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SHOULD MONETARY AUTHORITIES PRICK ASSET PRICE BUBBLES? EVIDENCE FROM A NEW KEYNESIAN MODEL WITH AN AGENT-BASED FINANCIAL MARKET

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SHOULD MONETARY AUTHORITIES PRICK ASSET PRICE BUBBLES? EVIDENCE FROM A NEW KEYNESIAN MODEL WITH AN AGENT-BASED FINANCIAL MARKET[2]

We develop the approach based on the synthesis of New Keynesian macroeconomics and agent-based models, and build a model, allowing for the incorporation of behavioral and speculative factors in financial markets in a New Keynesian model with a financial accelerator, `a la Bernanke et al. (1999). Using our model, we study the optimal strategy of central banks in pricking asset price bubbles for the maximization of social welfare and preserving financial stability. Our results show that pricking asset price bubbles can be a policy that enhances social welfare, and reduces the volatility of output and inflation; especially, in the cases when asset price bubbles are caused by credit expansion, or when the central bank conducts effective information policy, for example, effective verbal interventions. We also argue that pricking asset price bubbles with the lack of the effectiveness of information policy, only by raising the interest rate, leads to negative consequences to social welfare and financial stability.

JEL classification: E03, E44, E52, E58, G01, G02.

Keywords: optimal monetary policy; asset price bubble; New Keynesian macroeconomics; agent-based financial market.

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1. Introduction

Crashes and bubbles in financial markets that lead to instability and volatile dynamics in the economy have been the subject of hot debate in the macroeconomic literature for a long time. The Global Financial Crisis of 2008–2009, and the recent stock market bubble in China, have only increased the interest in these phenomena, stressing several drawbacks in existing macroeconomic frameworks. These include issues related to the influence of behavioral and speculative factors in financial markets on the economy and to the necessary response of regulatory authorities to financial bubbles.

One stream of research that arose after the Great Recession is the incorporation of agent-based financial markets, which may reproduce speculative phenomena in financial markets, in traditional macroeconomic frameworks. The further development of this approach is the first contribution of our paper. For this purpose, we construct a more complex model than the models from previous literature in this field. This complication allows us to make a second contribution, the most significant contribution of our paper. Using our constructed model, for first time in the literature (to the best of our knowledge), we study the optimal strategy of central banks in pricking asset bubbles for the maximization of social welfare and preserving financial stability.

The hot debate about the necessary response of monetary policy on asset price bubbles, among policy makers and in academia, is known as the "clean" versus "lean" debate. Following the "clean" approach, central banks should not respond to asset price bubbles before the bubble bursts, above the necessary reaction for the stabilization of inflation and employment, but just clean up the consequences of the bubble. This approach may be more preferable for monetary policy, because of several possible reasons: generally, bubbles are hard to detect; a bubble may exist only in a small market; and raising interest rates may not sufficiently affect bubbles or, sometimes, may cause the bubble to burst more severely. The "clean" approach prevailed in central banks and academia before the Global Financial Crisis of 2008–2009. According to another point of view, following the "lean" approach, central banks should conduct monetary policy that leans against asset price bubbles and leads to increasing interest rates above the necessary reaction for the stabilization of inflation and employment. After the Global Financial Crisis, the "lean" approach has become preferable. Nowadays, the focus of macroeconomic discussion has changed, from the question of *whether* central banks should respond on asset price bubbles or not, to the question of *how* central banks should respond to asset price bubbles, in which cases should they actively respond, and which strategy is best to use.[3]

Although the optimal response of monetary policy on asset price bubbles has been the subject of hot debate in mainstream macroeconomics for decades and has been studied by many authors (e.g. Bernanke and Gertler (2000), Cecchetti (2000), Bordo and Jeanne (2002), Bean (2004), Gruen et al. (2005)), surprisingly, there is a lack of research on cases when monetary policy serves to prick asset price bubbles, although this topic has been widely discussed in the literature (e.g. in Roubini (2006) and Posen (2006)). In the case of the identifying the need for pricking, the central bank has already missed time when the bubble grew and now it has to decide which strategy for pricking the bubble would be best, or whether it would be better not to do anything against the bubble. Almost all of the papers on this topic do not concentrate on such cases, when the central bank is already in an unfavorable position. But analysis of such cases is important, because of problems related to the identification of bubbles at the early stage. At this stage, misalignment is not yet noticeable and monetary policy usually can start affecting the bubble only after it has grown to a substantial size. The lack of research on the pricking of asset price bubbles is caused by the lack in development of potentially appropriate methods for analysis. The framework constructed in our paper fills this gap.

In this paper, we outline a joint model consisting of a New Keynesian model with a financial accelerator, `a la Bernanke et al. (1999), which determines the real sector, and an agent-based model that sets the financial market populated by bounded rational traders. The market price of assets in this joint model, which is determined through trading (the interaction of traders in the financial market), can sometimes significantly deviate from the fundamental price of assets. In such cases, bubble cases, traders may start selling their assets, which leads to the bursting of the bubble and, perhaps, to a crisis in the economy. The monetary policy in the joint model, in addition to the interest rate change from the Taylor rule, can raise the interest rate in order to prick the bubble, or can influence traders' expectations much earlier than the bubble bursting by itself; for example, it can announce the existence of a bubble in the media. The influence of the central bank on traders' expectations in the model is the central bank's information policy, which can be more or less effective, if traders believe or ignore the announcements of the central bank, respectively.

[3] For more detailed discussion of the "clean" versus "lean" debate see, for example, Mishkin (2011) or Brunnermeier and Schnabel (2015).

There are only two papers in this field that study the necessary response of monetary policy on asset price bubbles, Filardo (2004) and Fouejieu et al. (2014), in which the authors consider pricking bubbles. In both papers, the authors use simple New Keynesian models, in which the interest rate is determined through the Taylor rule and affects the probability of the bursting of asset price bubbles, so the bubble endogenously depends on the interest rate. In comparison to these papers, we construct a framework that includes not only basic equations for New Keynesian models, but also the production function, capital and labor markets, credit market frictions, and the amplification mechanism of the financial sector. This allows us to analyze the influence of pricking asset price bubbles on social welfare and other macroeconomic variables. Moreover, in our model, in addition to the endogenous relationship between the interest rate and the probability of bursting the asset bubble, there are two extra possible effects of monetary policy on asset price bubbles. First, the central bank can raise the interest rate above the necessary reaction from the Taylor rule at certain times, when the deviation of the market asset price from the fundamental asset price becomes too large. Second, the central bank can influence traders' expectations about the future development of asset bubbles through its information policy, for example, through verbal interventions.

We calculated social welfare losses and the volatility of output and inflation in various cases, which differ by a variety of factors. These factors included, the size of the response of monetary policy on asset price bubbles, the efficiency of the central bank's information policy, or by the existence of the liquidity flow from the real sector to the financial sector that allows us to mimic situations in which bubbles are partially boosted by credit expansion, such as the Global Financial Crisis of 2008-2009. Our results demonstrate that, in some cases, pricking asset price bubbles by the central bank can reduce social welfare losses from asset price bubbles, as well as the volatility of output and the volatility of inflation. This effect is larger, in cases when asset price bubbles are caused by credit expansion and when the central bank conducts effective information policy; in other words, it can effectively influence traders' expectations. We also argue that pricking asset price bubbles only by raising the interest rate, with a lack of effective information policy, leads to negative consequences for social welfare and financial stability.

Our paper also concerns another stream of research, in which authors integrated financial market models with, or at least following the logic of, agent-based models, which may generate speculative phenomena in financial markets in traditional macroeconomic models of the real economy. The financial market, in the models from this field, is usually constructed following the logic of the chartists/fundamentalists agent-based model of the financial market, because this model allows researchers to simply include the main stylized facts of financial markets in the analysis. In the early papers in the field Kontonikas and Ioannidis (2005) and Kontonikas and Montagnoli (2006), the authors add rules for the behavior of a financial market to a simple New Keynesian model with rational expectations. A large part of more recent papers in the field (Scheffknecht and Geiger (2011), Spelta et al. (2012), Lengnick and Wohltmann (2013), Pecora and Spelta (2013), and Lengnick and Wohltmann (2016)) continue the development of this approach, but focus on using bounded-rational expectations in the real sector of economy. Some authors (Bask and Madeira (2011), Bask (2012) and Gwilym (2013)) still work with rational expectations, integrating financial market models into existing, more complex traditional frameworks (Westerhoff (2012), Naimzada and Pireddu (2014) and Naimzada and Pireddu (2015)) use traditional Keynesian income-expenditure models for the real sector, in order to pay more attention to the analysis of interactions between the real sector and the financial market, than on the complexity of the joint model. In our paper, we use a more complex agent-based model of the financial market than in previous literature, integrating it into a New Keynesian model with a financial accelerator, `a la Bernanke et al. (1999), with rational expectations. Using this exact combination allows us to make the largest contribution of our paper: to study the optimal strategy for central banks in pricking asset price bubbles for the maximization of social welfare and the preservation of financial stability.

