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No Man Is an Island: The Impact of Heterogeneity and Local Interactions on Macroeconomic Dynamics

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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.

Keywords: Agent-Based Model, Local Interactions, Heterogeneous Agents, DSGE Model.

JEL classification: E03, E32, E37.

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1 Introduction

In this work, we develop an 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.

Since the "New Classical" revolution, most macroeconomists have been developing micro-founded macroeconomic model 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). The nemesis has come under the semblance of the Great Recession. Indeed, standard macroeconomics incarnated in Dynamic Stochastic General Equilibrium (DSGE, Clarida et al., 1999; Woodford, 2011) models has had serious difficulty in explaining the emergence of such a deep downturn (Krugman, 2011) because it was unequipped to account for the agents' heterogeneities and interactions that were at the core of key drivers of the crisis such as inequality, systemic risks and banking crises (Stiglitz, 2015; Stiglitz, 2011).

At the same time, since the seminal contribution of Leijonhufvud (1970), a 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. Clower and Leijonhufvud, 1975; Solow and Stiglitz, 1968). In the latter case, mismatches between demand and supply of goods and labor are the norm, coordination failures (Cooper and John, 1988) can emerge, and one can explain the emergence of involuntary unemployment without assuming a plethora of imperfections and frictions.

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 (Battiston et al., 2016; Dosi, 2012; Farmer and Foley, 2009; Kirman, 2010, 2016; Rosser, 2011). This is the methodological core of agent-based computational economics (ACE, LeBaron and Tesfatsion, 2008; Tesfatsion and Judd, 2006). 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. Camerer et al., 2011; Gigerenzer and Brighton, 2009; Gigerenzer and Goldstein, 2011; Hommes, 2014; Tversky and Kahneman, 1986).

An increasing number of agent-based models has studied decentralized interactions of heterogeneous agents in goods and/or labor markets.[1] In this work, however, we take a different path. Our aim is to develop a parsimonious model which bridges the agent-based framework with the DSGE one (see Fagiolo and Roventini, 2012, 2016, for a comparison of the DSGE and ACE paradigms) in order to study the role of coordination mechanisms in decentralized market economies. Indeed, our ABM is characterized by the presence of a full employment symmetric equilibrium, which can be considered as the reference point for the dynamics of the economic system. Moreover, as in the 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 model considers an economy where heterogeneous firms and households trade in the goods and labor markets. Market interactions 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

[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 Ashraf et al. (2011), Assenza et al. (2015), Dawid et al. (2014), Delli Gatti et al. (2010), Dosi et al. (2013, 2015, 2010, 2016), Lamperti et al. (2016), Popoyan et al. (2015), Riccetti et al. (2015), Russo et al. (2007), and Seppecher and Salle (2015). See also Fagiolo and Roventini (2016) for a survey of macro agent-based models.

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, in this scenario the emerging coordination failures prevent real wage movements from driving 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. This suggests that macroeconomic models should seriously take into account agents' heterogeneity and decentralized market interactions.

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.

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 labour 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. Also 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 the 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 behaviours and employ heuristics (see e.g. Camerer et al., 2011; Gigerenzer and Brighton, 2009; Gigerenzer and Goldstein, 2011; Hommes, 2014; Tversky and Kahneman, 1986), 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 of its own peers. The latter effect allows to study how social interactions with neighbours (see Brock and Durlauf, 2001; Durlauf, 2004) influence the decisions of each agent.

The wage of a typical firm f is set as:

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

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 labour 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. Diamond, 1982; Mortensen and Pissarides, 1999). The third term captures social interaction effects, measuring the deviations of firm wage with respect to the average wage set by the N_f neighbors of the firm in the previous period, i.e. $\bar{W}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} W_{j,t-1}$. 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.[2]

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

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

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 (Diamond, 1971; Greenwald and Stiglitz, 2003; Phelps and Winter, 1970), 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 ($\bar{P}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} P_{j,t-1}$). 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 ($n_{f,t}$):

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

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

where $a_{f,t}$ is the firm-specific labour productivity. Firms set desired production ($\hat{q}_{f,t}$) using a rule accounting for both within and network effects:

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

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 $q_{f,t-1} - \bar{q}_{f,t-1}$, with $\bar{q}_{f,t-1} = \sum_{j=1}^{N_f} \omega_{f,j} q_{j,t-1}$ 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 keep into account the empirically relevant effect that wealth variation has on consumption (see Jawadi and Sousa, 2014; Sousa, 2009). Moreover, household consumption is affected by social interaction effects, captured by the average level of past consumption across neighbors, $\bar{c}_{h,t-1} = \sum_{j=1}^{N_h} \omega_{h,j} c_{j,t-1}$. Such a social interaction effect allows one to account for external habits (see Abel, 1990; Duesenberry, 1949). To sum up, desired consumption is fixed according to:

