted the Matlab functions built by Bounova and de Weck (2012) and available online at http://strategic.mit.edu/downloads.php?page=matlab_networks.

determining the degree of search frictions (and imperfect information) in the market. The higher the value of ρ^{LM}, the higher the probability that workers will queue up for any given difference between the firm's wage and average one. It follows that higher values of ρ^{LM} also imply higher intensity of competition in recruiting workers, which become more sensitive to wage differences across firms.

Finally, as in the previous scenario, the effective hours at the firm level are determined by the short side of the market, according to (8). However, notice that, differently from the centralized scenario, decentralized matching implies that frictional unemployment (or labor rationing) may arise even when the notional aggregate labor demand and aggregate labor supply are equal.

2.3.2. The goods market

The determination of supply is common in both scenarios: right after the labor market closes and workers have been allocated to the firms, the production of goods take place by means of the linear production process specified in Eq. (3).

Centralized matching scenario. Desired consumption (cfr. Eq. (5)) is aggregated over households. Then total consumption, $\widehat{C}_t = \sum_h \widehat{c}_{h,t}$ is allocated to each firm f on the basis of the firm's price relative to the average one in the market. The (real) goods demand for a single firm f is computed as follows:

$$q^d_{f,t} = \frac{\widehat{C}_t}{F}\left[1 - \left(\frac{P_{f,t}}{\overline{P}_t} - 1\right)\right]. \tag{11}$$

Notice that the above allocation is equivalent to the one that would emerge in equilibrium in Dixit-Stiglitz monopolistic competition. Moreover, the quantity of the consumption good effectively sold by a firm depends on the shortest side of the market:

$$q_{f,t} = \min\{q^d_{f,t}, q^s_{f,t}\}. \tag{12}$$

If demand is higher than supply, then consumers are rationed in a symmetric fashion. On the contrary, if supply is higher than demand, the firm is not able to sell all its output and may experience losses.

Decentralized matching scenario. Contrary to the previous scenario, there is no centralized device attributing consumption shares to firms, and demand allocation is an emergent property of a costly search and matching processes. In addition, similarly to the decentralized labor market scenario, we assume that consumers decide whether to queue-up ($\Phi^{GM}_{h,t} = 1$) or not ($\Phi^{GM}_{h,t} = 0$) for the goods sold by firms with a Bernoulli trial, which is formulated as follows

$$\Phi^{GM}_{h,t} = \begin{cases} 0 & \textit{with probability } 1 - p^{GM}_{f,t} \\ 1 & \textit{with probability } p^{GM}_{f,t}. \end{cases} \tag{13}$$

The probability of a success $p^{GM}_{f,t}$ reads:

$$p^{GM}_{f,t} = \frac{1}{\rho^{GM}}\left[1 - \left(\frac{P_{f,t} - \overline{P}_t}{\overline{P}_t}\right)\right]. \tag{14}$$

A household queues up only in one firm, demanding $\widehat{c}_{h,t}$ units of the good. Notice that the probability of queuing up falls with the price $P_{f,t}$. Accordingly, more price-competitive firms will get longer queues and higher demand for their good. Moreover, the parameter $\rho^{GM} \in (1, \infty)$ in Eq. (14) is inversely related to the quality of the matching in the market. The higher is the value of the parameter, the lower the reaction of firms to differences between their price and the average price in the market. Accordingly, higher values of ρ^{GM} imply higher matching frictions and less competitive markets for goods.

Once all the households have queued up, the effective amount of product sold by a firm, $q_{f,t}$, is determined by the short side of the market as in Eq. (12). Again, if demand is higher than supply, consumers are symmetrically rationed. If the opposite happens, the firm will have some unsold non-storable output that perishes.

2.4. Financial conditions, exit and entry

After the matching process in the goods market is concluded, households determine their effective real consumption $c_{h,t} \le \widehat{c}_{h,t}$ and their consumption expenditures $\sum_{f=1}^{F} P_{f,t} c_{hf,t}$. They also compute savings, as the difference between income and effective nominal consumption. Households' income is represented by the earned wage $W_{h,t}$, and the fraction of firms profits paid as dividends, $D_{h,t}$. Accordingly, savings, $S_{h,t}$, are determined as:

$$S_{h,t} = W_{h,t} + D_{h,t} - \sum_{f=1}^{F} P_{f,t} c_{hf,t}. \tag{15}$$

We assume that the only assets available in the economy is money, which pays a zero interest rate. Households update their wealth ($A_{h,t+1}$) accordingly:

$$A_{h,t+1} = A_{h,t} + S_{h,t}. \tag{16}$$

Whenever the current wealth is higher than the initial one, the excess wealth fuels a fund to bail-in bankrupted households and firms. A household is declared bankrupt whenever her wealth becomes negative. In turn, her wealth is reconstituted at the initial level employing the resources in the bail-out fund.[5]

Firms' profits $\Pi_{f,t}$ are equal to total sales revenues net of labor costs:

$$\Pi_{f,t} = q_{f,t} P_{f,t} - n_{f,t} W_{f,t}. \tag{17}$$

Whenever profits are positive, firms pay a fraction $1 - \vartheta$ as dividends to households. As firm ownerships is symmetric, each household receives a fraction 1/H of the dividends paid by each firm. It follows that the dividends received by household h in period t are equal to:

$$D_{h,t} = \frac{(1 - \vartheta)}{H} \sum_{f=1}^{F} \Pi^+_{f,t}. \tag{18}$$

If profits are negative, firm's net worth is reduced accordingly. The law of motion of $A_{f,t+1}$ is than equal to:

$$A_{f,t+1} = \begin{cases} A_{f,t} + \vartheta \Pi^+_{f,t} \\ A_{f,t} + \Pi^-_{f,t} \end{cases} \tag{19}$$

where $0 \le \vartheta \le 1$ is a parameter governing the fraction of retained profits ($\Pi^+_{f,t}$), and $\Pi^-_{f,t}$ denotes losses.

A firm is declared bankrupt when her net-worth is negative. In such a situation, the firm exits the market and it is replaced by a new entrant. The net-worth of the new firms is drawn from the bail-out fund and it is equal to the initial one. Households own an equal share of the new firm, receiving its future dividends (if any). Finally, prices, wages and desired production of the entrant are computed as the average ones of the incumbents.

