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Integrating Real and Financial Markets in an Agent-Based Economic Model: An Application to Monetary Policy Design

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Abstract This article presents an agent-based integrated model of a real, financial, and monetary economy. The model is characterized by a monopolist firm that supplies a single homogeneous product in the goods market, hires workers in the labor market, and demands loans in the credit market; a trade union that sets the nominal wage; N heterogeneous households that buy the consumption good, provide the labor force, and trade the firm's equity in the stock market; and a bank that lends money to the firm at an interest rate set according to a monetary policy strategy. The model is used to perform monetary policy experiments. A monetary policy rule which targets the gap between the current output and the potential output in the full employment case is investigated, studying the effects on the economy for different degrees of policy tightness. The monetary policy rule is compared to a random policy rule that conserves a similar structure. Results show that a tight monetary policy clearly over performs the random policy rule. Moreover, results corroborate the effectiveness of monetary policy in limiting inflation and increasing welfare.

Keywords Agent-based computational economics · Monetary policy design · Financial markets and the macroeconomy

JEL classifications C63 · E44 · E52

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1 Introduction

The field of agent-based computational economics has been characterized by a great deal of development in recent years; see Tesfatsion and Judd (2006) for a recent survey. During the last decade, several research papers have appeared focusing on different fields of economic theory. In particular, there have been many studies regarding finance, see Lebaron (2006) for a review, while others have focused on labor and goods markets (Tassier 2001; Tesfatsion 2001) and industrial organization (Kutschinski et al. 2003). However, only a few partial attempts have been made in order to model a multiple-market economy as a whole (Basu et al. 1998; Bruun 1999; Sallans et al. 2003). Basu et al. (1998) developed an agent-based computer simulator of the US economy characterized by a detailed financial sector including a banking system and a bond market, simulating agent learning by means of genetic algorithms. Bruun (1999) studied an agent-based macroeconomic model with Keynesian features which included both the production and the financial sector of the economy. Sallans et al. (2003) presented a model of coupled financial and consumer markets, populated by agents with sophisticated learning features, and gave emphasis to the validation technique. In this respect, the model presented in this article integrates the real, the monetary and the financial sectors of the economy by considering four different markets, i.e., a labor and a goods market, representing the real side of the economy, a credit market and a stock market. The distinctive feature of this study consists in modeling agents according to well-established optimizing behavior, or to simple and parsimonious rules of thumb. Furthermore, prices in real markets are not governed by a Walrasian tatonnement process, but depend on price-setting agents on the supply side; this feature allows potential short-term real effects of monetary policy. In this respect, the article proposes an utilization of the model for purposes of monetary policy design.

The agent-based framework provides a powerful computational facility for economics, where experiments concerning scientific hypotheses and policy design issues can be performed. It offers a realistic environment, characterized by non-clearing markets and bounded rational agents, well suited for studying the out-of-equilibrium transitory dynamics of the economy caused by changes of policy parameters. In previous works the authors have studied the effect of monetary (Raberto et al. 2006a) and fiscal policies (Raberto et al. 2006b) in agent-based models characterized by price-taking agents. It is worth noting that, in the context of price-setting agents, prices may not be set to their market clearing values; this can be due to the possession of insufficient information owned by the price setters, or to price decision mechanisms that do not necessarily lead to the clearing of the market. These features offer a microfoundation of nominal rigidities, that in the new Keynesian literature are a well-known source of monetary nonneutrality (Mankiw et al. 1991).

We present a discrete-time, agent-based, economic model composed by a monopolistic firm, a trade union, a central bank and N heterogeneous agents, that are at the same time consumers, workers, and financial traders. The firm produces a single homogeneous good using labor as the only input, and is characterized by a Cobb-Douglas technology. Households possess cash and stocks, earn labor and financial income, take consumption decisions and act as traders in the stock market. The bank borrows money from households and lends it to the firm, while the trade union's main role is to set the optimal wage for the workers' community.

The real economy side of the model includes a labor market and a goods market. The trade union sets a wage at the beginning of the period and households decide whether to apply for a job or not, according to their real reservation wages. The firm knows the aggregate labor supply and the aggregate goods demand and sets the good's price and the quantity to be produced according to a profit maximizing behavior. Then the labor market clears and households can be rationed. Considering their labor and financial incomes, households formulate their demand, trying to smooth consumption over time (Deaton 1991). Given demand and supply, the goods market clears and the households can be rationed again in this market.

Once transactions in the goods and labor markets are completed, the stock market opens. Households/traders are characterized by an endowment of cash, which derives from the dynamics of the real economy, and an endowment of a single asset, representing the equity of the monopolistic firm. The stock market is characterized by a clearing house for the formation of price and by a Markowitz portfolio selection mechanism.

It is worth noting that the bank plays a central role, because it sets the lending rate, that is the instrument for conducting monetary policy in the model.

The central problem of the theory of monetary policy is to provide principles that can be used in selecting a desirable rule for setting a central bank's interest rate (Woodford 2003; Taylor 1993). In this respect, the article examines the implications of using a nominal interest rate as the operational instrument of monetary policy. In particular, we investigate how the interest rate set by the central bank influences the economy, when the system is close to full employment. It can be observed that, when a full employment state is reached, and consequently the output cannot be further increased, the firm tends to raise prices, generating a higher inflation rate. This may give rise to instability, thus undermining the economy. In order to keep inflation under control and to guarantee stability, a monetary policy that keeps the output somewhat below the maximum potential output, given by full employment, should be pursued. Consequently, we propose an interest rate setting rule based on the control of the output gap, i.e., the difference between current output and full employment output.