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

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; Assenza et al., 2015; Dosi et al., 2016; Popoyan et al., 2015; Riccetti et al., 2015; Seppecher and Salle, 2015). 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 labour market

Firms demand labor to fulfill their production plans. Workers supply labour inelastically and have a zero reservation wage. Labour 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 labour supply allocated to each firm f is:

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

where $W_{f,t}$ is the firm wage and $\bar{W}_t$ is market average wage. From (3) and (4) it follows that the labour demand of each firm is

$$n^d_{f,t} = \frac{\hat{q}_{f,t}}{a_{f,t-1}}. \tag{7}$$

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

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

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 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 if and 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 offered by a firm with a probability increasing in the wage posted by the firm. Labour 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:

$$\Phi_{h,t}^{LM} = \begin{cases} 0 & with \;\; probability \;\; p_{f,t}^{LM} \\ 1 & with \;\; probability \;\; 1 - p_{f,t}^{LM} \end{cases} \tag{9}$$

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

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

In the above equation. $\bar{W}_t$ is the market average wage and $\rho^{LM} \in (1, \infty)$ is a parameter 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 the average one. It follows that higher values of ρ^{LM} also imply higher intensity of competition in recruiting workers, as workers 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 labour market closes and the 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, equation 5) is aggregated over households. Then total consumption, $\hat{C}_t = \sum_h \hat{c}_{h,t}$ is allocated to each firm f on the basis of the firm's price relative to the average in the market. The (real) demand of the good for a single firm f is computed as follows

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

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:

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

If demand is higher than supply, then consumers are rationed in a symmetric fashion. In contrast, if supply is higher than demand, the firm will have unsold output that perishes (as the good is not storable) and might incur into 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 process. In addition, similarly to the decentralized labour 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

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

where the probability of a success $p^{GM}_{f,t}$ reads

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

A household queues up in only one firm, demanding $\hat{c}_{h,t}$ units of the good. Notice that the probability of queuing up falls with the price $P_{f,t}$. Accordingly, more price-competitive firms will also get longer queues and higher demand for their good. Moreover, the parameter $\rho^{GM} \in (1, \infty)$ in 14 is inversely related to the quality of the matching in the good market. The higher is the value of the parameter, the lower the reaction of firms to differences between firm's 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 sold product by a firm, $q_{f,t}$, is determined by the short side of the market as in Equation (12). Again if demand overcomes 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 $c_{h,t} \leq \hat{c}_{h,t}$ and their consumption expenditure $\sum_{f=1}^{F} P_{f,t}c_{hf,t}$. They also compute savings, as the difference between income and effective nominal consumption. Households' income is represented by the wage they receive for the work they supply, $W_{h,t}$, and the fraction of firms profits paid as dividends, $D_{h,t}$. Accordingly, savings, $S_{h,t}$, are determined as:

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

Furthermore, we assume that the only assets available in the economy is money, which pays a zero interest rate. Household's wealth at the beginning of the next period $A_{h,t+1}$ is accordingly determined as:

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

A household is declared bankrupt whenever her wealth becomes negative. In such a situation, household's wealth is reconstituted via a fund created by the non-bankrupt households and is set equal to the average of the non-bankrupt households.

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

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

If $\Pi_{f,t} > 0$, firms distribute dividends to households. More precisely, if profits are positive, a firm f pay the fraction $1 - \vartheta$ as dividends. If profits are negative, firm's net worth is reduced accordingly. The law of motion of $A_{f,t+1}$ is than equal to:

$$A_{f,t+1} = \begin{cases} A_{f,t} + \vartheta \Pi^{+}_{f,t} \\ A_{f,t} + \Pi^{-}_{f,t} \end{cases} \tag{18}$$

where $0 \leqslant \vartheta \leqslant 1$ is a parameter governing the fraction of retained profits and $\Pi^{+}_{f,t}, \Pi^{-}_{f,t}$ are respectively positive or negative profits of the firm f in the period t. As firm ownerships is symmetric, each households 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

$$D_{h,t} = \frac{(1-\vartheta)}{H} \sum_{f=1}^{F} \Pi^{+}_{f,t} \tag{19}$$

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, which is constituted by the households, consistently with the fact that they are the owners. The initial amount of net-worth provided to the newly established firm is equal to the average net-worth of all the alive firms. Prices, wages and desired production of the new firm are also computed as the average 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 contrast with the typical DSGE model, agents' behavior is adaptive and not grounded on hyper rational, forward looking behavior (see Fagiolo and Roventini, 2012, 2016, for a direct comparison of DSGE and agent-based models).