The paper is organized as follows. Section 2 includes the description of the model, where Sections 2.1 and 2.2 describe the New Keynesian part and the agent-based part of the model correspondingly, and Section 2.3 shows how we connect two parts in the joint model. The calibration of the model is discussed in Section 3. Section 4 presents the first simulations of our model and the discussion of their robustness, while Section 5 contains the analysis of the optimal strategy of monetary policy in pricking asset price bubbles. Finally, Section 6 concludes the paper.

2. Model

Our joint model consists of two parts: the real sector, which is similar to the financial accelerator framework with a bubble from Bernanke and Gertler (2000) and the financial sector, which is set by the agent-based model. The model includes seven types of agents, six of them: households, entrepreneurs, retailers, capital producers, the central bank, and the government, as related to the New Keynesian part of the joint model. The agent-based financial market is populated by bounded rational traders, who trade futures contracts on capital from the real sector using behavior rules and, thereby, set the market price of capital in the real sector. We construct the agent-based financial market using the logic of the model from Harras and Sornette (2011), but change the essence of the behavior rules for traders, add the liquidity flow from the real sector to the financial market, and calibrate the model to the real data. The agent-based financial market is calibrated in order to reproduce possible bubbles.

In comparison to the original paper of Bernanke and Gertler (2000), we exclude money and exogenous shocks from the model, for the simplicity of the analysis. In the model, the central bank sets the interest rate according to the Taylor rule, but can also additionally raise the interest rate to try to prick bubbles in the market price of capital. This may also affect traders' expectations or their opinions; we name the influence of the additional increase in the interest rate on the traders' opinions "the information policy of the central bank." The change of market price in the agent-based financial market is transmitted to the real sector through the market change impulse. The market price impulse is not a random shock, but is a variable with a complex dynamic that is set by the agent-based financial market. The deviation of the market price of capital from the fundamental price in the real sector, first of all, influences the costs of resources for entrepreneurs through the financial accelerator mechanism.

To sum up, the real sector and the financial market are connected through four transmission mechanisms: the dynamics of the financial market determines the market price of capital in the real sector; the real sector affects traders' opinions about the fundamental price of capital; the central bank can also affect traders' opinions by the information policy; and there are liquidity flows from the real sector to the financial market. It is worth noting, that the periods of operation in two parts of the joint model are different: in the real sector, the period corresponds to one quarter, in the financial market it corresponds to one week. Section 2.1 further presents the description of the New Keynesian part of the joint model that sets the operation of the real sector. Section 2.2 provides the specification of the agent-based part of the model - the financial market, while the interaction of parts with each other is discussed in Section 2.3.

2.1. Real Sector

2.1.1. Households

The model consists of a continuum of households, normalized to 1. The representative household solves the following standard utility maximization problem:

$$maxE_0 \sum_{t=0}^{\infty} \beta^t U(C_t, L_t) = maxE_0 \sum_{t=0}^{\infty} \beta^t \left\{ \log C_t - \frac{{L_t}^{1+\sigma_l}}{1+\sigma_l} \right\}, \tag{1}$$

which depends on the current consumption C_t and the labor supply $L_t(h)$. $0 < \beta < 1$ denotes the discount factor and σ_l is the inverse elasticity of labor supply.

The budget constraint of a household has the following form:

$$C_t + B_t = W_t L_t + \frac{R_{t-1} B_{t-1}}{\pi_t} + \Pi_t - T_t, \tag{2}$$

where B_t and B_{t-1} denote credits to entrepreneurs at time t and $t-1$, respectively. Credit repayments at time $t-1$, $\frac{R_{t-1} B_{t-1}}{\pi_t}$, are adjusted for the inflation rate $\pi_t = \frac{P_t}{P_{t-1}}$ at time t, the interest rate R_{t-1} is set by the central bank. The household gets from entrepreneurs the wage W_t in exchange for its labor L_t, pays lump sum taxes T_t , and owns retail firms, obtaining their profit - Π_t.

The first order conditions for the problem $(1) - (2)$ are standard and have the following form:

$$\frac{1}{C_t} = \beta \frac{1}{C_{t+1}} \mathrm{E}_t \left(\frac{R_t}{\pi_{t+1}} \right) \tag{3}$$

$$\frac{W_t}{C_t} = {L_t}^{\sigma_l}, \tag{4}$$

where (3) and (4) are the Euler equation and the labor-supply condition, respectively.

2.1.2. Entrepreneurs

Entrepreneurs manage perfectly competitive firms that produce intermediate goods and borrow from households in order to finance the purchase of the capital K_{t+1} for the production process at time $t+1$. In the production process at time t they also use households' labor L_t; the production function of a representative entrepreneur is assumed to be of the Cobb-Douglas type:

$$Y_t = A K_t^{\alpha} L_t^{(1-\alpha)\Omega}, \tag{5}$$

where the parameter A represents technology process, α and $(1-\alpha)$ are the shares of capital and labor in the intermediate product, respectively, while Ω denotes the share of households' labor in the total labor. The amount of entrepreneurs' labor is normalized to 1, and the share of entrepreneurs' labor is equal $(1-\Omega)$.

With the probability $(1-\upsilon)$ an entrepreneur can become bankrupt in each period. Under this assumption, entrepreneurs always have to finance their capital purchases using both their net worth, N_t, and credits from households, B_t:

$$B_t = Q_t K_{t+1} - N_t, \tag{6}$$

where Q_t is the fundamental price of capital at time t.

Bernanke and Gertler (2000) introduce the "financial accelerator" mechanism from BGG (1999), in which the interest rate for external financing, R_t^F, is greater than the interest rate, R_t, because of agency costs and asymmetric information, and depends on the ratio of the market value of capital to the net worth:

$$E_t R_{t+1}^F = \frac{R_t}{\pi_{t+1}} \left(\frac{F_t K_{t+1}}{N_t}\right)^{\psi}, \tag{7}$$

where R_{t+1}^F denotes the expected rate of external financing, F_t is the market price of capital at time t, ψ denotes the parameter of financial accelerator mechanism. $lev = \frac{F_t K_{t+1}}{N_t}$ is the ratio of the market value of capital to the enterpreneurs' net worth or their financial leverage.

The net worth of entrepreneurs is determined according to the following equation:

$$N_t = \nu[R_t^F F_{t-1} K_t - E_{t-1} R_t^F (F_{t-1} K_t - N_t)] + W_t^e, \tag{8}$$

where $(1-\alpha)(1-\Omega) A_t K_t^{\alpha} L_t^{(1-\alpha)(1-\Omega)}$ is the labor income of entrepreneurs. Entrepreneurs, who become bankrupt at time t, consume the rest of the net worth in the amount C_t^e.

The interest rate of external financing in (7) and the dynamics of entrepreneurs' net worth in (8) depend on the market price of capital F_t, which is changed as follows:

$$\ln(F_t) - \ln(Q_t) = \ln(F_{t-1}) - \ln(Q_{t-1}) + \tau_t^F, \tag{9}$$

where the variable τ_t^F is the exogenous market change impulse set by the interaction of traders on the financial market, who trade futures on capital. Calculations in the real sector take place in the end of the current quarter, while τ_t^F is calculated on the basis of the dynamics of the financial market over 13 weeks in the current quarter. The setting of τ_t^F will be described further in Section 2.3. Equation (9) determines the size of the deviation of the market price of capital from the fundamental price of capital, and we suppose that without the market change impulse,

τ_t^F, the deviation value remains the same over time. This assumption seems very reasonable, because the prediction of financial markets is a very complicated problem, if it is possible at all. Financial markets can go up or down, so without proper prediction, it is the most suitable way to suppose that the deviation will be the same over time without exogenous shocks.

The following condition is fulfilled under the optimal demand on capital:

$$R_t^F = \frac{(R_t^k + (1-\delta)F_t)}{F_{t-1}}, \tag{10}$$

where R_t^k is the marginal return on capital. The first order conditions for entrepreneurs are as follows:

$$R_t^k = \frac{\alpha Y_t}{K_t} MC_t \tag{11}$$

$$W_t = \frac{(1-\alpha)Y_t}{L_t} MC_t \tag{12}$$

$$W_t^e = (1-\alpha)(1-\Omega)Y_t MC_t, \tag{13}$$

where $\frac{1}{MC_t}$ is the markup of retailers at time t, its description will be given further.