It is worth noting that, in the optimizing sticky price model of the new Keynesian literature (Clarida and Gali 1999), a concept of output gap, defined as the deviation of output from its level under flexible prices, plays a central role both as a source of fluctuations in inflation (represented by the new Keynesian Phillips curve), and as a policy target (e.g. the well-known Taylor's rule). It worth noting that the output gap, irrespective of the different definition provided in our model, has a similar role here both as a determinant of inflation dynamics and as a key policy variable.

The paper is organized as follows. The model is outlined in Sect. 2, while computational experiments and results are discussed in Sect. 3. Section 4 provides concluding remarks.

2 The Model

The model is characterized by four markets.

- A labor market, where households supply labor and are organized in a trade union that sets the wage. The labor force is hired by the monopolistic firm in order to produce the scheduled quantity of output.
- A goods market, where the firm acts as a price setter and supplies the output according to a profit maximizing behavior. The aggregate demand is the sum of each household's demand, which depends on its past income stream in order to smooth consumption over time.
- A credit market, where the firm borrows money from the bank in order to pay wages, and the bank sets the interest rate according to the policy rule.
- A stock market, where a number of shares of the monopolistic firm is traded by the households.

In the following, we present a detailed description of the behavior of agents in each market.

2.1 The Trade Union

Households are represented by a trade union that sets the nominal wage in order to adaptively increase the workers' utility U, defined as the aggregate real labor income U according to the equation $U = (w/p)N$, where N is the number of workers, with $N \leq M$, M being the total number of households, and w/p is the real wage. It is worth noting that the trade union does not know the optimizing behavior of the firm in setting its wage policy; in particular, it does not know the values of N and p that will be set by the firm after its choice of w. It only forms expectations about p on the basis of past prices. However, the trade union is able to take into account the externality due to the choice of N on the part of the firm by considering if past nominal wage choices led to an increment of the aggregate real labor income. Under this respect, the trade union looks at the past, according to a fixed time window T^U, to verify the effectiveness of its wage policy. If the correlation $\rho(dU, dw)$, computed in T^U, is positive, it means that nominal wage increments dw led to aggregate workers' utility increments dU, and the trade union will confirm the past policy by a raise of the nominal wage. Whereas, if the correlation is negative, the trade union will not change the nominal wage. In case of an increment, the wage will be adjusted according to an inflation rate equal to planned inflation π^*, set by the central bank. The trade union's decision rule can be summarized as

$$w_t = \begin{cases} w_{t-1}(1+\pi^*) & \text{if} \quad \rho(dU, dw) \geq 0 \\ w_{t-1} & \text{if} \quad \rho(dU, dw) < 0 \end{cases}$$

This wage indexation rule has been selected in accordance with the current practise in some European countries, e.g., Germany and Italy. An interesting alternative wage indexation rule could be anchoring the rate of change of the nominal wage to past, or better to expected inflation. However, a positive feature of the anchoring method proposed in our model is that bounding labor-cost inflation avoids destabilizing wage-price spirals dynamics.

2.2 The Households

Each household possesses a real reservation wage, below which it is not willing to work. After the trade union has decided current period nominal wage w_t, each household decides whether to apply for a job or not, considering the previous period goods price p_{t-1} for the evaluation of the current real wage. The labor supply N_t^s is then given by the number of households willing to work.

Household consumption choice is inspired by a rule proposed by Deaton (1991) and is based on the comparison between the current income and past income stream realized in the last time window T^i. The rule has been modified in order to take into account price inflation. Let us define the cash on hand X_{t-1}^i as the amount of liquidity at the ith household disposal at the beginning of period t before its consumption choice c_t^i at period t. Cash on hand consists of a cash deposit remunerated at the fixed interest rate r^D. The dynamics of cash on hand is given by interest payments on deposit, by labor income and dividends, minus household expenses for consumption, as outlined in Eq. 6. The households's disposable income for consumption I_t^i is composed from the previous period wage, w_{t-1}, and the dividends from profits that the firm made in the previous period, i.e., $I_t^i = \eta_{t-1}^i w_{t-1} + m_{t-1}^i d_{t-1}$, where η_{t-1}^i is equal to 0 or 1, depending on the employment status of the household at time $t-1$ and the integer m_{t-1}^i is the number of shares in the portfolio of household i in the previous period. Dividends d_{t-1} are given by $p_{t-1}\Pi_{t-1}/S$, where Π_{t-1} are the real profits realized by the firm in the previous period and S is the total number of shares of the monopolistic firm.

The households's target is to maintain a stable rate of consumption; saving when income is high in order to accumulate cash for periods of low income. Deaton assumes that individuals consume cash on hand as long as current nominal income is less in real terms than the average past real income $\bar{I}_t^i$, while, if the income exceeds in real terms $\bar{I}_t^i$, households save a constant fraction $(1-\upsilon)$ of the excess income. Formally, given the price p_t set by the firm in the current period, Deaton's decision rule can be written as:

$$c_t^i = \begin{cases} \min\left(\bar{I}_t^i, (I_t^i + X_{t-1}^i)/p_t\right) & \text{if } I_t^i/p_t \le \bar{I}_t^i\,, \\ \bar{I}_t^i + \upsilon(I_t^i/p_t - \bar{I}_t^i) & \text{if } I_t^i/p_t > \bar{I}_t^i\,. \end{cases} \tag{1}$$

Aggregate goods demand Y_t^d is then given by $Y_t^d = \sum_i c_t^i$.