Moreover, our model is characterized by the presence of a full employment symmetric equilibrium. More precisely, we define the full employment symmetric equilibrium as a situation characterized by

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

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 skeleton we have a possible emerging limit case in which not only the system is characterized by a situation of full-employment equilibrium, but also by agents' homogeneity. Such a result further improves the assessment of the results generated by our model vis-à-vis those of DSGE ones.

Let us now consider several simulation exercises[3] 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.

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
ρ^{LM}	2	easiness of matching in the labour 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

Table 1: Baseline parametrization of the model.

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, symmetric 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,

[3]Simulations are performed with Matlab-R2014a on a Linux OS.

idiosyncratic change in the value of firm productivity. The dynamics of the shock writes as:

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

where μ_η, σ_η, and ρ_η represent, respectively, the mean, the standard deviation and the autoregressive persistence of the shock. Finally the parameter t^*, represents the time-period at which the shock takes place for the first time.[4]

In what follows, the effect of supply shocks will be studied in both the *fully centralized* scenario, wherein matching is centralized in both the labor and goods market, as well as in the *fully decentralized* regime, wherein the 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[5] 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 their standard-error bands.

In all simulations we set the number of households $H = 200$ and the number of firms $F = 20$, and we run the economy for $T = 1500$. We tune the shock by setting $\mu_\eta = -0.01$, $\sigma_\eta = 0.002$, $\rho_\eta = 0.98$ and $t^* = 50$. All the simulations parameters are reported in Table 1.

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. Eq. 1). As a consequence, households are rationed

[4]The above formulation of the productivity shock is also in line with Cooper and Schott (2013), who introduce firm heterogeneity in a simple RBC 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.

[5]Methodological issues concerning the exploration of the properties of agent-based models are discussed in Fagiolo et al. (2007) and Fagiolo and Roventini (2012, 2016).