2.1.3. Capital Producers

The representative competitive capital producer purchases the amounts of final goods I_t at the price P_t from retailers at the beginning of each period. Subsequently, she transforms the final goods into the equal amount of new capital and sells newly produced capital to the entrepreneurs at the price P_t^K. We assume that the representative capital producer maximizes the following function:

$$\max_{I_t} \left[Q_t I_t - I_t - \frac{\chi}{2}\left(\frac{I_t}{K_t} - \delta\right)^2 K_t \right], \tag{14}$$

where $\frac{\chi}{2}\left(\frac{I_t}{K_t} - \delta\right)^2 K_t$ is quadratic adjustment costs; $Q_t = \frac{P_t^K}{P_t}$ denotes the relative fundamental price of capital at time t; δ and χ represent the depreciation rate and the parameter of adjustment costs correspondingly. The first order condition in this case is the standard Tobin's □□equation:

$$Q_t - 1 - \chi\left(\frac{I_t}{K_t} - \delta\right) = 0 \tag{15}$$

The aggregate capital stock evolves according to:

$$K_t = (1-\delta)K_{t-1} + I_t \tag{16}$$

2.1.4. Retailers

We introduce nominal price rigidity through the retail sector following Calvo (1983), populated by a continuum of monopolistic competitive retailers of mass 1, indexed by z. At time t retailers purchase intermediate goods Y_t at the price P_t^w from entrepreneurs in a competitive market, differentiate them at no costs into $Y_t(z)$, and then sell to households and capital producers in the amount Y_t^f at the price $P_t(z)$ using a CES aggregation with the elasticity of substitution $\epsilon_y > 0$:

$$Y_t^f = \left(\int_0^1 Y_t(z)^{\frac{\epsilon_y - 1}{\epsilon_y}} dz\right)^{\frac{\epsilon_y}{\epsilon_y - 1}} \tag{17}$$

Each retailer faces the following individual demand curve:

$$Y_t(z) = \left(\frac{P_t(z)}{P_t}\right)^{-\epsilon_y} Y_t^f, \tag{18}$$

where P_t denotes the aggregate price index, which is determined as follows:

$$P_t = \left(\int_0^1 P_t(z)^{1-\epsilon_y} dz\right)^{\frac{1}{1-\epsilon_y}} \tag{19}$$

In each period, the share of retailers $(1-\theta_p)$ can adjust their prices to maximize the following profit function:

$$\Pi_t = \sum_{k=0}^{\infty} \theta_p^k \mathrm{E}_{t-1}\left[\Lambda_{t,k} \frac{P_t^* - P_{t+k}^w}{P_{t+k}} Y_{t+k}^*\right], \tag{20}$$

where $\Lambda_{t,k} \equiv \beta \frac{C_t}{C_{t+k}}$ denotes the discount factor of retailers, which is equal to the stochastic discount factor of households, P_t^* and $Y_t^*(z) = \left(\frac{P_t^*(z)}{P_t}\right)^{-\epsilon_y} Y_t$ are the optimal price and optimal demand at time t.

The first order condition of retailers is:

$$\sum_{k=0}^{\infty} \theta_p^k \mathrm{E}_{t-1} \left[\Lambda_{t,k} \left(\frac{P_t^*}{P_{t+k}} \right)^{-\epsilon_y} Y_{t+k}^*(R) \left[\frac{P_t^*}{P_{t+k}} - \left(\frac{\epsilon_y}{\epsilon_y - 1} \right) \frac{P_{t+k}^w}{P_{t+k}} \right] \right] = 0 \qquad (21)$$

2.1.5. Central Bank

The Central Bank in the model sets the interest rate using the standard Taylor rule:

$$\ln\left(\frac{R_t}{\bar{R}}\right) = \rho_r \ln\left(\frac{R_{t-1}}{\bar{R}}\right) + (1-\rho_r)\left(\rho_\pi \ln\left(\frac{\pi_t}{\bar{\pi}}\right) + \rho_y \ln\left(\frac{Y_t}{\bar{Y}}\right)\right) + \Delta r_t^{Bubble}, \qquad (22)$$

where $\bar{R}$, $\bar{\pi}$, $\bar{Y}$ represent the steady state values of R_t, π_t, Y_t, respectively; ρ_r, ρ_π, ρ_y denote the weights in the Taylor rule. Δr_t^{Bubble} is an additional increase in the interest rate set by the central bank in response to bubbles in the market price of capital in order to prick bubbles. We will discuss how pricking bubbles works in more details further in Section 2.3.

2.1.6. Government Sector

Government expenditures are financed by lump-sum taxes:

$$G_t = T_t \qquad (23)$$

2.2.Financial Market

The agent-based part of the model, that sets the operation of the financial market for futures on capital, includes S traders, who form by trading $p_{m,w}$ - the market price of capital in the financial market in week w. We assume that the volume of capital, used by traders in trading in the financial market, is a small part of investment in each period, and the change of the amount of capital that is used in trading does not affect the amount of investment in each period. The main part of new capital is purchased by entrepreneurs from capital producers directly, but the market price of capital is determined in the financial market, often under the influence of speculative forces.

The behavior of traders in the model is based on the certain number of rules, parameters of which vary from trader to trader and are drawn randomly from distributions. This approach allows us to take into account the heterogeneity of agents on the financial market. The agent-based part of the model is constructed in the spirit of Harras and Sornette (2011) model with significant modifications relevant for our research. From the original model we use the elements related to the price formation in the financial market and the structure of the main mechanisms, however, we change the rules by which traders make decisions. We also include liquidity flows from the real sector to the financial market and calibrate the model parameters to the stylized facts about stock returns.

2.2.1. Trading Strategies

Each week w trader i makes one of the three decisions: buy futures, sell futures or do not participate in trading. It is worth noting, that our model does not include the possibility of short positions. The trader's decision is based on her opinion about future price movements. The opinion of the trader i in week w - $\omega_{i,w}$ can be affected by 3 types of information sources: the fundamental information, $Fundamental_w$, about the fundamental value of capital, which is common for all traders on the market, the market information, $Market_w$, which is also common for all traders, and the private information, $Private_{i,w}$, which is different for each trader. $\omega_{i,w}$ is determined by the following equation:

$$\omega_{i,w} = c_{1i} * Fundamental_w + c_{2i} * Market_w + c_{3i} * Private_{i,w}, \tag{24}$$

where c_{1i}, c_{2i}, and c_{3i} represent the coefficients that are unique for each trader and have a uniform distribution over the respective intervals $[0, C_1]$, $[0, C_2]$, and $[0, C_3]$, where C_1, C_2, and C_3 denote parameters in the model. The private information has a simple standard normal distribution, $Private_{i,w} \sim N(0,1)$.

The market information reflects the market sentiments, including market trend and economic, political, and geopolitical news, and is set as:

$$Market_w = \varepsilon_w^{market} + \overline{LRtrend} + MRtrend_w, \tag{25}$$

where ε_w^{market} is a random global news shock in week w that has a standard normal distribution, $\overline{LRtrend}$ is a model parameter, which represents - a fixed long-run component in the market infromation, while $MRtrend_w$ refers to a variable medium-run component in the market information and is equal, in week w, to the difference between two moving averages of the market price for the last 52 and 104 weeks multiplied by the parameter $trendpar$:

$$MRtrend_w = trendpar * \left(\sum_{j=w-52}^{w-1} p_{m,j} - \sum_{j=w-104}^{w-1} p_{m,j}\right) \tag{26}$$

The fundamental information is based on the deviation of the market price $p_{m,w}$ in week w on the financial market from the fundamental price of capital Q_{t-1} in the last quarter $t-1$ calculated from the real sector of the model as follows:

$$Deviation_w = \frac{p_{m,w} - Q_{t-1}}{Q_{t-1}} \tag{27}$$

As $Deviation_w$ becomes larger, more and more traders take it into consideration in their decision process. This may not lead to the bursting of the bubble because traders may believe that the bubble will exist further, but in some cases, when traders fear that the bubble will burst in the near future, a large value of $Deviation_w$ will force traders to sell futures and cause the bursting of the bubble. To include this phenomenon in our model, we assume that the fundamental information depends also on the traders' fear in week w, $Fear_w \geq 0$, of the forthcoming burst of the bubble:

$$Fundamental_w = Fear_w * \left(Deviation_w + \varepsilon_w^{fundam}\right), \tag{28}$$

where ε_w^{fundam} is a normally distributed fundamental information shock with zero mean and standard deviation σ^{fundam} , i.e. $\varepsilon_w^{fundam} \sim N(0, \sigma^{fundam})$. The variable $Fear_w$ is determined according to the following rule:

$$Fear_w = \left(1 + |\max(0, Deviation_{w-1})| * \left|\min\left(0, \frac{p_{m,w-1} - p_{m,w-memory}}{p_{m,w-memory}}\right)\right|^{\mathrm{f1}} * f2\right) * (1 + IPparam ** \Delta r_{t-1}^{Bubble}), \tag{29}$$

where the first factor, $\left(1 + |\max(0, -Deviation_{w-1})| * \left|\min\left(0, \frac{p_{m,w-1} - p_{m,w-memory}}{p_{m,w-memory}}\right)\right|^{\mathrm{f1}} * f2\right) \geq 1$, represents the effect of the deviation of the fundamental price from the market one in last week, $Deviation_{w-1}$, and the effect of the market return over several last weeks, $\frac{p_{m,w-1} - p_{m,w-memory}}{p_{m,w-memory}}$, on traders' fear. $memory$ denotes the number of weeks used in the calculation of the cumulative market return, while $f1$ and $f2$ are model parameters. The first factor is equal 1, if the fundamental price is greater than the market price, or if the market return over several last weeks is positive.