3. Simulation results

As anticipated in the introduction, the aim of this paper is to investigate the conditions that allows an economy populated by heterogeneous, interacting agents to converge to the full-employment equilibrium. In particular, we want to study how the matching protocols in labor and good markets affect the convergence process. The model presented in the previous section contains a deterministic skeleton that can be hit by exogenous stochastic shocks affecting structural variables (e.g. productivity). Such a structure is akin to DSGE models (e.g. Clarida et al., 1999; Woodford, 2011) and it allows a direct comparison of the impulse-response functions (IRFs) generated by both types of models. However, in our model all decisions are based on heuristic rules and, in

[5] Note that the presence of the bail-out fund guarantees the stock-flow consistency of the model as to the entry and exit of households and firms. Simulation results show that the resources in the fund are always sufficient to rescue bankrupted agents.

contrast with the typical DSGE model, agents' behavior is adaptive and not grounded on hyper rational, forward looking behavior (see Fagiolo and Roventini (2012, 2017), for a direct comparison of DSGE and agent-based models). Moreover, differently from the DSGE framework, where Walrasian markets clear via price and wage movements, in our model the causality goes from quantities to prices (see Eqs. (1) and (2)).

Our agent-based model is characterized by the presence of a full-employment homogeneous-agents equilibrium (derived in Appendix B). More precisely, we define the full-employment homogeneous-agents equilibrium as a situation characterized by

$$\begin{cases} \Delta x_t = 0, \quad \forall\, x \in \Omega \\ \tilde{u}_t = 0, \quad \tilde{y}_t = 0, \quad \tilde{\pi}_t = 0. \end{cases} \tag{20}$$

where Ω is an array containing all the model (micro and macro) variables (x), $\tilde{y}_t$ is the output gap, and $\tilde{u}_t$ and $\tilde{\pi}_t$ are respectively the deviation of unemployment and inflation from their steady state values. This means that, consistently with the DSGE framework, in our agent-based model we have a possible equilibrium featuring both full-employment, as well as agents' homogeneity. Such an equilibrium is equivalent to the representative agent equilibrium used in DSGE models, and this allows us to directly compare the outcomes generated by our model with those of DSGE ones.

In the next section, we will perform several simulation exercises[6] in order to study the stability of the full-employment equilibrium under different productivity shocks for alternative matching scenarios in the labor and goods markets (cfr. Section 3.1). We will then assess the robustness of our results in Section 3.2. Table 1 contains the values of the parameters of our baseline simulation environment.

3.1. The effects of productivity shocks

We begin by initializing the variables of the model (consumption, wages, prices, production, firms' net worth, households' wealth, etc.) at values compatible with the full-employment, homogeneous-agents equilibrium of the economy (cfr. conditions (20) above). We then let a negative technology shock hit the economy at the firm level and we study the stability of the ensuing equilibrium and the convergence properties of the model. More precisely, we consider a negative, idiosyncratic change in the value of firm productivity at time t^*. The dynamics of the shock writes as:

$$a_{f,t} = \tilde{a}(1 - \eta_{f,t}) \quad where: \begin{cases} if \quad t < t^* \quad \eta_{f,t} = 0 \\ if \quad t = t^* \quad \eta_{f,t} \sim \mathcal{N}(\mu_\eta, \sigma_\eta) \\ if \quad t > t^* \quad \eta_{f,t} = \rho_\eta \eta_{f,t-1}, \end{cases} \tag{21}$$

where μ_η, σ_η, and ρ_η represent, respectively, the mean, the standard deviation and the autoregressive persistence of the shock.[7]

In what follows, the effect of supply shocks will be studied in both the fully *centralized* and *decentralized* scenarios. In the first regime, matching is centralized in both the labor and goods markets, while in the second one, search and matching processes are local in both markets.

The non-linearities in agents' decision rules and their interaction patterns imply that the model does not allow for analytical, closed-form solutions. This is a general feature of agent-based models[8] and it forces us to perform extensive Monte-Carlo analyses to wash away across-simulation variability in order to study the dynamics of micro and macro variables. Consequently, all results below refer to across-run averages over 100 replications and we report the standard-error bands. All the simulations parameters are reported in Table 1.

Table 1
Baseline parametrization of the model.

Model Parameters		
Symbol	*Value*	*Meaning*
MC	100	Monte Carlo realizations
T	1500	time simulations
H	200	number of households
F	20	number of firms
α	0.4	sensitivity to main economic effects
β	0.4	sensitivity to social effects
γ	0.4	sensitivity of wage/price indexations
ϑ	0.5	percentage of retained profits
φ	5	sensitivity of labor demand to real wage
ρ^{LM}	2	easiness of matching in the labor market
ρ^{GM}	2	difficulty of matching in the goods market
μ_η	−0.01	supply shock average
σ_η	0.002	supply shock variance
ρ_η	0.98	supply shock persistence

3.1.1. Productivity shocks in the fully centralized scenario

In presence of a negative productivity shock, firm production falls immediately causing a period of excess demand in the goods market (cfr. Fig. 1). As a consequence, households are rationed and are forced to increase saving. Such a situation increases prices and in turn induces firms to demand more labor, putting inflationary pressure on wages. In addition, prices will rise further as they are indexed to wages and there is still excess demand in the market for goods. However, as prices change more than wages, the real wage will fall.

The centralized allocation mechanism at work in the labor market avoids any rise of frictional unemployment. This fact, together with the higher savings from demand rationing, contributes to keep aggregate demand high,[9] and the excess demand in the two markets to persist as long as production is constrained by low productivity. However, as time goes by, productivity will monotonically return to its equilibrium level. Accordingly, production will be back to the equilibrium level, causing excess demand to vanish. The system settles down in the original equilibrium (cf. Fig. 1). In this scenario, out-of-equilibrium dynamics are only temporary and the system is able to effectively reabsorb the shock.[10]

Fig. 2 shows the evolution of the variance of the distributions of some key micro variables of the model. The figure provides insights about the agents' heterogeneity that underlies the aggregate dynamics exposed above. As the plots reveal, the micro-level heterogeneity introduced by the productivity shock is only temporary, very mild, and limited to few variables of the system. In particular, constant hours worked, together with steady full-employment, lead to homogeneity in wages. Finally, the effects of agents' heterogeneity do not persistently affect macroeconomic dynamics and eventually dies off when the effect of the shock become nil.

The foregoing results show that an economy with fully centralized matching protocols is able to restore the full-employment equilibrium without creating persistent distortions in the system and the emergence of coordination failures. This result is perfectly in line with DSGE macroeconomics. In particular, the simulation dynamics in this scenario replicates the behavior of standard impulse response functions (IRFs) produced by Real Business Cycles and New Keynesian DSGE models (e.g. Clarida et al., 1999), as well the standard results in the empirical

[6] The pseudo-code of the model is reported in Appendix Appendix C. The code is available from the authors upon request.