2.3 The Monopolistic Firm

The model includes a single monopolistic that produces an homogeneous perishable good according to a production function that has labor as the only input:

$$Y_t = \zeta N_t^\alpha \tag{2}$$

The parameters $\zeta > 0$ and $\alpha > 0$ are determined by the current technology and are kept fixed in this study.

The firm knows the nominal wage w_t that has been already set by the trade union, and acts as a price setter, facing the problem to decide the price p_t of the good and the quantity Y_t of goods to be produced. It is assumed that the firm adjust adaptively the price and the quantity of goods, according to the following steps,

- The firm knows the labor supply N_t^s and has a perfect knowledge of the demand elasticity.
- The firm takes into consideration a set of hypothetical prices $p^{(h)}$, that lie in a neighborhood of the last market price p_{t-1}. The prices $p^{(h)}$ are chosen inside a grid indexed by (h) and parameterized by $(1 + h\delta)p_{t-1}$, with $h = -n, -n + 1, \ldots, n - 1, n$, where δ represents the minimum relative variation of the price and δn is the higher bound for variation. Consequently, the firm calculates a grid of exact goods' demands $Y^{d(h)}$ relative to each price $p^{(h)}$ of the price grid.
- The firm computes, for each pair $\left(p^{(h)}, Y^{d(h)}\right)$, a grid of real profits values $\Pi^{(h)}$, defined as

$$\Pi^{(h)} = Y^{d(h)} - C^{(h)}/p^{(h)}\,, \tag{3}$$

  considering $C^{(h)}$ as a grid of nominal costs given by:

$$C^h = (1 + r_t^L)w_t N^{(h)}\,, \tag{4}$$

  where r_t^L is the lending interest rate that has to be paid on the loan $w_t N^{(h)}$, and $N^{(h)}$ is the amount of labor necessary to produce the demanded quantity of output $Y^{d(h)}$, i.e., $N^{(h)} = (Y^{(h)}/\zeta)^{1/\alpha}$, with the constraint $N^{(h)} \leq N_t^s$.
- A price and quantity couple (p_t, Y_t) is therefore chosen by the firm as the one that corresponds to the higher real profits, i.e.,

$$(p, Y)_t = \text{argmax}_{\left(p^{(h)}, Y^{(h)}\right)} \Pi^{(h)}\,, \tag{5}$$

  with the relation between p_t and Y_t being $Y_t = Y^{d(h)}(p_t)$ if the firm is not constrained in the labor market in the optimal plan, otherwise $Y_t = \zeta\left(N_t^s\right)^\alpha$ whatever p_t.

Finally, the firm distributes profits to households. Each household will receive dividends at the beginning of the next period, proportionally to the number of stocks it owns.

It is worth remarking that a single monopolistic firm has been considered in the model in order to consider a full knowledge of the goods demand and labor supply curves by the corporate sector and thus to facilitate the interpretation of monetary policy results within a price-setting productive sector. Conversely, within an oligopolistic or a monopolistic competition framework, each firm would face an uncertain residual goods demand and an uncertain residual labor supply and no full knowledge on the side of the price-setting productive sector could be considered, thus making the interpretation of a study on monetary policy far more complicate.

2.4 The Labor and Goods Markets

As described in Sect. 2.3, the firm knows in advance the schedule of labor supply and goods demand. Accordingly, the firm takes price and quantity decision in order not to be rationed. So, it chooses the goods supply in order to match the goods demand, considering its possible rationing in the labor market. The goods market usually clears unless there is not enough labor to produce the desired quantity of goods. On the other hand, households are often rationed in the labor market, because $N_t \leq N_t^{\mathrm{S}}$. In that case, a priority list of individuals is randomly generated according to a uniform distribution; agents' supply of labor is therefore matched according to the priority list, until the total labor demand N_t is satisfied. After transactions in the goods and labor markets, households cash is reallocated for the next period, i.e., for the ith agent:

$$X_t^i = X_{t-1}^i + \eta_{t-1}^i w_{t-1} + m_{t-1}^i d_{t-1} - p_t c_t^i + r^D X_{t-1}^i \,, \tag{6}$$

where r^D is the fixed rate on deposit of the bank, η_{t-1}^i indicates the employment state of agent i at time $t-1$, i.e., $\eta_{t-1}^i = 1$ or $\eta_{t-1}^i = 0$, and $m_{t-1}^i d_{t-1}$ denotes the capital income due to m_{t-1}^i stocks paying dividend d_{t-1}. Then the stock market opens.

2.5 The Central Bank

The model incorporates a bank, which fulfills the functions of both a commercial bank and a central bank. The bank performs the following actions:

- sets a planned inflation target π^*,
- remunerates the household's cash account at a fixed rate on deposit r^D,
- provides credit to firms at a lending rate r_t^L,
- sets r_t^{L} according to a monetary policy rule.