The second factor, $(1 + IPparam * \Delta r_{t-1}^{Bubble})$, shows the influence of the information policy of the central bank on the traders' fear, where Δr_{t-1}^{Bubble} is an additional increase in the interest rate from the New Keynesian part of the model, used by the central bank to prick the bubble. $IPparam$ denotes the parameter of information policy, which determines the efficiency of the central bank's information policy, and shows the effect of the additional increase in the interest rate on the traders' fear of the bursting of the bubble in the near future.

Initially, the portfolio of the trader i consists of cash, $cash_{i,0}$, and some amount of futures, $futures_{i,0}$. These values have uniform distributions over the intervals $\left[0, \overline{cash}\right]$ and $\left[0, \overline{futures}\right]$ correspondingly, where $\overline{cash}$ and $\overline{futures}$ are the parameters of the model.

As in Harras and Sornette (2011), in order to introduce the differences in risk aversion for traders, we suppose that in each week trader i decides on her participation in trading based on the parameter $\underline{\omega_i}$, set randomly for each trader over the interval $\left[0, \underline{\Omega}\right]$, where $\underline{\Omega}$ is the parameter of the differences in risk aversion. The value of $\underline{\omega_i}$ is compared with the value of $\omega_{i,w}$, and the trader i makes the decision on the basis of the following rules:

$$if \quad \omega_{i,w} > \underline{\omega_i} : \; s_{i,w}^d = +1 \; (buying), \; v_{i,w}^d = share * \frac{cash_{i,w-1}}{p_{m,w-1}}$$

$$if \quad -\underline{\omega_i} \leq \omega_{i,w} \leq \underline{\omega_i} : s_{i,w}^d = 0 \quad (hold), \; v_{i,w}^d = 0$$

$$if \quad \omega_{i,w} < -\underline{\omega_i} : \quad s_{i,w}^d = -1 \; (selling), \; v_{i,w}^d = share * futures_{i,w-1} \qquad (30)$$

where $v_{i,w}^d$ is the number of futures trader i wants to buy or sell, $s_{i,w}^d$ denotes the indicator of the trading operation. $share$ is the model parameter reflecting the share of futures contracts in the trader's portfolio, $futures_{i,w}$, the trader wants to sell or the share of cash in her portfolio, $cash_{i,w}$, the trader wants to spend on buying futures contracts. Following Harras and Sornette (2011), we use the value for $share$ that are much smaller than 1 in order to ensure time diversification.

2.2.2. Liquidity Flows

We assume that the portfolio of each trader may vary not only due to trading operations that are based on the trader's decisions, but also due to liquidity flows from the real sector to the financial market. Traders also buy (sell) futures in the case of the positive (negative) flow of the liquidity from the real sector to the financial market.

The variable $liquidity_w$ shows by how much the value of the trader's portfolio should be changed due to the liquidity flow: if $liquidity_w > 0$ then the liquidity flow is positive, and if $liquidity_w < 0$ then the liquidity flow is negative. The trader i additionally buy and sell futures according to the following rules:

$$if \quad liquidity_w > 0: \; s_{i,w}^l = +1, \; v_{i,w}^l = liquidity_w * futures_{i,w-1},$$

$$if \quad liquidity_w = 0: \quad s_{i,w}^l = 0\,, \; v_{i,w}^l = 0$$

$$if \quad liquidity_w < 0: \quad s_{i,w}^l = -1 \; v_{i,w}^l = liquidity_w * futures_{i,w-1} \tag{31}$$

where $v_{i,w}^l$ is the number of futures the trader i wants to buy or sell due the liquidity flow, $s_{i,w}^l$ is the indicator of the trading operation.

2.2.3. Price Clearing Condition

Once all traders have made their decisions on the basis of opinions and liquidity flows, they send their orders without any transaction costs to a market maker, who has an unlimited amount of cash and stocks. The market maker sets the price in week w according to the following market clearing rules:

$$r_w = \frac{1}{\lambda * S} \sum_{i=1}^{S} \left(s_{i,w}^d * v_{i,w}^d + s_{i,w}^l * v_{i,w}^l \right) \tag{32}$$

$$log[p_{m,w}] = log[p_{m,w-1}] + r_w \tag{33}$$

where $r(week)$ is the market return and λ represents the market depth, i.e. the relative impact of the excess demand upon the price.

2.2.4. Cash and Futures Positions

The dynamics of cash and futures positions of trader i is the following:

$$cash_{i,w} = liquidity_w * cash_{i,w-1} - \left(s_{i,w}^d * v_{i,w}^d + s_{i,w}^l * v_{i,w}^l\right) * p_{m,w} \tag{34}$$

$$futures_{i,w} = futures_{i,w-1} + s_{i,w}^d * v_{i,w}^d + s_{i,w}^l * v_{i,w}^l \tag{35}$$

2.3.The Interaction of the Real Sector and the Financial Market

As mentioned earlier, one period in the New Keynesian part of our model corresponds to one quarter, which does not match with the weekly frequency of the agent-based part. In order to combine the two parts of the model into the joint one, we suppose that one quarter always consists of 13 weeks, so one year, which is four quarters, always includes 52 weeks in the model.

The interaction between the New Keynesian part and the agent-based part of the joint model is based on four transmission mechanisms. Firstly, the market price of capital in the financial market determines the market price of capital in the real sector. The deviation of the market price of capital, F_t, from the fundamental price of capital, Q_t, in the New Keynesian part of the model in the current quarter t is set through equation (9) using the market change impulse τ_t^F calculated according to the following equation, which is based on the average market price in financial market for 13 weeks $\frac{\sum_{week=1}^{13} p_{m,w}}{13}$:

$$\tau_t^F = sensitivity_1 * \left(\frac{\frac{\sum_{week=1}^{13} p_{m,w}}{13} - Q_{t-1}}{Q_{t-1}} \right) - (f_{t-1} - q_{t-1}), \tag{36}$$

where $sensitivity_1$ represents the model parameter responsible for the sensitivity of changes in the real sector due to changes on the financial market, while $f_{t-1} = \frac{F_{t-1} - \bar{F}}{\bar{F}}$ and $q_{t-1} = \frac{Q_{t-1} - \bar{Q}}{\bar{Q}}$ are the deviations of the market price of capital and the fundamental price of capital from their steady state values $\bar{F}$ and $\bar{Q}$, respectively. All calculations in the New Keynesian part of the model take place in the end of each quarter, when we know the dynamics of the agent-based model in this quarter.

The second transmission mechanism is the liquidity flows from the real sector to the financial market. In our model, we suppose that liquidity flows are proportional to the change of the net worth of entrepreneurs and set according to the following rule:

$$liquidity_w = sensitivity_2 * (n_{t-1} - n_{t-2})^{\frac{1}{13}}, \tag{37}$$

where $n_{t-1} = \frac{N_t - \bar{N}}{\bar{N}}$ is the deviation of the entrepreneurs' net worth from its steady state value. $sensitivity_2$ is the model parameter that shows how the change in the net worth deviation affects liquidity flows to the financial market. The assumption about the relationship between the net worth and liquidity flows to the financial market in the joint model seems to be reasonable, because the growth of the net worth of firms in the economy in the reality means the increase in the amount of possible collateral for credits, which, subsequently, leads to the growth of liquidity available in the economy as well as to the increase in liquidity flows to financial markets. Moreover, the higher the value of the net worth, the more firms or institutional investors can spend on investments, including investments in different funds, like mutual and hedge funds, that operate on the financial markets.