[7] The above formulation of the productivity shock is also in line with Cooper and Schott (2013), who introduce firm heterogeneity in a simple real business cycle model by means of idiosyncratic technology shocks. In what follows, the shock will hit all the firms, but the results are robust also with respect to shocks that hit only sub-samples of firms.

[8] Methodological issues concerning the exploration of the properties of agent-based models are discussed in Fagiolo et al. (2007) and Fagiolo and Roventini (2012, 2017).

[9] In particular, real savings from demand rationing rise more than the fall in real income due to lower real wages.

[10] We performed experiments under positive supply shocks. We observed two main differences occur with respect to the negative shocks dynamics. The first concerns the behavior of the unemployment, which initially rises due to a substitution effect between workforce and productivity. The second one concerns the type of convergence to the full-employment equilibrium, which is oscillatory rather than monotonic.

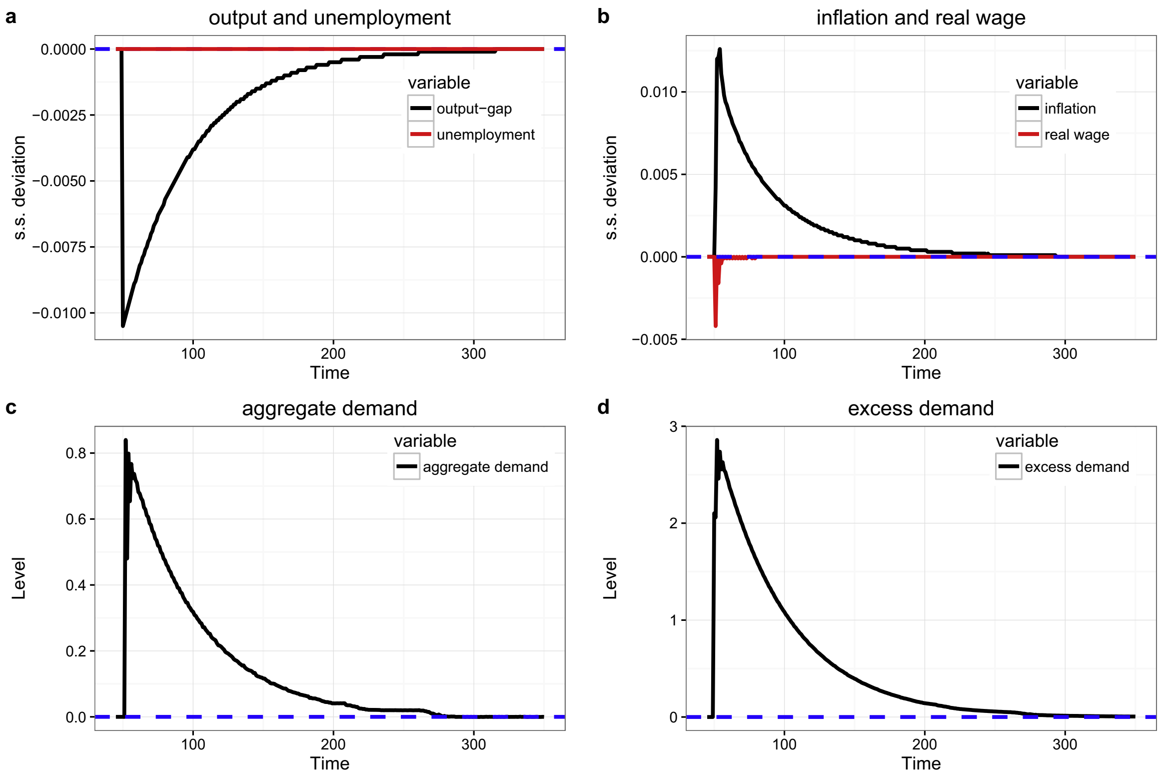

Fig. 1. Emergent macroeconomic dynamics under supply shocks. Fully centralized scenario.

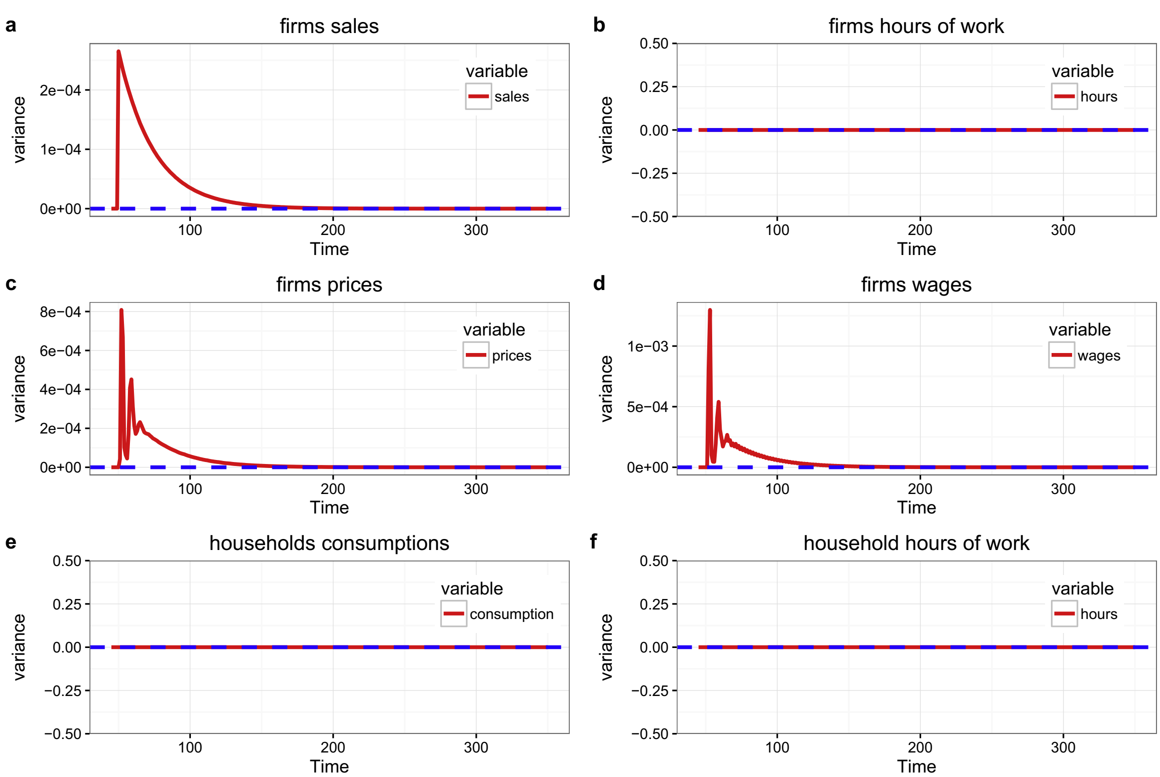

Fig. 2. Micro-level variances under supply shocks. Fully centralized scenario.

macro literature, showing that in presence of supply shock, prices and output move in opposite directions (see Blanchard, 1989).