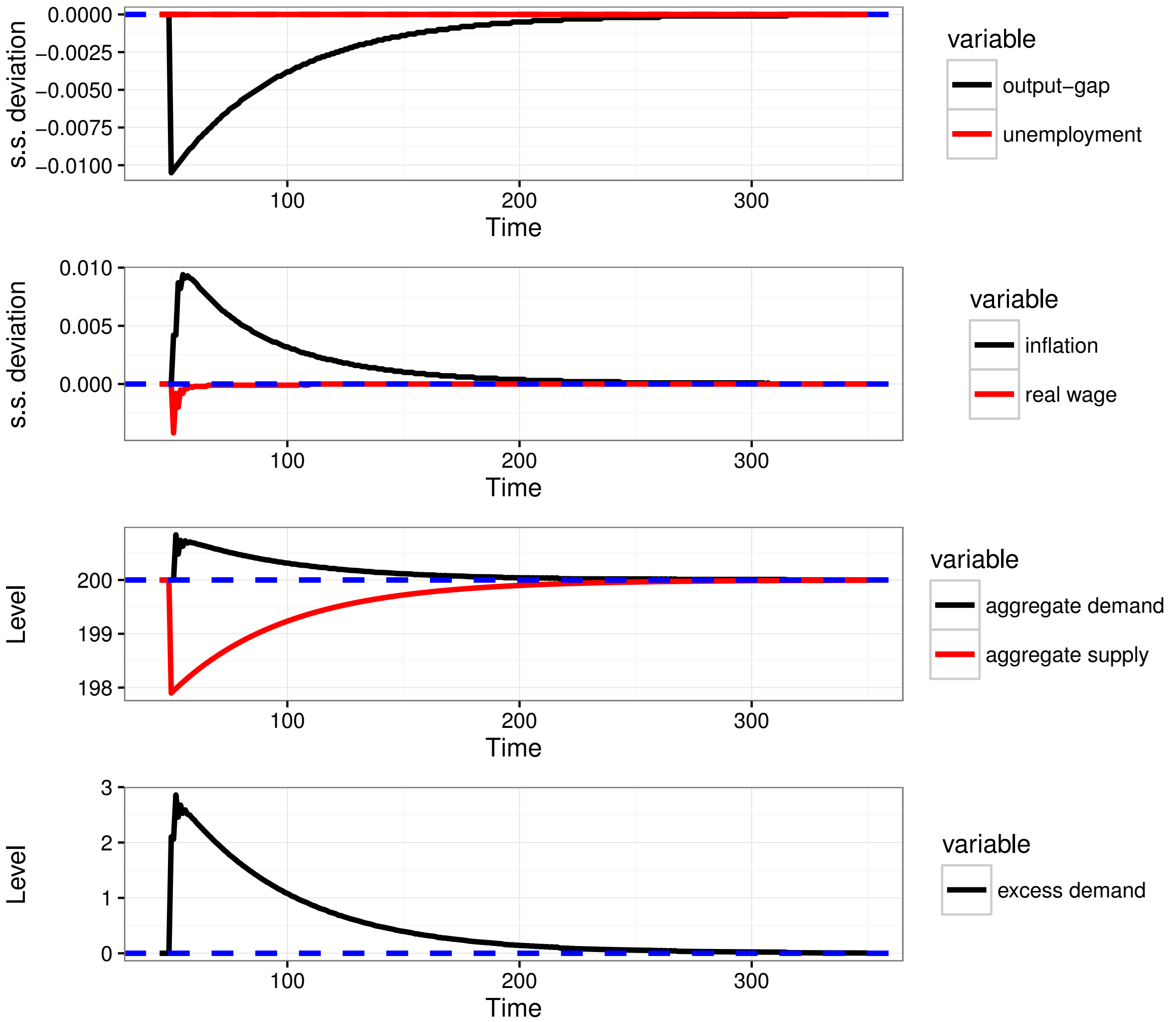

Figure 1: Emergent macroeconomic dynamics under supply shocks. Fully centralized scenario.

and are forced to increase saving. Such a situation causes the firms to increase the demand for labour. In the next period, as the system is still in full employment, the increase in labor demand leads to a wage increase. In addition, prices will also rise as they are indexed to wages and there is excess demand in the market for goods. However, as prices move before wages, the real wage will fall.

The centralized allocation mechanism at work in the labor market avoids any rise in frictional unemployment. This fact, together with the higher savings from demand rationing, contributes to keep aggregate demand high,[6] 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

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

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. In this scenario, out-of-equilibrium dynamics are only temporary and, as it is revealed by Figure 1, the system is able to effectively reabsorb the shock.

Figure 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, in general very mild, and limited to few variables of the system. In particular, constant hours worked together with 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 shock effects 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 behaviour 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 macro literature that in presence of supply shock, prices and output react by moving 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 Figure 4) now emerges both at the firm level (in terms of prices, wage offers, output and labor demand) as well as at household level (in terms of hours worked and incomes).

What is more, micro heterogeneity has now consequences at the aggregate level, amplifying the effects of the initial shock. More precisely, the initial frictional unemployment stemming