The rate on deposit r^D is set by the bank at the target level of inflation, in order to let the money aggregate of the households grow at the planned inflation rate.

Two monetary policy rules, that use the nominal interest rate r_t^L as the operational instrument, have been designed. The first one, henceforth the random policy rule, sets r_t^L as,

$$r_t^L = r^{Lmin} + \phi\, \xi_t \,, \tag{7}$$

where r^{Lmin} is the fixed minimum value for the lending rate, generally set somewhat higher than r^D, ϕ is the policy strength, while ξ_t is a random value extracted from a uniform distribution in the interval [0, 1]. The random policy rule aims to investigate the firm's reactions to random variations of the interest rate. These reactions are mainly studied in terms of correlations, as shown in Table 1 of Sect. 3.

The second policy rule, henceforth the output gap control rule, is based on the control of the output gap,

$$r_t^L = r^{Lmin} + \phi \exp\left(-\beta \frac{Y^p - Y_t}{Y^p} \right) , \tag{8}$$

Table 1 Correlation values between interest rate variations Δr^L and percentage variation of goods price, production and real profits

	$\rho\left(\Delta r^L, \frac{\Delta p}{p}\right)$	$\rho\left(\Delta r^L, \frac{\Delta Y}{Y}\right)$	$\rho\left(\Delta r^L, \frac{\Delta \Pi}{\Pi}\right)$
$\phi = 0.1$	$0.28(10^{-17})$	$-0.14(10^{-5})$	$-0.35(10^{-28})$
$\phi = 0.2$	$0.34(10^{-25})$	$-0.36(10^{-29})$	-0.89 ($\sim$0)
$\phi = 0.5$	0.56 (10^{-76})	$-0.26(10^{-15})$	-0.91 ($\sim$0)

All correlation values are significantly different from zero, as shown by the corresponding p-values, given in brackets

where β is a policy tuning parameter and Y^p is the potential output, in the case of full employment, i.e., $Y^p = \zeta M^\alpha$. The output gap control rule (Eq. 8) is characterized by two nonlinear transformations. The first one is given by considering the ratio between the output gap and the potential output, and has been designed in order to target the relative output gap instead of its absolute value. The second nonlinearity is given by the exponential function, that have been considered in order to give a steep rise of the lending rate when Y_t is approaching Y^p.

The effects on the economy of the two alternatives rules represented by Eqs. 7 and 8 are diffusely discussed in Sect. 3.

2.6 The Stock Market

The stock market is populated by M agents, as each household of the economic model becomes a trader in the stock market. Traders are characterized by an endowment of cash, which derives from the dynamics of the real economy, and an endowment of a single asset, which is the equity of the monopolistic firm of the system.
The essential steps performed in the stock market can be summarized as:

- Traders form beliefs on the asset's risk and returns.
- Traders decide their optimal wealth allocation and formulate their limit prices.
- Traders issue orders.
- The market clears (rationing and financial wealth allocation).

Let us now examine more in detail how the stock market works. Traders are characterized by heterogeneous time windows T^i through which they can look at the past, in order to form their expectations about the future. Each trader calculates the historical volatility $\sigma_t^i(T^i)$ of the stock price s according to its time window. Then, the price return estimation by the ith trader is calculated by means of an MA(0) model, and corresponds to $\varrho_t^i = zN(0, \sigma_t^i)$, where z is a parameter. Consequently, each trader sets a limit price, above which it is not willing to buy, if it is a buyer, or below which it is not willing to sell, if it is a seller, according to:

$$s^i_{\lim,t} = s_{t-1}(1 + \varrho^i_t)\,. \tag{9}$$

However, when agents have to decide the share of their financial wealth to allocate into stocks, they will consider the overall stock return R that takes into account also the dividends paid by the stock. In this respect, traders have full knowledge of the value d_t of the dividend paid by the firm for holding stocks. Traders beliefs on overall stock return, considering both expected dividends and a component related to the standard deviation of historical price returns, are given by:

$$R_t^i = \frac{d_t}{s_{t-1}} + \varrho_t^i\,. \tag{10}$$

Concerning the decision on portfolio allocation, each agent is characterized by a specific attitude toward risk, represented by its risk aversion value ν^i. Given this heterogeneous risk aversion, the trader takes into consideration the expected stock return, the risk free interest rate r^D, and the stock's price volatility, in order to allocate its portfolio. According to the Markowitz portfolio selection theory (Markowitz 1952), the percentage of total financial wealth that the trader invests in the stock is given by the weight ω_t^i, where

$$\omega_t^i = \frac{R_t^i - r^D}{\nu^i \sigma_t^i}\,. \tag{11}$$

These weights are then mapped into a (0,1) interval according to:

$$\omega_t^{*i} = \begin{cases} \frac{2}{\pi}\arctan(w_t^i) & \text{for } \omega_t^i \geq 0\,, \\ 0 & \text{for } \omega_t^i < 0\,. \end{cases} \tag{12}$$

The choice of this mapping for Markowitz weights is an ad-hoc rule to confine them in the (0,1) interval in order to not allow short selling (i.e., $w < 0$) and to address the nonborrowing constraint imposed to the households. This transformation change the weights magnitude, but preserves their order, thereby maintaining the features of mean-variance portfolio selection criteria. This choice is also useful from a simulation perspective, because it smoothes fluctuations in the stock demand, and avoids extreme behavior that would be given by weights values bigger than 1, without significantly altering lower weights.