The third transmission mechanism is the influence of the central bank's information policy on traders' fear of the bursting of the bubble in the future, defined in equation (29). As discussed earlier, in the reality asset price bubbles can be hard for identification, so we suppose in our model that the central bank can start suspecting about the existence of a bubble only when the market price has already deviated significantly from the fundamental price. If the central bank starts suspecting about the existing of the bubble, it can raise the interest rate by Δr^{Bubble}. In order to simulate a noninstantaneous response of the central bank on bubbles, we introduce the reaction parameter of the central bank, $levCB$, into our model, that shows the value of the deviation of the market price from the fundamental one (equation (28)), after which the central bank starts to raise the interest rate in each quarter until the deviation exceeds this level. The central bank uses the following rule in the setting of the additional increase of the interest rate Δr_t^{Bubble} in the Taylor rule:

$$
\begin{aligned}
&If\ Deviation_w \geq levCB: && \Delta r_t^{Bubble} = \Delta r^{Bubble} \\
&\quad Else: && \Delta r_t^{Bubble} = 0
\end{aligned}
\tag{38}
$$

The fourth transmission mechanism is the impact of the fundamental price of capital from the real sector on traders' opinions about the fundamental price, which is set by equation (27).

To sum up, in the joint model the central bank can prick bubbles on the capital market by three possible ways. First of all, the cumulative growth of the interest rate from the Taylor rule (22) increases the probability of the bursting of the bubble, because it slows down the economy, which subsequently leads to the decrease of the fundamental price of capital, affecting the traders' opinions about the true fundamental price in equation (28). The second way is to additionally increase the interest rate in the Taylor rule (22); in this case, the central bank significantly raises the interest rate in the situation when the bubble is already large enough, to suddenly diminish the fundamental price of capital and try to influence traders' opinions about the true fundamental price in equation (28). Finally, the central bank can implement an information policy and affect the traders' fear of the bursting of the bubble in the near future in equation (29).

In order to solve the joint model, we firstly loglinearize the New Keynesian part, which sets the real sector, and obtain transition matrixes following typical steps when solving DSGE models. The loglinearized version of the New Keynesian part is presented in Appendix A. Then, we simulate the dynamics of the agent-based model during 13 weeks in the current quarter to calculate the market price change impulse τ_t^F from the real sector. At the end of the current quarter, using the transition matrixes, we compute the values of the variables from the New Keynesian part. Then we simulate once again the agent-based model during 13 weeks in the next quarter and so on.

3. Calibration

Our goal in the calibration of the model is to reproduce the dynamics of the economy in deviations from the steady state for the period of 20 years, mainly focusing on the realistic dynamics of the financial market with possible bubbles and crashes. As a benchmark for the financial market we use the S&P 500 stock market index. A summary of the parameter values used can be found in Appendix B.

We calibrate the agent-based model in order to reproduce main stylized facts - faithful statistical characteristics of realistic price dynamics of the S&P 500 index for the period of 1996-2016 years for the weekly data that is presented on Figure 1a. Over the sample period on the US stock market there were two large crashes on the stock market: the Dot-com bubble and the Financial Crisis of 2007-2009 years. Thus, for each realization of random shocks our model should generate approximately from 1 to 4 crises, whereas a greater number of crisis seems unrealistic, because over the sample period the historical life cycle of a bubble on the US stock market is approximately equal to 5-6 years. For example, the growth and the burst of the Dot-com bubble took 6 years as well as in the case of the bubble that preceded the Asian financial crisis of 1997 year.

The statistical characteristics of the market price of capital set by the agent-based model should comply with the following stylized facts:

- Weekly returns have small autocorrelation. Figure 1c shows that autocorrelation in weekly returns over the period 1996-2016 is insignificant for any lag.
- The distribution of weekly returns does not follow the normal distribution. Figure 1b illustrates that the real distribution has fatter tails, is more peaked around zero and also negatively skewed. Moreover, it is not possible to reject the hypothesis about a zero mean return.
- The dynamics of market price can be divided on several volatility clusters; in some periods volatility will be high, while in others it will be low. A positive aurocorrelation in squared returns on Figure 1d represents this phenomenon.
- In the periods of high volatility the market price is more likely to fall, while in the periods of low volatility, it is more likely to grow. Thus, there is a negative correlation between volatility and stock returns.

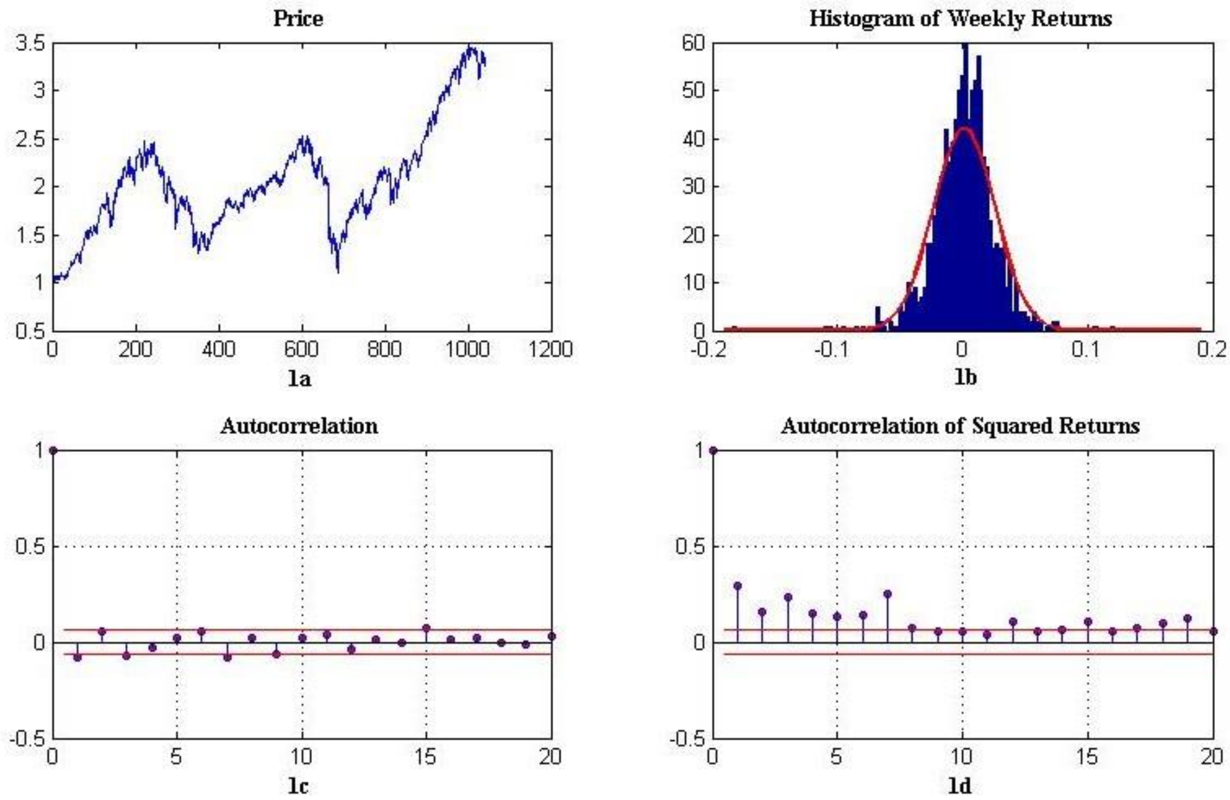

Fig. 1. Statistical Characteristics of the S&P 500 index.

The figure presents the following data for the period of 1996-2016: the weekly adjusted price of the S&P 500 index (Figure 1a), the histogram of weekly S&P 500 returns (Figure 1b) , the autocorrelation of weekly S&P 500 returns (Figure 1c), and the autocorrelation of squared weekly S&P 500 returns (Figure 1d). The red line on Figure 1b shows the probability density function of a normal distribution with the mean and standard deviation of weekly S&P 500 returns over the sample period.

Our agent-based part of the joint model has many possible combinations of parameters that correspond to mentioned stylized facts (as usual for agent-based models). For this reason, in the description of the parameters calibration we focus primarily on the expalanation of the parameters' effects on the statistical characteristics of the market price.

The number of traders in the model is set at a relatively large value $S = 10000$. Values for the amount of cash and futures in the initial week, $\overline{cash} = 1$ and $\overline{futures} = 1$, are taken from Harras and Sornette (2011), as well as the share of traders' cash or stocks they trade each time, $share = 0.02$. In the reality, the world economy has positive average long-term growth rates over the last several decades after the World War II, so we suppose that the fixed long-run component in the market information, $\overline{LRtrend}$, is positive and equal to 0.6. To create a growing dynamics of the financial market with $\overline{LRtrend} = 0.6$, we find that the parameter of a variable medium-run component in the market information, $trendpar$, the distribution parameter of fundamental information, C_1, and the distribution parameter of market information, C_2, should have approximately the following values: $trendpar = 1.2$, $C_1 = 1$, $C_2 = 20$. At the same time, to allow the bursting of bubbles, the parameters of traders' fear $f1$ and $f2$, the memory parameter $memory$, and the standard deviation of the fundamental information shock σ^{fundam} may have the following values: $f1 = 3$, $f2 = 750$, $memory = 12$, and $\sigma^{fundam} = 2$. The parameters of the differences in risk aversion, $\underline{\Omega}$, and the market depth, λ, specify the form and the scale of the distribution of returns , respectivly. To match the form and the scale of the distribution of returns from the agent-based part model with the same distribution from Figure 1b, we calibrate these parameters as $\underline{\Omega} = 40$ and $\lambda = 0.05$. The distribution parameter of private information, C_3, allows us to simultaneously adjust the autocorrelation of returns and the autocorrelation of squared returns. We find that with $C_3 = 15$ the market price in the agent-based model has realistic levels of the autocorrelation of returns and the autocorrelation of squared returns that are similar to the levels on Figures 1c and 1d. A smaller value of C_3 leads to a higher value of autocorrelations and vice versa.