3.1.2. Productivity shocks in the fully decentralized scenario

As search and matching processes are fully decentralized in both the labor and goods markets, the productivity shock creates both frictional unemployment in the labor market, and micro mismatches between demand and supply in the goods market. As a result, significant heterogeneity (see Fig. 4) now emerges both at the firm (in terms of prices, wage offers, output and labor demand) and at household level (in terms of hours worked and incomes).

What is more, micro heterogeneity has now consequences at the

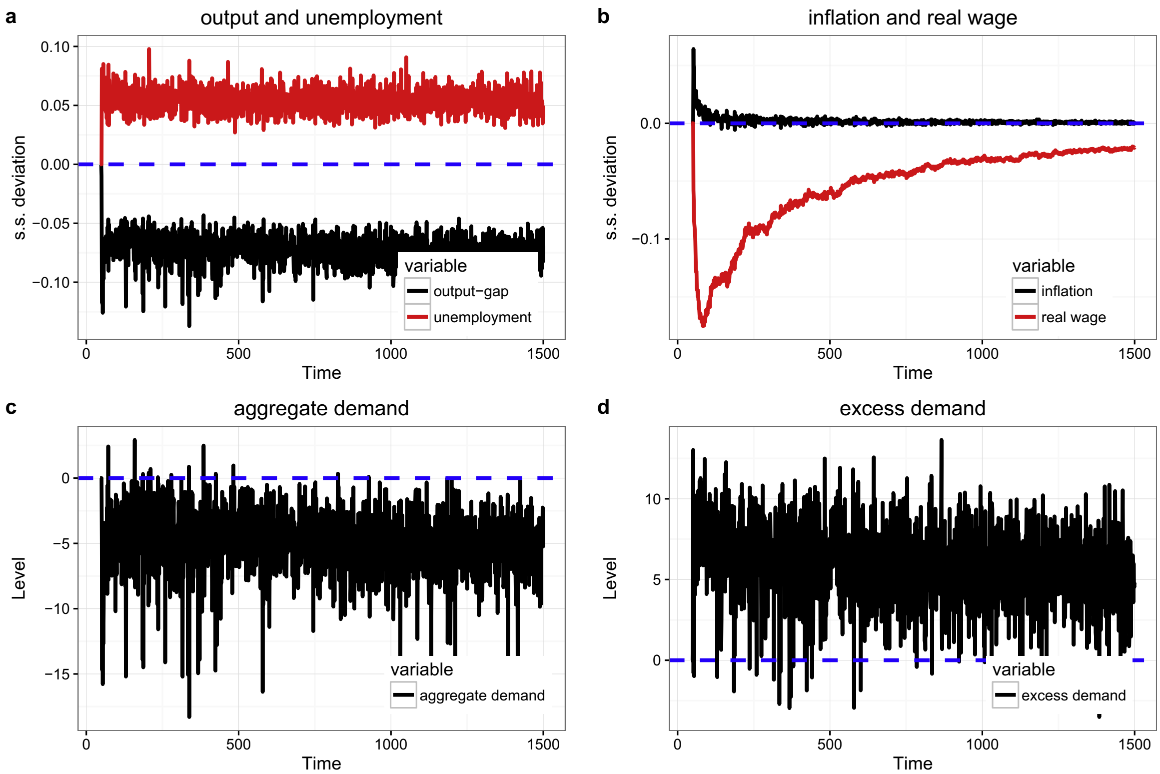

Fig. 3. Emergent macroeconomic dynamics under supply shocks. Fully decentralized scenario.

aggregate level, amplifying the effects of the initial shock. More precisely, the initial frictional unemployment stemming from decentralized matching in the labor market feeds back into lower consumption in the goods market, further contributing to depress firm output, and, in turn, labor demand, and real wages. Indeed, the fall in real wages is much stronger now than in the centralized scenario (compare the second panels in Figs. 3 vs. 1).

The emerging result is a disequilibrium wherein aggregate demand is lower than in the full-employment case and fluctuates around the supply level, causing also *involuntary* unemployment to emerge (cfr. Fig. 3; see Dosi et al., 2010, 2013, 2015, 2016, for agent-based models where involuntary unemployment emerges because of low aggregate demand).

Furthermore, differently from the fully centralized regime, coordination failures emerge and the economy is not able to reabsorb the shock. At the aggregate level, the output-gap and the unemployment keep fluctuating around values that are, respectively, significantly lower and higher than the full-employment equilibrium (cfr. Fig. 3). The same occurs for the levels of aggregate demand and supply, which are persistently lower than full-employment ones. Finally, and again in contrast with the fully centralized scenario, micro-level variance does not fade away in the long-run (see Fig. 4).

The only exceptions to the above general dynamics are represented by price inflation and real wage. Indeed, the fluctuations of such variable are in the long-run much milder than for the other variables (basically zero for inflation) and around steady-state values.

As both the mean and the variance of all the variables in the model exhibit fluctuations around stable values in the long-run, in this scenario the economy self-organizes in a new statistical equilibrium, defined as *a state where some relevant statistics of the system are stationary* (Grazzini and Richiardi, 2015; Guerini and Moneta, 2016).

The persistent heterogeneity at the micro-level arises because frictions in the search and matching processes get now amplified by aggregate demand feedbacks in the goods market and by involuntary unemployment. As a consequence, micro-level heterogeneity now matters for the aggregate, and it is in particular responsible for the persistent deviation of aggregate variables from their full-employment levels. In addition, and well in line with the original Keynes' analysis (see Clower and Leijonhufvud, 1975), price rigidity is not the source of underemployment and coordination failures. Indeed, persistent unemployment and low aggregate demand emerge notwithstanding the fact that the real wage falls and then eventually converges to values close to the old steady-state ones.

3.1.3. *Taking stock of productivity shocks in different search and matching scenarios*

Table 2 summarizes the results obtained so far by presenting the long-run values of the main aggregate variables following the negative supply shock under different matching scenarios. The values presented in the table are averages across 100 Monte-Carlo iterations.

As the table shows quite neatly, the economy is always able to return to the full-employment equilibrium in the fully centralized scenario. In contrast, the presence of an under-employment statistical equilibrium emerges as a robust property[11] across simulation runs in the fully decentralized scenario. Such a statistical equilibrium is always characterized by persistent (negative) output gap and unemployment. Moreover the real wage is lower than in full-employment (see the last column of Table 2). However, differently from DSGE models, a fall in the real wage is not able to eradicate unemployment in the labor market.