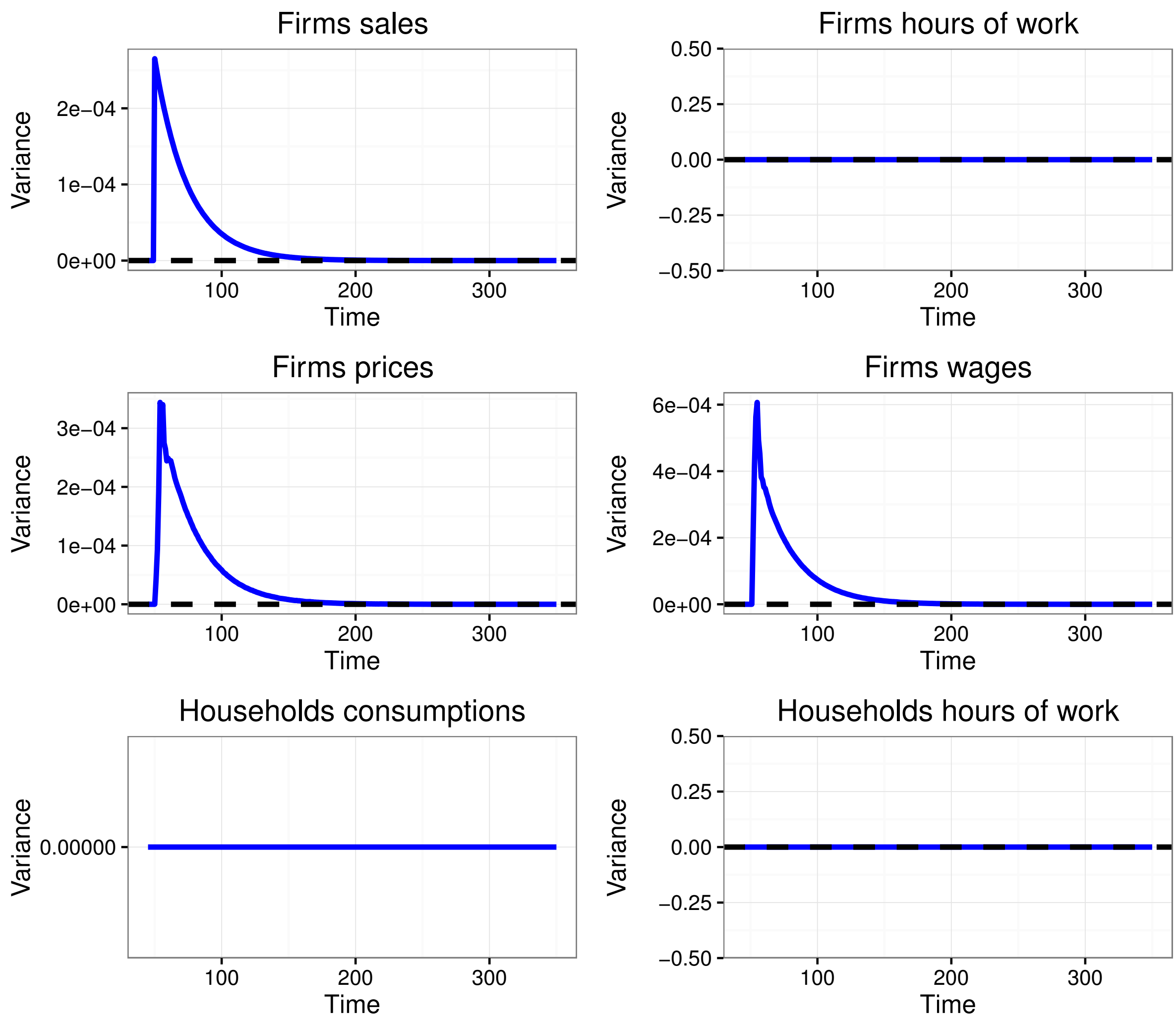

Figure 2: Micro-level variances under supply shocks. Fully centralized scenario.