For the sensitivity parameters, $sensitivity_1$ and $sensitivity_2$, we take the values leading to realistic fluctuations of output over the 20 years, i.e. $sensitivity_1 = 0.06$ and $sensitivity_2 = 0.075$.

In the New Keynesian part of the model, for almost all of the parameters, except the two, we use the values frequently used in the literature. These values can be found in Table B1 in Appendix B. The value of the additional increase in the interest rate for pricking asset price bubbles, Δr^{Bubble} , is set to $\Delta r^{Bubble} = 0.25\%$, because it is the minimum value that is typically used by the Federal Reserve System. For the parameter of the financial accelerator mechanism we take the value $\psi = 0.02$, this value decreases the financial accelerator effect, but it completely keeps the causal relationships in the model.

4. The Dynamics of the Model

In this section we analyze the dynamics of the model over the period of 1040 weeks. We suppose that each quarter consists of 13 weeks, so the analyzed period is equal to 20 years or 80 quarters. In Section 4.1 we firstly show the dynamics of the New Keynesian part of the joint model in response to an exogenous bubble as in Bernanke and Gertler (2000). Then in Section 4.2 we consider the dynamics of the agent-based financial market in the case, when it operates without any connections with the New Keynesian part of the model. Finally, in Section 4.3 we analyze the dynamics of the joint model.

It is worth noting, that we present the dynamics of the agent-based model in Section 4.2 and the dynamics of the joint model in Section 4.3 for some realization of random shocks. For other realizations the dynamics will be different, but will also generate bubbles and correspond to stylized facts that are set by calibration.

4.1. The Dynamics of the New Keynesian Part in the Case of an Exogenous Bubble.

As in Bernanke and Gertler (2000) we consider an exogenous bubble – a 1% market price change shock, which grows twice in each quarter and bursts, when the market price is 16% percent higher than the fundamental price. The impulse responses to the bubble are presented in Figure 2. The creation of the bubble leads to the rapid growth in the market price of capital, which causes the increase in the net worth of entrepreneurs and the acceleration of inflation. The increase in the net worth means that entrepreneurs start borrowing more funds from households, purchase more capital, hire more household labor and produce more output, but the acceleration of inflation and the growth of output force the central bank to raise the interest rate. For the values of the parameters, used in our paper, the negative effect from the increase of the interest rate on capital and investment during the creation phase of the bubble is approximately the same as the positive effect from the increase in the net worth. The growth of output leads to the growth of consumption before the bursting of the bubble. After the bursting of the bubble almost all key variables in the economy, including consumption, sharply fall, so the welfare of households also decreases.

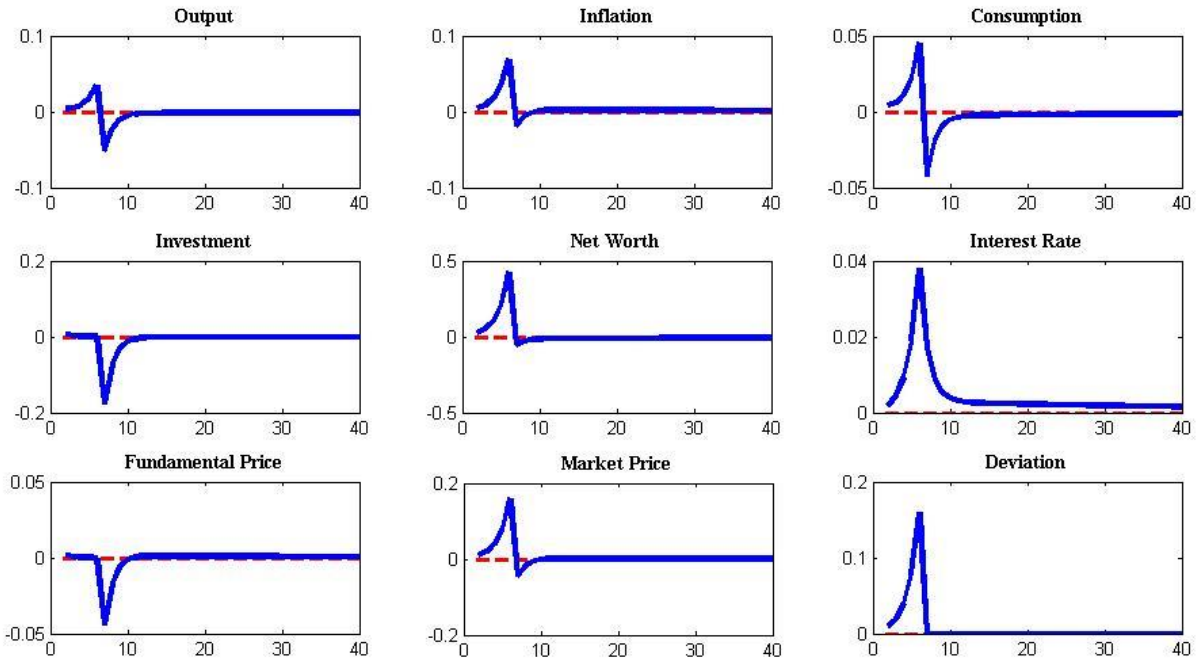

Fig. 2. Impulse Responses of the New Keynesian Part of the Joint Model to an Exogenous Bubble.

4.2. The Dynamics of the Agent-Based Financial Market.

As already mentioned, the dynamics of the market price in the agent-based part of the model depends on the realization of random shocks, and there exists an infinite number of possible realizations. A typical realization of the agent-based financial market is presented at Figure 3. The dynamics of the market price, the distribution of market returns, and the autocorrelation of market returns and squared market returns are quite similar to the real data in Figure 1. Over 1040 weeks on the agent-based financial market, there were two large crashes of the financial market and one smaller correction. The first two episodes are very similar to bubbles, where the creation of a bubble takes approximately four years. As in real data weekly market returns on the agent-based financial market have small autocorrelation, but there is a significant autocorrelation in squared market returns. The distribution of weekly market returns on the agent-based financial market also has fat tails, is more peaked around zero than normal distribution and negatively skewed. We also present in Figure 3 the dynamics of the variable $Fear_w$ that shows traders' fear in week w of the bursting of the bubble. We can see that a rapid growth of $Fear_w$ precedes a sharp fall in the market price.