Our simulation results show the importance of heterogeneity and interactions for explaining persistent fluctuations in decentralized markets. Indeed, depending on the type of search and matching process, an ecology of heterogeneous agents following adaptive rules may (or not) generate a situation of persistent under-employment. Such a difference in dynamics cannot be typically observed in New Keynesian DSGE models as they are nested in the representative agent equilibrium framework.

[11] We also tested the robustness of the statistical equilibrium by performing Kolmogorov-Smirnov tests of equality in distributions of the Monte-Carlo time series generated by the model for the different macroeconomic variables (see the test for statistical equilibrium performed in Guerini and Moneta (2016)). The results of the test shows that the distributions across Monte Carlo are equivalent over time, indicating that the aggregate variables converge to a statistical equilibrium.

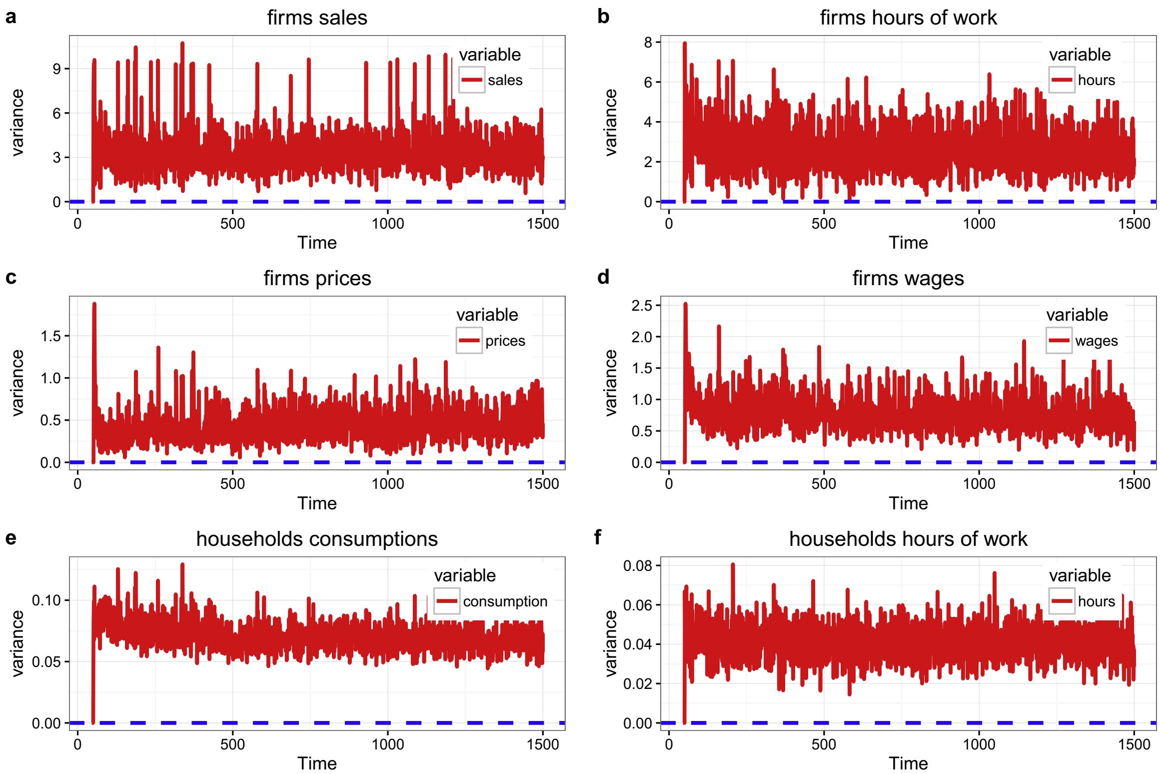

Fig. 4. Micro-level variances under supply shocks. Fully decentralized scenario.

Table 2
Long-run values of the main aggregate variables for different matching scenarios. Values are averages over MC=100 Monte-Carlo iterations. Monte-Carlo standard errors in parentheses. FC: fully centralized scenario. FD: fully decentralized scenario.

	output-gap	unemployment	inflation	real-wage
Supply Shock FC	−0.00 (0.0001)	0.00 (0.0001)	0.00 (0.0001)	−0.00 (0.0001)
Supply Shock FD	−0.06 (0.0001)	0.05 (0.0001)	0.00 (0.0001)	−0.03 (0.0001)

3.2. Robustness analysis

In the previous section we documented how an economy endowed with a decentralized search and matching structure is not able to reabsorb the effects of an adverse supply shock and to go back to the full-employment equilibrium. In this section we turn to investigate the robustness of the foregoing result to changes in some of the key parameters of the model.

We start with the seed in the random number generator governing the impact of the shock in Eq. (21). We find that all simulation results are robust to different sequences of random numbers.

We then study how the results of the model are affected by the persistence of productivity shocks (cfr. Eq. (21)). As expected, increasing the persistence of the shock has only effects in the fully centralized scenario, lowering the speed of convergence of the economy to the full-employment equilibrium.[12]

The parameter regulating the percentage of profits that firms distribute as dividends $(1 - \vartheta)$ is particularly relevant to study as it provides a neat assessment of the role that aggregate demand dynamics plays in the model. Indeed, higher amount of dividends (see Eq. (18)) could possibly compensate the fall in real wages experienced by workers after a negative productivity shock, increasing the resilience of the economy.

However, as Fig. 5 shows, this is not the case. The output-gap and unemployment are basically invariant with respect to an increase in the share of dividends paid to households. Only the inflation rate and the real wage are affected for extreme high values of the parameters. A scenario where almost all profits are paid out as dividends spurs excess demand. As a consequence, firms increase prices, thus leading to the surge of average inflation observed for extremely high values of $1 - \vartheta$. Finally, high inflation rate together with the depressing effect of unemployment on nominal wages explains the fall observed in the real wage.

As an additional robustness exercise, we change the parameters ρ^{LM} and ρ^{GM}, which capture matching frictions in the labor and goods markets. Higher values of ρ^{LM} increase the probability that workers queue up at any given firm, thus increasing the quality of matching in the labor market. Moreover, lower levels of ρ^{GM} raise the probability that households queue up at any given firm in the goods market, thereby boosting the matching quality in that market. In our sensitivity exercise we change the two parameters independently. The results are reported in the heat maps presented in Fig. 6. We find that decreasing matching frictions in both markets improves the overall resilience of the economy, which show an improved ability to get closer to the full-employment equilibrium after a productivity shock (bottom left corners). Indeed, output increases, unemployment and inflation fall, and the real wage is on average smaller. Such results are not surprising: improving matching quality makes market interactions less local: workers and consumers queue up at a larger fraction of firms for any given price and wage differences. Moreover, lower matching frictions imply higher sensitivity of labor and consumption demand to cross-firms price differentials in both markets.