When the portfolio selection is completed, traders check their current wealth allocation and compare it with the desired one given by weights ω_t^{*i}. The financial wealth of agent i, W_t^i, is given by $W_t^i = X_t^i + m_{t-1}^i s_{t-1}$, where m_{t-1}^i is the number of stocks hold in the portfolio. Current weight of equity is given by $m_{t-1}^i s_{t-1}/W_t^i$. Consequently each agent decides to issue buy or sell orders to cancel the gap between what they have m_{t-1}^i and what they want m_t^{*i}, where m_t^{*i} is the integer value of $\omega_t^{*i} W_t^i$. Each order can then be identified by the limit price $s_{\text{lim},t}^i$ and the associated quantity q_t^i of shares, given by $q_t^i = m_t^{*i} - m_{t-1}^i$. If the $q_t^i > 0$, the order is a buy order, otherwise, it is a sell order.

The price formation process is centralized and modeled according to a clearing house mechanism. Buy and sell orders are collected by the clearing house that builds a demand curve and a supply curve on a common price grid. The price s_t that clears the market, at the crossing of demand and supply, is chosen in order to maximize the transacted amount of shares.

All the traders whose limit prices are compatible with the clearing price ($s^i_{\lim,t} \geq s_t$ for buyers, $s^i_{\lim,t} \leq s_t$ for sellers) are selected for the transaction; however, some of them will be rationed. A priority order is randomly generated and agents carry out their transactions following the order. When all the amount of stocks is traded, agents in the successive positions are rationed.

3 Results and Discussion

We present, as a main result, a study on the effects of using a nominal interest rate as the operational instrument of monetary policy.

The interest rate r^L has an influence on the economy through the decision making of the firm, which borrows money to pay wages. Given the nominal wage set by the trade union, nominal costs incurred by the firm in order to hire the labor input depend directly on the interest rate level, as Eq. 4 clearly shows. Thereby, a rise of the interest rate at time t makes the marginal cost curve goes up so that the intersection with the marginal revenue curve[1] implies a lower output and a higher price. It is worth noting that, given the general equilibrium framework of the model, in the long run this effect could be canceled by second-order effects, e.g. downward shifts of the demand curve or employment reduction.

In order to empirically investigate the consequences of interest rate changes, we have computed the correlation ρ between the time series of interest rate variations and the time series of percentage variations of some macroeconomic variables, related to the same simulation trajectories. Table 1 reports these correlations for different values of the policy strength ϕ, in the case of a random monetary policy rule, see Eq. 7. The random rule was preferred to the output gap rule in order to avoid spurious statistical effects due to serial correlation in the interest rates.

Results show, as expected, that interest rate changes Δr^L are significantly correlated with price relative variations $\Delta p/p$ and anti-correlated with output relative variations $\Delta Y/Y$. Furthermore, the anti-correlation values between interest rate changes and real profit variations $\Delta\Pi/\Pi$ are even more significant, due to the firm's risen costs for paying higher interest on debt.

Figures 1–3 present three different trajectories, starting with the same initial conditions, of six economic variables. The monetary policy rule employed in the simulations is based on the output gap control (see Eq. 8), and each trajectory refers to a different policy strength parameter ϕ. These computational experiments have been performed with the following parameter values: $M = 1000$, $T^U = 20$, $\pi^* = 0.5\%$, $\zeta = 1$, $\alpha = 0.9$, $\delta = 0.1$, $n = 50$ (implying a maximum price variation of $\pm 5\%$), $r^D = 0.005$, $r^{Lmin} = 0.01$. Moreover, the reservation wages of households are set to 0, implying a constant labor offer set to M. The productive capacity of the economy is

[1] The marginal revenue curve at time t is not affected by the interest rise because households' demand depends on the income stream of the economy up to the previous time step, see Eq. 1.

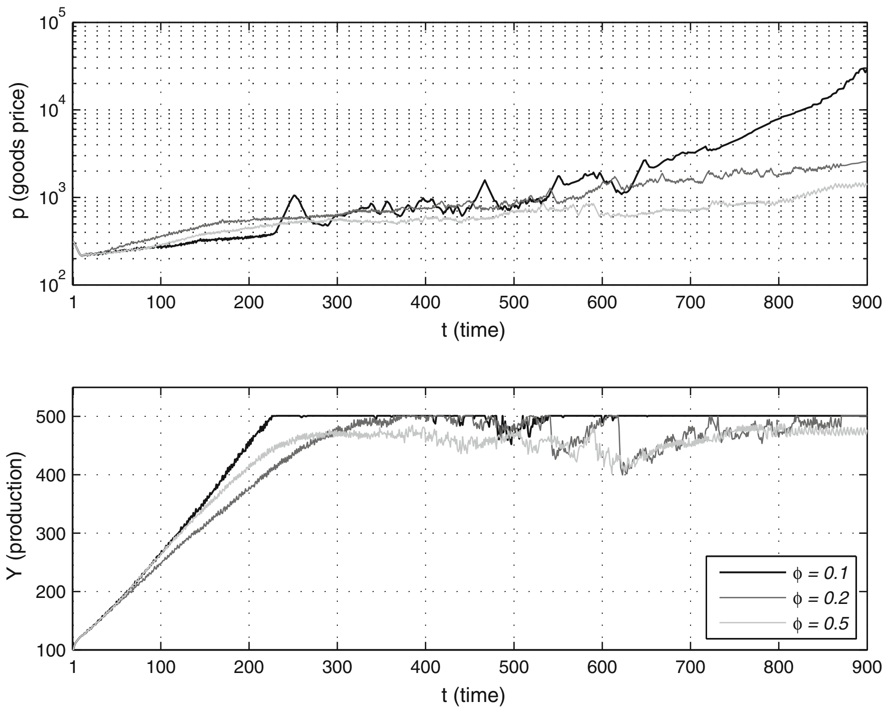

Fig. 1 Time series of goods price and production for different values of policy strength ϕ