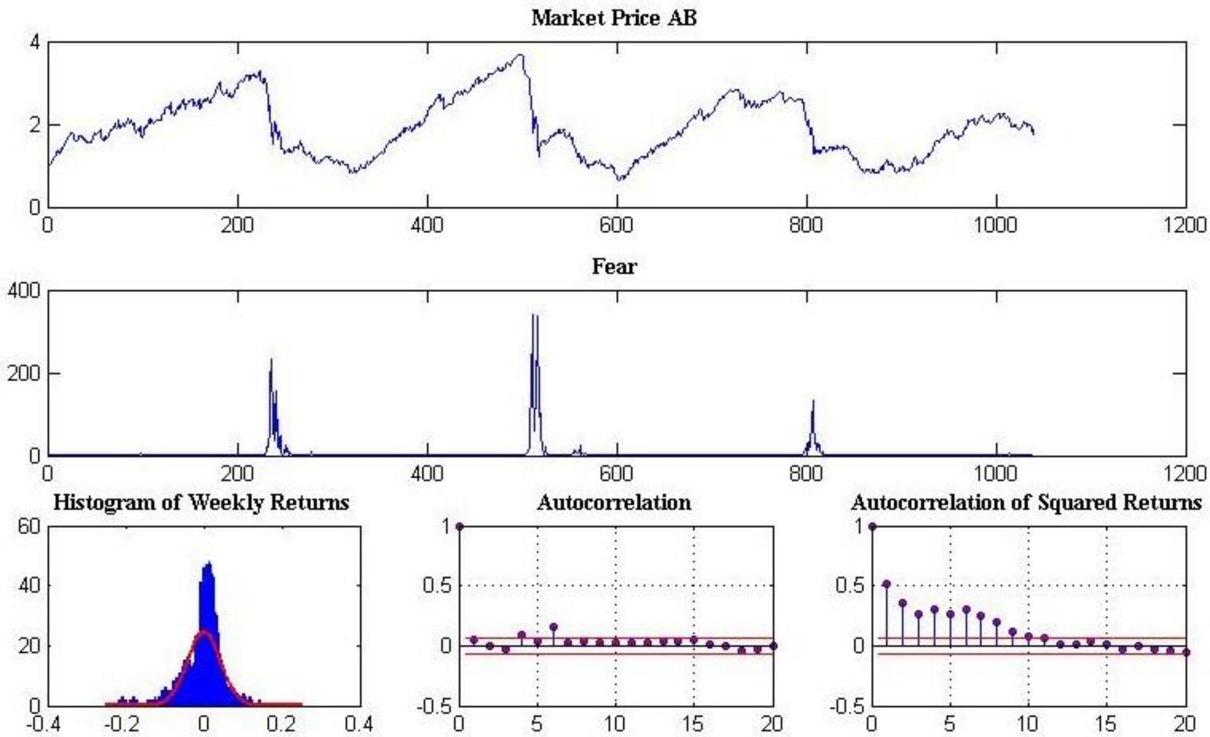

Fig. 3. The Dynamics of the Agent-Based Financial Market.

4.3. The Dynamics of the Joint Model.

Figure 4 presents the dynamics of the New Keynesian and agent-based parts of the joint model in the case, when both parts operate simultaneously with endogenous relationships between two parts. The red and blue lines on both of the graphs show the dynamics of the joint model with and without liquidity flows from the real sector to the financial market, respectively. From the graphs we can see that the growth of the market price in the agent-based part leads to the increase in output, consumption, the net worth of entrepreneurs, and the utility of households. In addition to the growth of output, inflation acceleration causes the interest rate to rise. We also observe the liquidity flow from the real sector to the financial market due to the increase in the net worth of entrepreneurs . In the case of the sharp fall in the market price, which is similar to the bursting of the bubble or to the market crash, the dynamics becomes the opposite. Moreover, the bursting of the bubble causes a larger change in absolute value of output, consumption, and the utility of households than during the time, when the market price increases. Usually the market crash in the model occurs quickly, whereas the recovery of output requires a longer time; such dynamics is very similar to the reality. From Figure 4 we can see that the inclusion of liquidity flows increases the amplitude of variables in the joint model.

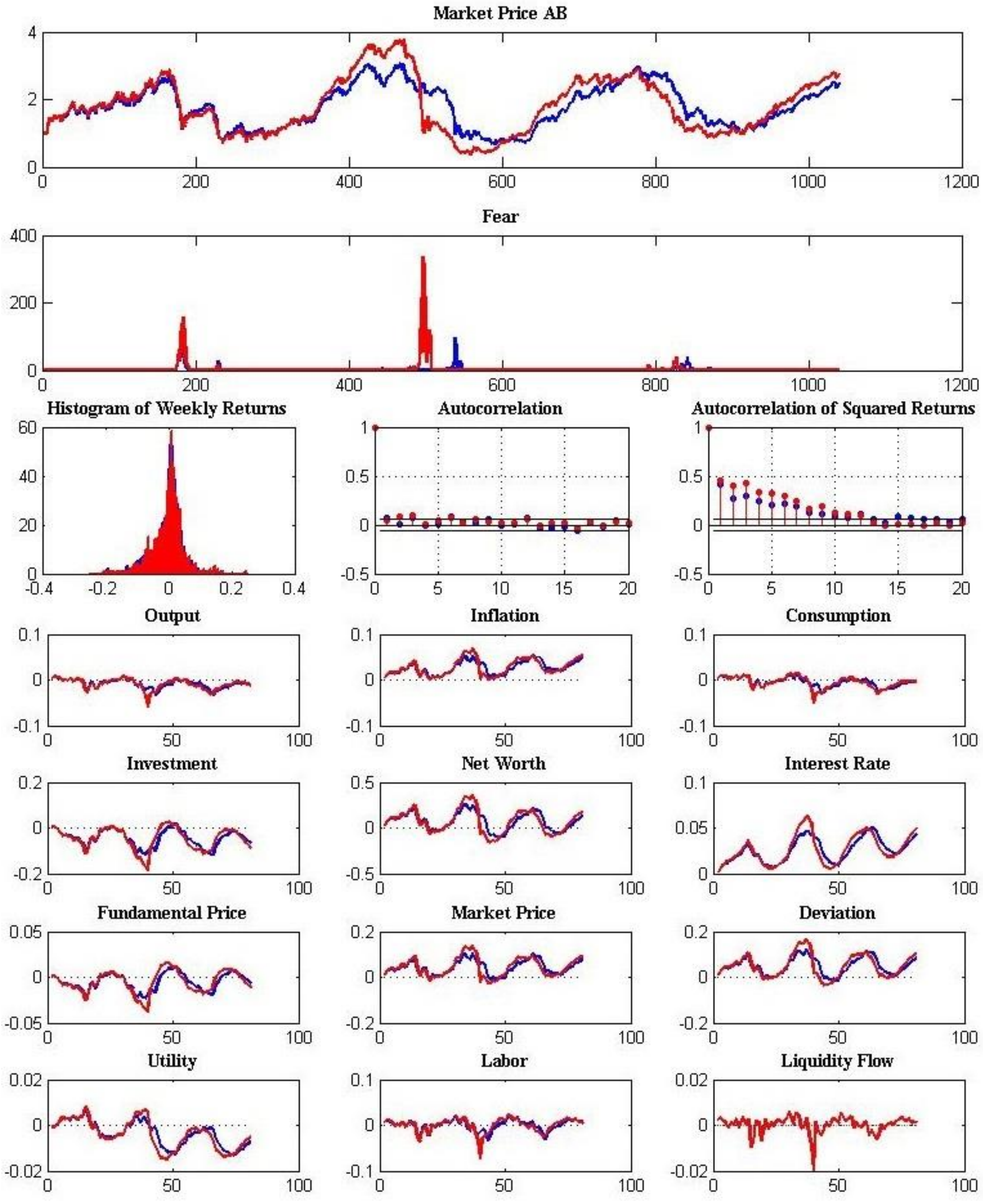

Fig. 4. The Dynamics of the Joint Model.

4.4.The Robustness of the Dynamics

In order to check the robustness of the model's dynamics, we simulate the joint model changing values of each parameter from the agent-based part that can affect statistical characteristics of the market price of capital, by 10%. The statistical characteristics of the market price of capital remain approximately the same for each 10% change of a parameter, when other parameters are fixed.

5. Should monetary policy prick the bubble?

In the analysis of the response of monetary policy on market bubbles we calculate the welfare of households and the volatility of output and inflation in both cases: when monetary policy follows the Taylor rule from equation (21) without the additional response to asset price bubbles, and when it suddenly raises the interest rate by Δr_t^{Bubble}.

We use several possible levels for the reaction parameter of the central bank: $levCB \in [1; 1.2; 1.4; 1.6; 1.8; 2]$; for the larger values of $levCB$ the central bank does not operate in some realizations. In such cases the larger values of $levCB$ are equivalent to the case, when the central bank does not prick asset price bubbles. This case is also analyzed further.

Another important parameter in our model for the analysis of pricking asset price bubbles is the parameter of the efficiency of the central bank's information policy, $IPparam \geq 0$. From the calibration, we find that this parameter should be $IPparam \leq 1000$. For the values larger than 1000 the model may generate unrealistic values of $Fear_w$. In order to understand the influence of $IPparam$ on the results of pricking asset price bubbles we consider several different possible values for $IPparam \in [0; 200; 400;\ 600; 800; 1000]$.

Figure 5 shows the possible effect from pricking asset price bubbles for $levCB = 1$ and $IPparam = 500$. The red and blue lines show the dynamics of different variables in the joint model with and without pricking asset price bubbles, respectively. From Figure 5 we can see that the dynamics of the market price in the case, when the central bank pricks asset price bubbles substantially differs from the case, when the central bank does not prick bubbles. The highest values of the market price are lower in the case of pricking bubbles, so the deviations of the market price from the fundamental price are smaller in this case. This creates the difference in the dynamics of the variables in the real sector, and the sizes of the fall in output, consumption, and households' utility are also smaller in the times of the market crash.