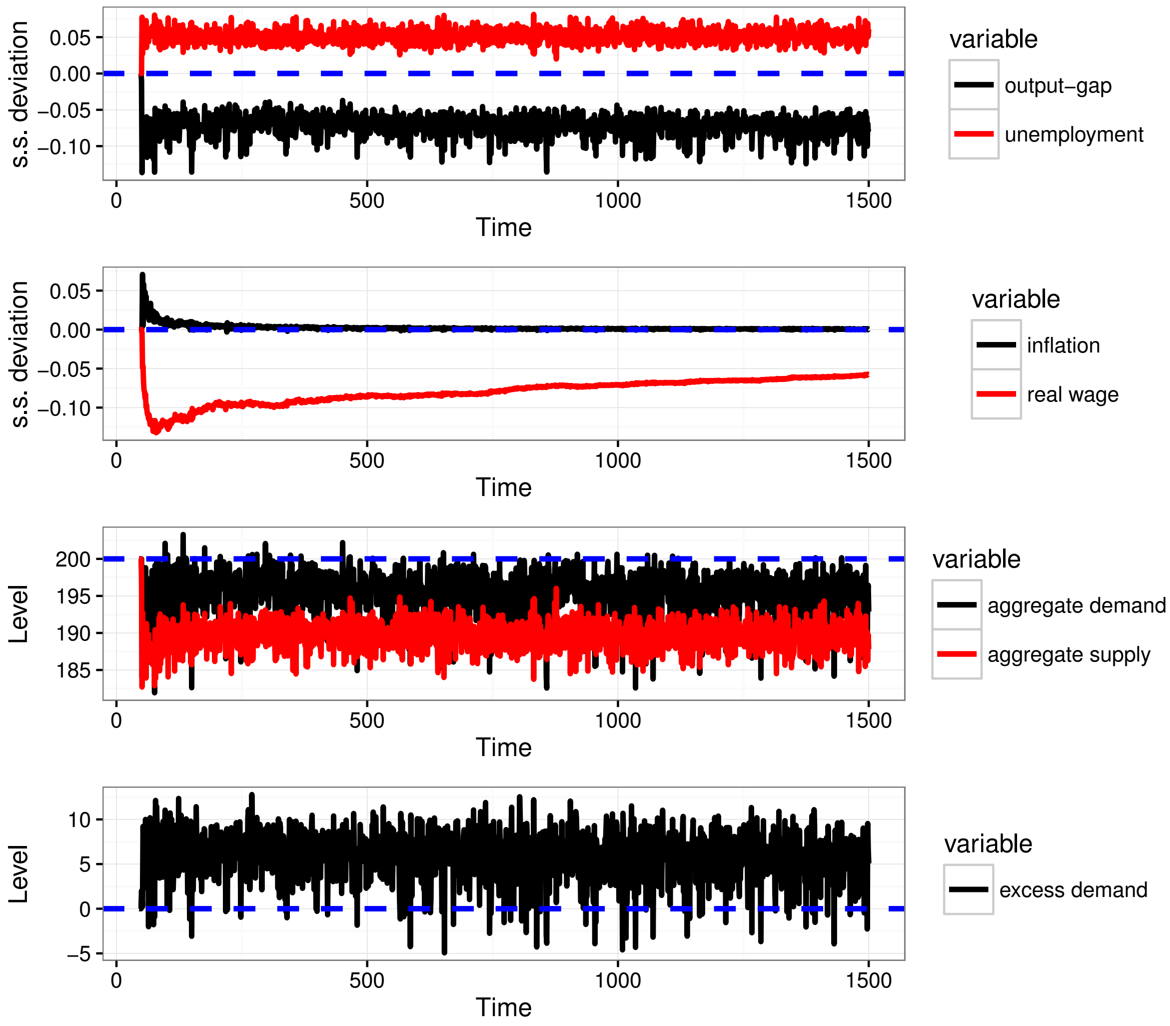

Figure 3: Emergent macroeconomic dynamics under supply shocks. Fully decentralized scenario.

from decentralized matching in the labor market feeds back into lower consumption in the goods market, thereby contributing to lower firm output, and therefore labor demand, and real wages. Indeed, the fall in real wages is much stronger now than in the centralized scenario (compare the second panel in Figures 3 and 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. Figure 3; see Dosi et al., 2013, 2015, 2010, 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

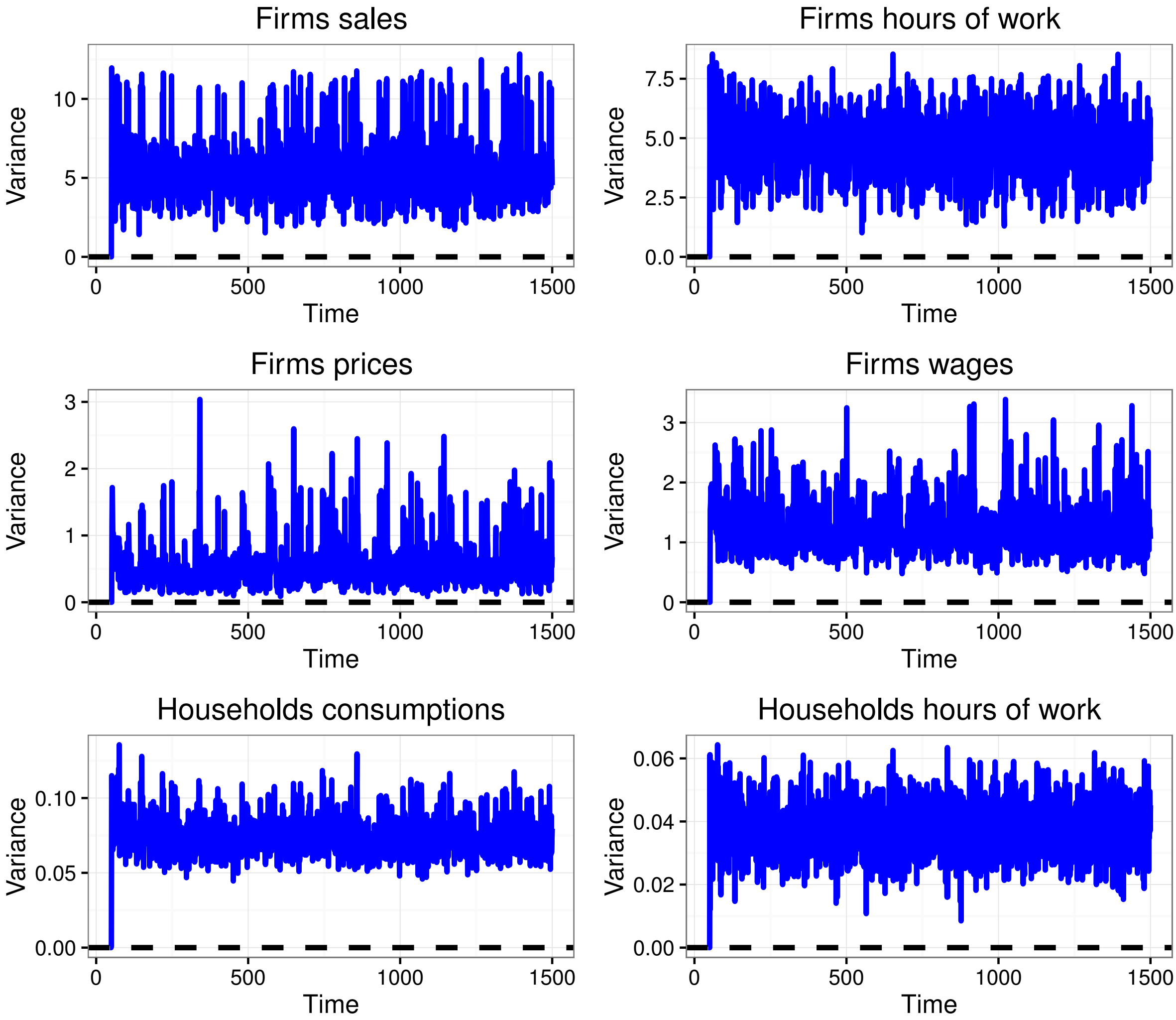

Figure 4: Micro-level variances under supply shocks. Fully decentralized scenario.