then fixed in the simulations and deterministically related to the total number of households M. Keeping a fixed productive capacity simplifies the framework and allow a better understanding of the policy effects. A separate study of the authors addresses the effects of monetary policy in presence of fixed heterogeneous reservation wages (Raberto et al. 2007). As far as the stock market is concerned, $z = 16$, the time window T^i varies from 20 to 100, and the risk aversion of traders varies from 1 to 5.

As Fig. 1 clearly shows, the trajectories start from the same initial conditions of market price and production, and are characterized by an output growth and inflation. Trajectories of production are bounded by an upper value, which corresponds to the maximum number of employable workers, i.e., M. The output dynamics indicate that there are two main phases; a first initial phase of steady growth and a second phase of fluctuations close to the upper bound of production. It can be noted that, for higher values of the policy strength, i.e., higher interest rate values, production is depressed: in the case of $\phi = 0.5$ output never reaches the maximum level. This evidence confirms the effectiveness of the output gap control rule, which uses r^{L} as a policy instrument, in driving the production level. The importance of keeping the economy below its maximum level of output is clearly evident by examining the price trajectories in Fig. 1. In particular, it is worth noting that in the initial phase of output steady growth the goods price is higher when the monetary policy is stronger, whereas in the second phase of fluctuations the effect of the output-gap-targeting monetary policy is to limit the price growth. The apparently counterproductive behavior of the price during the first phase

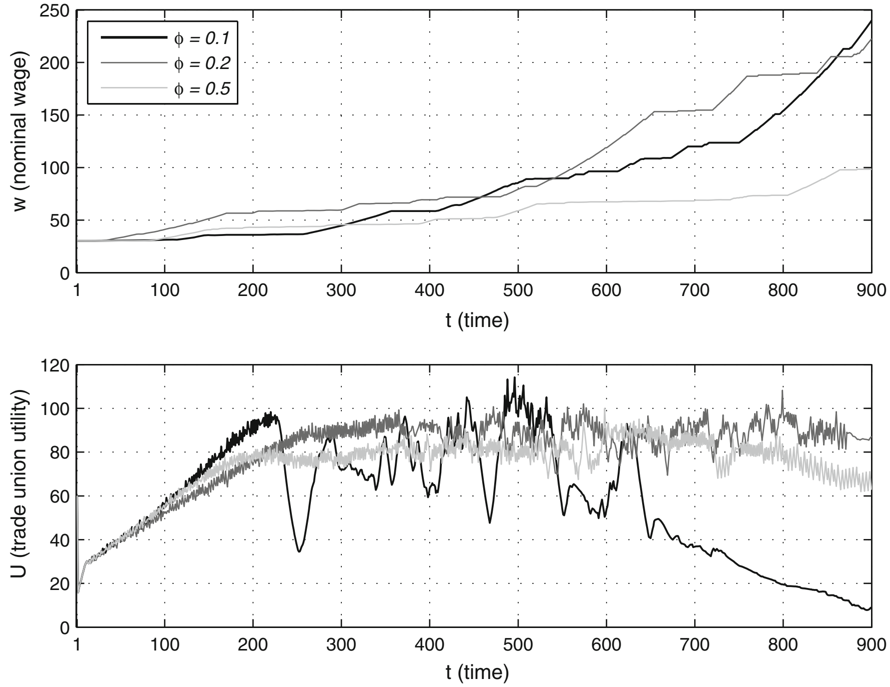

Fig. 2 Time series of nominal wage and trade union utility for different values of policy strength ϕ

is due to a cost channel effect, i.e., a cost channel is present when firms marginal cost depends directly on the nominal rate of interest (Ravenna and Walsh 2006). Actually, in the first phase, in order to compensate the expected profits loss due to a lending rate raise, the price-setting firm is induced to raise the price. However, when the output gets close to the production capacity bound, the price growth limiting effect of the monetary policy prevails because it prevents the raise of the price due to the saturation effect.

The price evolution, in the case of weak output gap control ($\phi = 0.1$), exhibits two main patterns: a first pattern of low steady growth and a second pattern characterized by a high growth and strong fluctuations. The change in pattern occurs after production achieves the upper bound; in particular, this event triggers a sudden rise in inflation. Indeed, the incentive for the monopolistic firm to raise price is stronger when it faces an high demand but cannot increase output, i.e., it is constrained in employment of labor input. However, a high inflation regime cannot be sustained indefinitely, as shown by the evident price falls in the figure, because it depresses real wages and consequently the aggregate demand. In this respect, the cap on nominal wage updates which equals the planned inflation $\pi^{\star}$ plays an important role, determining the maximum value of sustainable price inflation. Nominal wage trajectories are shown in Fig. 2. The decrease in aggregate demand and thus in production is particularly evident in the trajectory of $\phi = 0.1$ before time step $t = 500$. This hyperinflation has a very strong effect on the trade union utility, i.e., on the welfare of the workers community, as shown in Fig. 2.