Finally, we explore the causal mechanisms responsible for the stability (or not) of the full-employment equilibrium. On one side, output and unemployment appear to be closer to the full-employment equilibrium in presence of large falls of the real wage. This correlation might suggest the presence of a typical Neoclassical mechanism at work. On the other side, the strong correlation between output, unemployment

[12] The results related to these first two robustness exercises are available from the authors upon request.

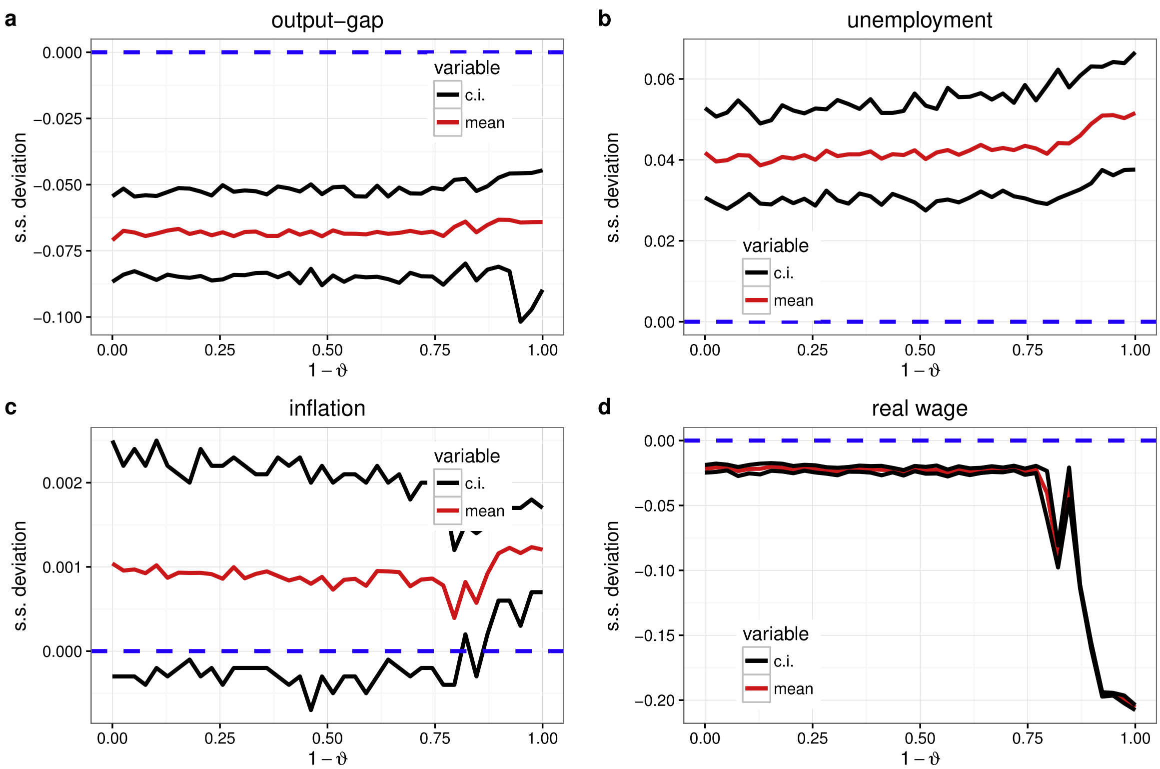

Fig. 5. Effects of a variation on the percentage of retained profits parameters ϑ. The red line represents the mean of the last $T_{ss} = 200$ periods of the simulation, for any parameter value. The black lines represent confidence intervals which are computed as the maximum and the minimum values attained in the same period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

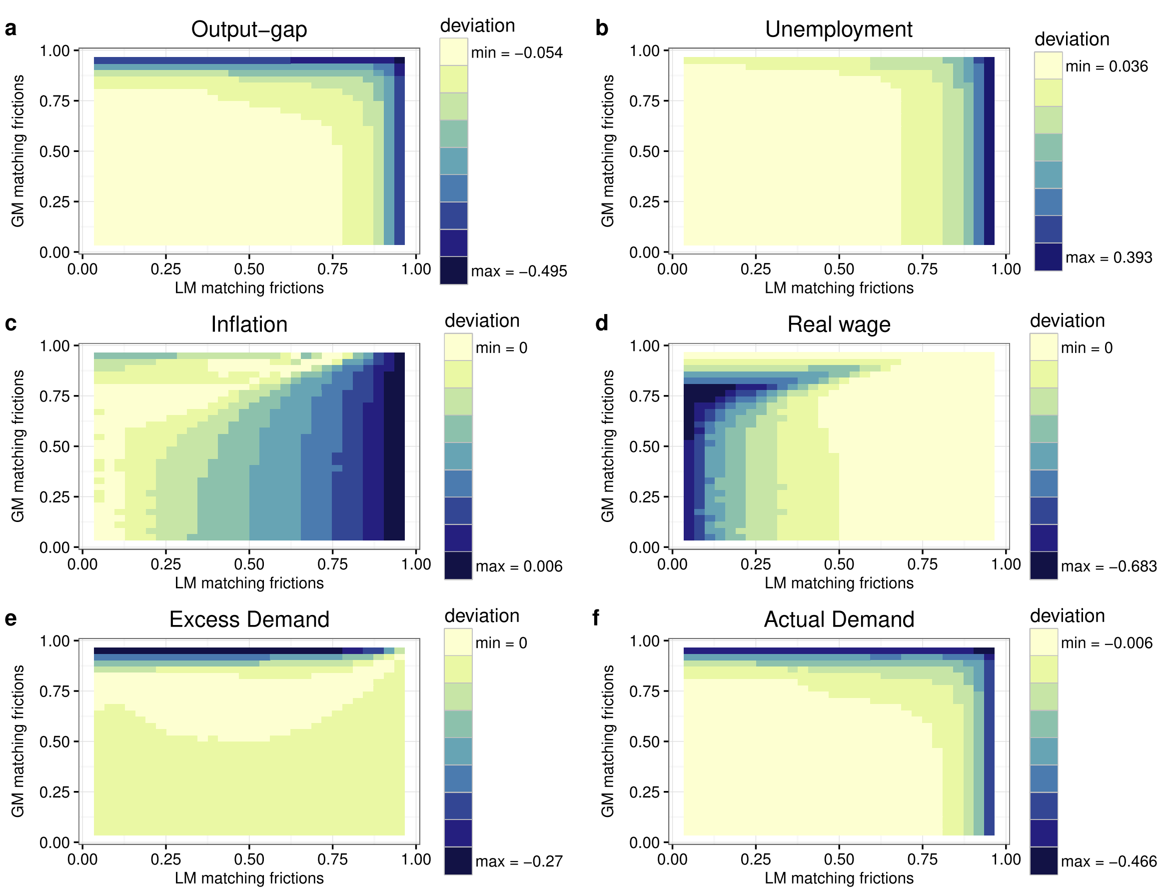

Fig. 6. Effects of a variation in the quality of matching in the labor (horizontal dimension) and in the goods markets (vertical dimension). From left/bottom to right/top the quality of matching deteriorates.