the economy is not able to reabsorb the shock. At the aggregate level, the output-gap and unemployment keeps fluctuating around values that are, respectively, significantly lower and higher that the full-employment equilibrium (cfr. Figure 3). The same occurs for the levels of aggregate demand and supply, which keep on fluctuating at values significantly below the 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 Figure 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, we say that in this scenario the economy converges to a 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 market of goods 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 close-to-steady-state values.

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

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

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.

equilibrium in the fully centralized scenario. In contrast, the presence of a statistical equilibrium different from the full employment one emerges as a robust property[7] across simulation runs in the fully decentralized scenario. Such a statistical equilibrium is always characterized by values of output and unemployment that are respectively lower and higher than the full employment equilibrium. 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 eliminate employment from 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 might or might not generate a situation of peristent underemployment. Such a difference in dynamics cannot typically be observed in New Keynesian DSGE models as they are nested in a representative agent equilibrium framework.

3.2 Robustness checks

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.

[7]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. Results of the tests showed that - for most variables - the distributions were the same in all Monte-Carlo iterations. This indicates that most variables converge to the same statistical equilibrium in the different Monte-Carlo iterations.

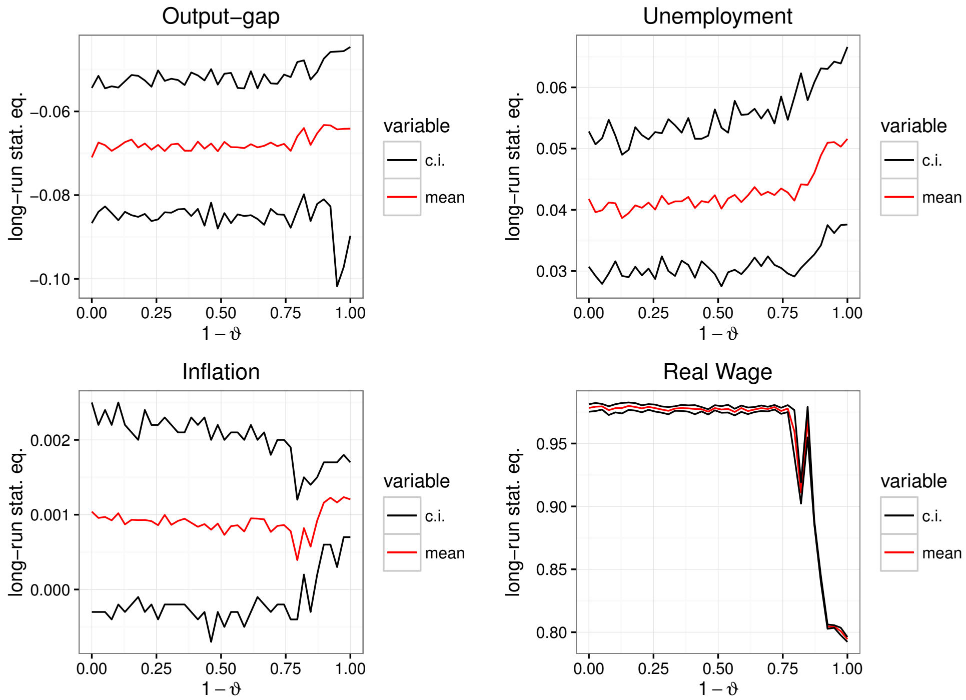

Figure 5: Effects of a variation on the percentage of retained profits parameters ϑ. The green line represents the mean of the last $T_{ss} = 200$ periods of the simulation, for any parameter value. The black lines represent instead the maximum and the minimum attained in the same time interval.

We first investigate the robustness of the model with respect to the seed in the random number generator governing the impact of the shock in Equation (21). We find that all results of the model 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. Equation 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.[8]

The parameter regulating the percentage of profits firms distribute as dividends $(1 - \vartheta)$ is particularly relevant to study as it provides a neat assessment of the role that aggregate demand dynamics play in the model. Indeed, higher amount of dividends could possibly compensate the fall in real wages experienced by workers after a negative productivity shock. The impact of this parameter on the main variables of the model is documented in Figure 5. As $1 - \vartheta$

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

increases, a larger amount of profits gets distributed to the households/workers (see Equation (19). This should counter-balance the negative effects of falling real wages on consumption demand, thus increasing the resilience of the economy. However, as Figure 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 (mildly) affected for extreme high values of the parameters. A scenario where almost all profits are paid out as dividends spur excess demand for goods for many firms as dividends finance consumption via savings. 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 of nominal wages explains the fall observed in the real wage.