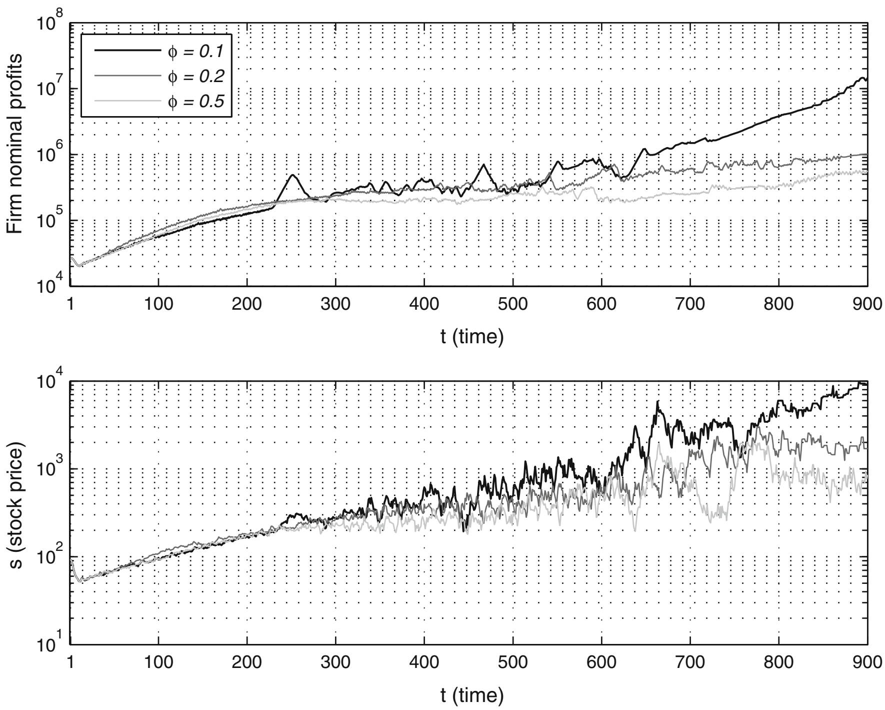

Fig. 3 Time series of nominal profits and stock price for different values of policy strength ϕ

The fall of real wages, due to high inflation, together with the decreased employment, due to the lowered demand, determines strong negative fluctuations in the trade union utility which end up with a downward trend, generated by the final steady growth in price. Higher values of the policy strength parameter may be used in order to prevent these negative outcomes. The monetary policy strategies corresponding to $\phi = 0.2$ and $\phi = 0.5$, have a relevant impact on inflation control. Indeed, price growth exhibits an increase in the first phase, i.e., before the output gap is canceled out, and a significant reduction in the second phase. These apparently incongruous price reactions to the interest rate are actually given by precise economic reasons. The behavior in the first phase can be explained according to the relation between interest rate and production costs, i.e., the firm supply curve, whose underlaying mechanism has been already clarified. On the other hand, the behavior in the second phase depends on the fact that a tighter monetary policy is able to keep the economy below its maximum capacity, preventing the inflation peaks caused by the labor input constraint. A tight output gap monetary policy rule, preventing the fall of the real wage by controlling inflation, guarantees a higher and more stable utility for workers. However, some caution has to be used in the tightening monetary policy, as shown by both the lower production level and the lower trade union utility level corresponding to the policy $\phi = 0.5$.

Tables 2 and 3 present the average values and the standard error of four economic time series, obtained by applying an output gap control policy rule and a random policy rule, respectively. A comparison of the two tables shows that for low ϕ values

Table 2 Output gap control policy rule: average values and standard error of four economic time series

	μ_Y $(\hat{\sigma}_Y)$	μ_U $(\hat{\sigma}_U)$	μ_π $(\hat{\sigma}_\pi)$	μ_{π^w} $(\hat{\sigma}_{\pi^w})$
$\phi = 0.05$	448.5 (3.5)	59.3 (0.8)	0.51 (0.10)	0.31 (0.01)
$\phi = 0.10$	447.4 (3.6)	57.6 (0.9)	0.56 (0.10)	0.23 (0.01)
$\phi = 0.15$	445.7 (3.5)	72.6 (0.6)	0.36 (0.11)	0.25 (0.01)
$\phi = 0.20$	421.8 (3.5)	80.0 (0.6)	0.31 (0.13)	0.22 (0.01)
$\phi = 0.25$	421.6 (3.4)	79.7 (0.6)	0.28 (0.12)	0.19 (0.01)
$\phi = 0.30$	428.3 (3.3)	77.0 (0.5)	0.28 (0.13)	0.18 (0.01)
$\phi = 0.35$	405.1 (3.1)	78.3 (0.6)	0.28 (0.12)	0.20 (0.01)
$\phi = 0.40$	413.3 (3.4)	71.5 (0.6)	0.22 (0.13)	0.16 (0.01)
$\phi = 0.45$	398.3 (2.9)	76.5 (0.5)	0.29 (0.13)	0.19 (0.01)
$\phi = 0.50$	415.4 (3.1)	74.0 (0.5)	0.25 (0.14)	0.13 (0.01)