and actual demand point to a Keynesian dynamics working via quantity adjustments. In order to shed some light on these possible alternative explanations, we repeat the last exercise on matching frictions by assuming a *fixed* real wage (i.e. by keeping $P_{f,t} = W_{f,t}$, cf. Eq. (2)). Simulation results are shown in Fig. 7. The plots reveal that the results do not vary with respect to the scenario with fully flexible real wages, thus showing that the inverse relation between the real wage on one hand and unemployment and the output-gap on the other hand is just a spurious results of the model. In addition, it confirms that the main drivers of our model are quantity adjustments in the goods and labor markets, and the presence of a Keynesian feedback mechanism going from the demand for goods to demand for labor.

4. Conclusions

In this paper, we have developed an agent-based model (ABM) where an ecology of heterogeneous firms and households interact in labor and good markets according to centralized or local search and matching processes. The model is characterized by a full-employment homogeneous-agents equilibrium and by a deterministic backbone that can be hit by exogenous, stochastic shocks. The structure of our ABM is akin to the one of DSGE models and it allows a direct comparison of the impulse-response functions observed in those frameworks. However, in DSGE models, a fully-rational representative agent takes optimal decisions, whereas in our ABM, heterogeneous agents behave according to adaptive rules and explicitly interact in markets. In that, the model takes explicitly into account the insights stemming from behavioral economics (e.g. Camerer et al., 2011; Gigerenzer and Goldstein, 2011) and search theory (e.g. Mortensen and Pissarides, 1999).

We study the response of the economy to a negative productivity shock under two different institutional arrangements governing interactions in labor and goods markets. In the fully centralized scenario, a fictitious auctioneer distributes the labor force and consumption demand across firms following allocation rules similar to those emerging in the equilibrium of monopolistically competitive markets. In the fully decentralized scenario, search and matching is local. Accordingly, frictions and firms and households heterogeneity can arise due to the imperfect allocation of labor and demand across firms.

We find that in the fully centralized scenario, the economy is always able to return to the full-employment equilibrium after a shock and it displays a dynamics very similar to the one generated by standard DSGE models. In contrast, when search is local the economy persistently deviates from full-employment, and converges to a statistical equilibrium where output and unemployment are respectively lower and higher than their equilibrium values and firms and households display persistent heterogeneity. The interplay between coordination failures in the labor markets and positive demand feedbacks is at the core of the above result. In the fully decentralized scenario the supply shock generates heterogeneity across firms and some frictional unemployment. The latter has however a negative impact on household consumption, thus triggering Keynesian involuntary unemployment. In such a situation, the fall in the real wage contributes to foster deviations of the economy from the full-employment rather than contributing to restore it.

We also investigated the robustness of the above result to different degree of efficiencies of matching in labor and goods markets. We show that higher matching efficiency has a beneficial effect on the ability of the economy to return to full-employment. Indeed, a better matching greases the wheel of the market allocation mechanisms, and the decentralized economy becomes more similar to the fully centralized one, where prices are able to put markets back to equilibrium (as in DSGE models). Such a result holds also when real wage is fixed, suggesting, again, the driving role of Keynesian adjustment mechanisms in the model.

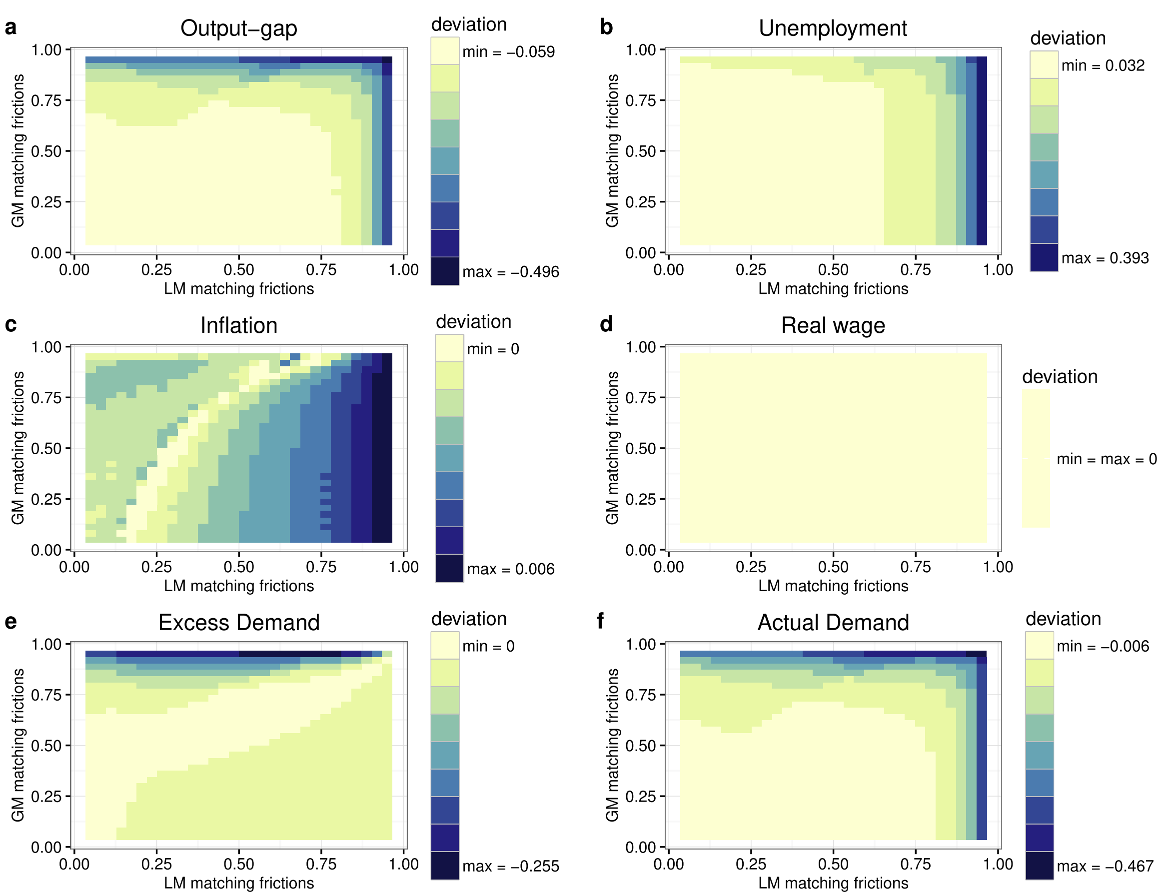

Fig. 7. Fixed real-wages simulation. Effects of a variation in the quality of matching in the labor (horizontal dimension) and in the goods markets (vertical dimension). From left/bottom to right/top the quality of matching deteriorates.