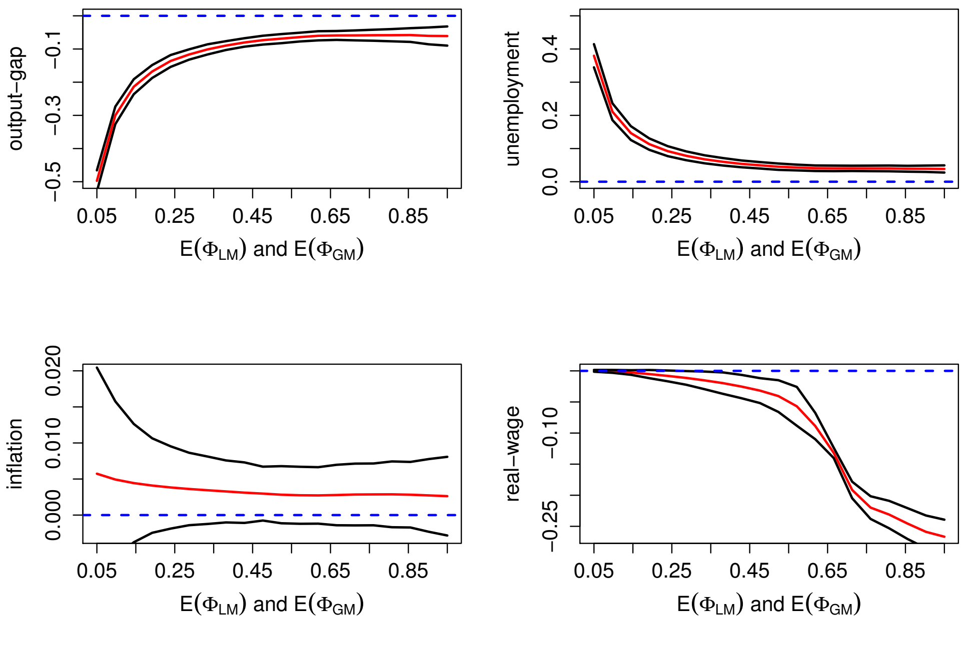

Figure 6: Effects of a simultaneous variation in the quality of matching in the labor and goods markets. The values on the x-axis represent the probability of queuing up in each market.

Our final robustness analysis exercise concerns the parameters ρ^{LM} and ρ^{GM}, which measure the quality of the matching in the labor and product market. 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, decreasing ρ^{GM} raises 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 at the same time both parameters, so that the quality of matching increases by the same amount in both markets. The results of this exercise are reported in Figure 6. We find that simultaneously increasing the easiness of the matching in both labor and goods markets improves the overall resilience of the system. Indeed, the average output gap increases and gets closer to the full employment value, unemployment and inflation falls. Finally, the average real wage is on average smaller. Simulation exercises show that, when the quality of the matching increases, the economy shows an improved ability to return to full employment equilibrium after a productivity shock, getting closer to the results of the fully centralized scenario. This is not surprising because, first, increasing the quality of the matching makes interactions in the labor and in the goods markets less local. With higher ρ^{LM} and lower ρ^{GM} workers and consumers queue up at a larger fraction of firms for any given price and wage differences. Second, a better matching also implies higher sensitivity of labor and consumption demand to cross-firms price differentials in both markets. Accordingly, price variations can quickly mop up micro-disequilibria in both markets and, as a result, adjustment mechanisms mimic the ones at work in representative agent DSGE models (e.g. unemployment is reduced via a fall in real wages).

4 Conclusions

In this paper we develop 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 symmetric 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 take optimal decisions, whereas in our ABM, heterogeneous agents behave according to adaptive rules and explicitly interact in markets. In that, our model takes 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 labour 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 lower than the full employment values and where firms and households display persistent heterogeneity. The interplay between matching frictions in the labour 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 and therefore on aggregate demand in the goods market, thus triggering involuntary unemployment of a Keynesian type. 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 restoring 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).

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 decison rules is able to generate dynamics resembling those produced by DSGE models, and in particular to display convergence to full employment equilibrium. At the same, our 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. Third, we could further explore the impact of different speed of adjustment in the goods and labor markets along the lines of Solow and Stiglitz (1968). 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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