Table 3 Random policy rule: average values and standard errors of four economic time series

	μ_Y $(\hat{\sigma}_Y)$	μ_U $(\hat{\sigma}_U)$	μ_π $(\hat{\sigma}_\pi)$	μ_{π^w} $(\hat{\sigma}_{\pi^w})$
$\phi = 0.05$	421.6 (3.7)	75.1 (0.8)	0.34 (0.12)	0.29 (0.01)
$\phi = 0.10$	434.1 (3.6)	65.4 (0.7)	0.49 (0.13)	0.27 (0.01)
$\phi = 0.15$	421.4 (3.8)	64.6 (0.8)	0.32 (0.12)	0.26 (0.01)
$\phi = 0.20$	429.9 (3.7)	78.3 (0.7)	0.41 (0.14)	0.29 (0.01)
$\phi = 0.25$	248.8 (1.8)	48.3 (0.4)	0.39 (0.15)	0.28 (0.01)
$\phi = 0.30$	381.8 (3.2)	70.5 (0.6)	0.27 (0.15)	0.14 (0.01)
$\phi = 0.35$	378.9 (3.2)	68.1 (0.6)	0.35 (0.15)	0.20 (0.01)
$\phi = 0.40$	250.3 (1.5)	45.2 (0.3)	0.33 (0.15)	0.21 (0.01)
$\phi = 0.45$	271.8 (2.0)	45.8 (0.4)	0.29 (0.15)	0.21 (0.01)
$\phi = 0.50$	210.7 (2.6)	36.3 (0.5)	0.32 (0.15)	0.23 (0.01)

the output gap control rule does not clearly outperform the random rule: it achieves a higher output but also a higher rate of inflation, thereby lowering worker's welfare. This is due to the weak impact of monetary policy for low values of ϕ. For higher values of ϕ, i.e., a strong policy impact, it emerges that generally the output gap rule has a better performance than the random rule, both in term of superior output and higher utility; price and wage inflation are also better controlled. Considering the values reported in Table 2, let us point out that an output gap control monetary policy leads to an increase in the worker's utility and keeps inflation under control, without implying substantial output losses. In this respect, the random rule is not able to obtain similar results.

Figure 3 shows the trajectories of nominal profits realized by the firm and the stock market price. According to the model of the stock market, the expected return of firm's equity is equal to the expected dividend yield plus a Gaussian random variable with zero average, see Eq. 10. Besides, since the portfolio allocation weights are based on Markowitz portfolio selection theory, the level of investment in stocks increases along with expected dividend yields. This feature is confirmed by examining Fig. 3, where the stock market price is clearly driven by nominal profits. Nominal profit trajectories are strictly related to the dynamics of the price level, implying that the stock market price is influenced by the monetary policy strategy through the dynamics of inflation. However, the high stock market price for low values of ϕ does not necessarily mean a higher profitability of the firm's equity in real terms. Indeed, the level of prices in the goods market must be taken into account to form a correct evaluation of stock market profitability.

The distribution of stock returns is characterized by fat tails. The presence of the random component in the expected returns formation, together with the volatility feedback effect, give rise to the well-known stylized facts in the distribution of returns, as pointed out in previous works of some of the authors (Raberto et al. 2001, 2003). The Jarque-Bera test and the Kolmogorov-Smirnov test reject the null hypothesis of a Gaussian distribution for returns at the 5% significance level. The ARCH test rejects the null hypothesis that the time series of returns is characterized by independent and identically distributed Gaussian disturbances, therefore pointing out the existence of ARCH effects.

4 Concluding Remarks

This article attempt is to contribute to the development of the field of agent-based computational economics, by providing an integrated model of a real economy and a financial market, and by showing how an agent-based model can be a very useful instrument for performing monetary policy experiments.

The field of macroeconomics has witnessed in recent years a marked increase in interest in monetary policy and there has been a considerable improvement in the underlying theoretical frameworks used for policy analysis. A new generation of small-scale monetary business cycle models, generally referred to as New Keynesian models, incorporate the techniques of dynamic general equilibrium theory with explicit consideration of frictions such as nominal rigidities, that are very important to evaluate the effectiveness of monetary policy. Indeed, the new Keynesian analytical framework is based on a log-linear approximation of agents' optimizing behavior and represents monetary policy by a rule for setting the nominal rate of interest. A notable feature of this recent approach to monetary policy is the emphasis given to the objective of maintaining a low and stable rate of inflation.

The present article has addressed these issues from a different perspective: that of an agent-based model within a general equilibrium framework. Our approach permits the avoidance of approximations of small-scale analytical models, by means of the computer simulation of large-scale interacting agent models. Results show that, through a monetary policy strategy based on the control of the output, it has been possible to target the objective of maintaining a low and stable rate of inflation. Moreover, results show that the monetary policy can have a positive effect on welfare, provided a proper calibration of the degree of policy tightness.

This research program aims at making significant progress toward the development of a framework the purpose of which is the evaluation of alternative monetary policies. Furthermore, future research will also investigate in depth the influence of assets traded in financial markets on monetary policy design.

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