Our results have at least two implications for the current macroeconomic theory. First they show that, under some conditions, an agent-based model embedding boundedly rational decision rules is able to generate dynamics resembling those produced by DSGE models, and in particular to display convergence to full-employment equilibrium. However, the results also show that such an outcome depends on the restrictive assumptions concerning the interaction structure in labor and goods markets. When information is dispersed in the economy (as it is typically the case in reality), and interactions are local, market mechanisms can generate significant heterogeneity across economic actors and trigger positive economic feedbacks that pull the economy away from full-employment.

Our model can be extended in many directions. First, we have not considered the possible stabilizing role of the interest rate. One could therefore modify the consumption rule introducing intertemporal substitution effects and then study the ability of monetary policy to put back the economy to the full-employment steady state. Second, we have not considered the possible effects of demand shocks in the model and the possible differences in dynamics with respect to the ones presented here. Finally, one could better study the role of social interaction effects in both markets, by changing the underlying structure of network interactions.

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Appendix A. Stock-flow consistency

Table A.3.

Table A.3
Transaction flow matrix.

	Households	Firms		Bailout Fund	Σ
		Current	Capital		
Consumption	−C	+C			0
Wages	+W	−W			0
Dividends	$+(1-\theta)\Pi$	$-\Pi$	$+\theta\Pi$		0
Contribution to bailout	−H			+H	0
Δ Net-Worth	ΔA_h	0	ΔA_f	ΔA_{bf}	0

Appendix B. Equilibrium conditions

In this section we show how to compute the full-employment equilibrium when agents are homogeneous. As subscript we will adopt the letters a, f and h for referring respectively to aggregate, firm-level, household-level variables. The conditions that we adopt in order to compute the equilibrium are simply based on homogeneity, market-clearing and zero profits.

Starting from the full-employment definition, aggregate employment is the sum of all firms' employees and equal to the number of households:

$$N_a^* = \sum_f n_f^* = H.$$

For the homogeneity condition, all the firms must have the same number of employees. This implies that:

$$n_f^* = \frac{N_a^*}{F} \quad \forall f = 1, \ldots, F.$$

Therefore, by recalling the linear technology in Eq. (3), the production of each firm is equal to:

$$q_{f,s}^* = a n_f^*.$$

Aggregate supply is equal to $q_{a,s}^* = \sum_f q_{f,s}^*$ and, in the equilibrium, it corresponds to aggregate demand:

$$q_{a,s}^* = q_{a,d}^*.$$

Aggregate demand stems in turn from the sum of consumption levels of households: $q_{a,d}^* = \sum_h \hat{c}_h^*$. Given the homogeneity of agents consumption is equal to:

$$\hat{c}_h^* = c_h^* = \frac{q_{a,d}^*}{H}$$

Again due to homogeneity, the goods demand of each household to a particular firm is equal to:

$$\hat{c}_{h-f}^* = c_{h-f}^* = \frac{c_h^*}{F}$$

Quantities are uniquely defined once the full-employment conditions are fulfilled. In contrast, we cannot identify a unique price and wage level that satisfy the zero-profit condition. However, as equilibrium employment n_f^* is necessarily different from zero, we can find a unique a real-wage that satisfies it:

$$\begin{aligned} \pi_f &= p_f q_f^* - w_f n_f^* \\ 0 &= p_f a n_f^* - w_f n_f^* \\ w_f &= p_f a \\ \frac{w_f}{p_f} &= a. \end{aligned}$$

Note that $1/a$ can be interpreted as firms' mark-up.

Appendix C. Pseudo code

```
UPDATE FIRMS NET-WORTH:
        if positive profits
                take previous net-worth
                add retained ones
        if negative profits
                take previous net-worth
                add losses

UPDATE HOUSE WEALTH:
        take previous wealth
        add returns from savings
        add quota of distributed profits

ENTRY-EXIT PROCESS:
        search bankrupt firms (net-worth < 0)
        search bankrupt house (wealth < 0)
        search "rich" house (wealth > wealth_0)
        if rich house
                take excess wealth
                put it in a "saving fund"
        compute amount in the saving fund
        if bankrupt firms
                take saving fund
                re-start net-worth (initial)
                re-start price (average)
                re-start wage (average)
                re-start expected demand (average)
        if bankrupt house
                take saving fund
                re-start wealth (initial)
                re-start price (average)
                re-start wage (average)
                re-start expected demand (average)
        compute remaining resources in the saving fund

DECISION PROCESS:
        firms set wage
        firms set price
        firms set expected demand
        house set desired consumption

LABOR MARKET:
        if centralized
                compute labor supply to each firm
                compute labor demand by each firm
                compute effective labor of each firm
                compute excess demand of labor
                update employer status
                update employee status
                update employee wage
        if decentralized
                firms post vacancies (labor demand)
                house search for jobs and queue up (labor supply)
                sequential matching (effective labor)
```

```
            compute excess demand of labor
            update employer status
            update employee status
            update employee wage

GOODS MARKET:
        update productivity (here the shock happens)
        if centralized
            compute supply by each firm
            compute demand to each firm
            compute effective sales of each firm
            compute excess demand of goods
            update firms sales
            update house consumption
        if decentralized
            compute production by each firm (supply)
            house search for goods and queue up (demand)
            sequential matching (effective sales)
            compute excess demand of goods
            update firms sales
            update house consumption

ACCOUNTING PROCESS:
        firms compute in-period profits
        firms compute in-period distributed profits
        firms compute in-period retained profits
        house compute in-period savings
        house compute in-period returns

AGGREGATION PROCESS:
        total consumption
        total savings
        total returns
        total production
        total profits
        aggregate price level
        aggregate wage level
        employment
        unemployment
        inflation
        output-gap
```
.

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