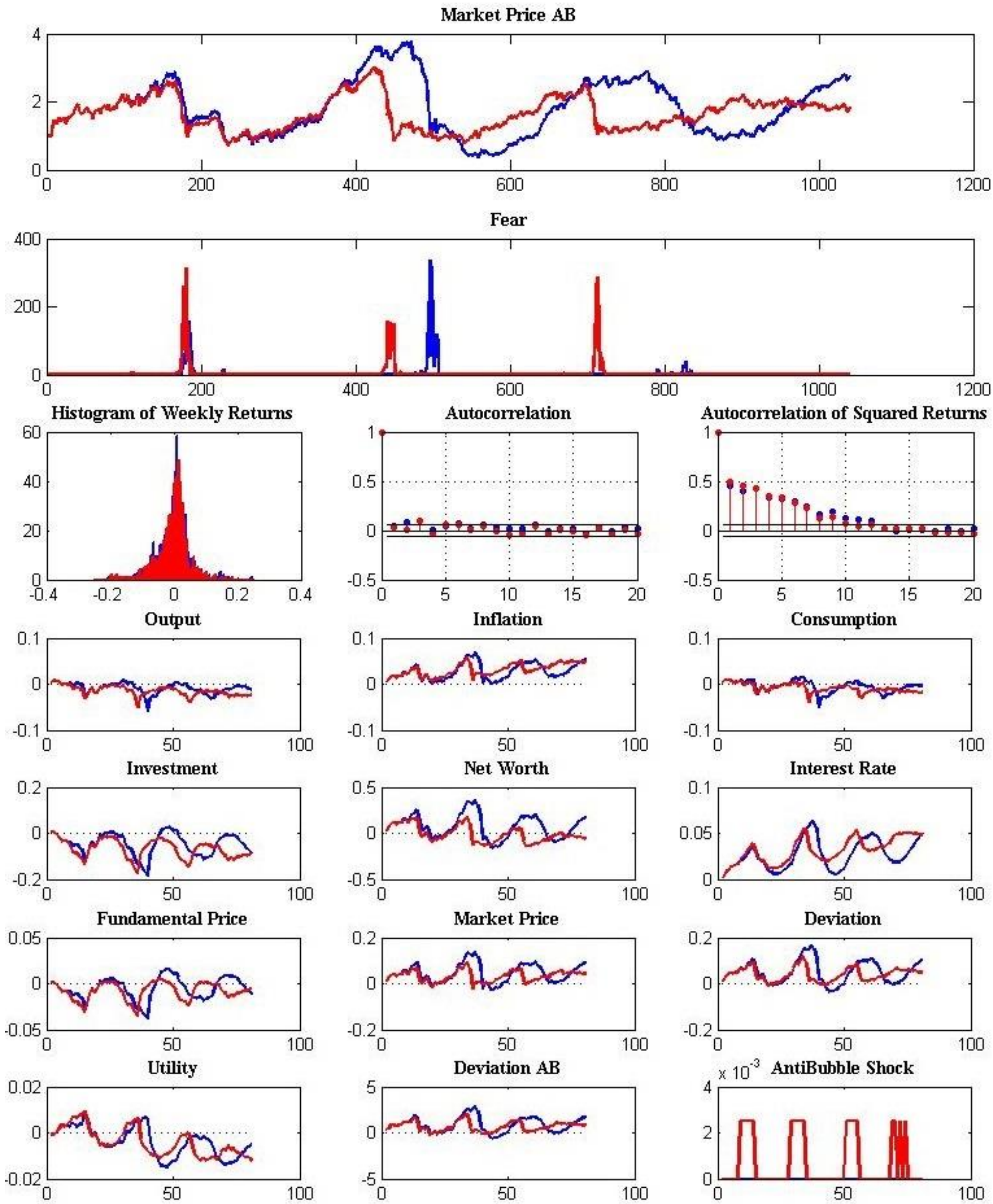

Fig. 5. The Dynamics of the Joint Model in the Case of Pricking Asset Price Bubbles.

The blue lines show the dynamics of variables in the case without pricking asset bubbles, while the red lines show the same information in the case, when the central bank pricks asset price bubbles with the values of the reaction parameter of the central bank $levCB = 1$ and the parameter of the efficiency of the central bank's information policy $IPparam = 500$.

For each combination of the parameters $levCB$ and $IPparam$ we calculate welfare losses from bubbles on the futures market during the considered period as the discounted differences between the utility of households in each period and the utility of households in the steady state divided by the consumption of households in the steady state:

$$W = \sum_{t=0}^{T} \beta^t \left(\frac{U_t - \bar{U}}{\bar{C}}\right), \tag{39}$$

where $\mathrm{U_t}$ is the utility of households at time t, $\bar{U}$ denotes the value of the steady state utility of households. Schmitt-Grohe and Uribe (2004) show that for the welfare analysis, it is necessary to use the second-order approximation of the welfare function:

$$U_t = \bar{U} + \frac{1}{\bar{C}}(C_t - \bar{C}) - \bar{L}^{\sigma_l}(L_t - \bar{L}) - \frac{1}{\bar{C}^2}\frac{(C_t - \bar{C})^2}{2} - \sigma_l \bar{L}^{\sigma_l - 1}\frac{(L_t - \bar{L})^2}{2}$$

$$= \bar{U} + c_t - \bar{L}^{\sigma_l + 1} l_t - \frac{{c_t}^2}{2} - \sigma_l \bar{L}^{\sigma_l + 1}\frac{{l_t}^2}{2}, \tag{40}$$

where $c_t = \frac{C_t - \bar{C}}{\bar{C}}$ and $l_t = \frac{L_t - \bar{L}}{\bar{L}}$ are the deviations of consumption and labor from the steady state values $\bar{C}$ and $\bar{L}$ at time t correspondingly. Using (39) and (40), we get:

$$W = \sum_{t=0}^{T} \beta^t \left(\frac{1}{\bar{C}} c_t - \frac{\bar{L}^{\sigma_l + 1}}{\bar{C}} l_t - \frac{1}{2\bar{C}} {c_t}^2 - \frac{\sigma_l \bar{L}^{\sigma_l + 1}}{2\bar{C}} {l_t}^2\right) \tag{41}$$

As already mentioned, the dynamics of the model depends on the realization of random shocks for the considered period of 1040 weeks, and it is different for different realizations of random shocks, although each realization corresponds to stylized facts that have been discussed in Section 3. In order to compare the values of welfare losses, the volatility of output, and the volatility of inflation for the different values of the parameters $levCB$ and $IPparam$, we calculate the average differences of welfare losses, $\Delta W_{average}^{loss}$, the volatility of output, $\Delta Var_{average}(y)$, and the volatility of inflation, $\Delta Var_{average}(\pi)$, between the case when the central bank does not prick bubbles and other cases for 200 realizations. For example, for $levCB = 1$ these values are calculated as:

$$\Delta W_{average,levCB=1} = \frac{\sum_{j=1}^{100} \Delta W_{j,levCB=1}}{100} = \frac{\sum_{j=1}^{100}(W_{j,levCB=1} - W_{j,wp})}{100} \tag{42}$$

$$\Delta Var_{average,levCB=1}(y) = \frac{\sum_{j=1}^{100} \Delta Var_{j,levCB=1}(y)}{100} = \frac{\sum_{j=1}^{100} \frac{Var_{j,levCB=1}(y) - Var_{j,wp}(y)}{Var_{j,wp}(y)}}{100} \tag{43}$$

$$\Delta Var_{average,levCB=1}(\pi) = \frac{\sum_{j=1}^{100} \Delta Var_{j,levCB=1}(\pi)}{100} = \frac{\sum_{j=1}^{100} \frac{Var_{j,levCB=1}(\pi) - Var_{j,wp}(\pi)}{Var_{j,wp}(\pi)}}{100}, \quad (44)$$

where j is the number of realization, $Var_{j,levCB=1}(y)$ and $Var_{j,levCB=1}(\pi)$ are the values of the volatilities of output and inflation, respectively, in the realization j when $levCB = 1$, while the values for the case without pricking bubbles are denotes by the subscript "wp".

Table 1 reports the results for different combinations of the parameters $levCB$ and $IPparam$ for the joint model without liquidity flows from the real sector to the financial market (in this configuration of the joint model $sensitivity_2 = 0$), while Table 2 reports the same information for the joint model with liquidity flows (in this configuration of the joint model $sensitivity_2 = 0.075$).

From Table 1 we can see that pricking bubbles in the joint model without liquidity flows and effective information policy is completely useless for the central bank. This usually leads to the additional social welfare losses and the growth of the output and inflation volatilities. In this case the central bank only raises the interest rate on Δr^{Bubble} beyond the Taylor rule in each quarter until the bubble bursts, without affecting traders' opinions. The gains from pricking bubbles are reflected in the potential decrease in the size of output drop after financial market crashes, however, in such case, these gains are lower than the losses from raising the interest rate, which, consequently, slows down the economy. Moreover, in some cases the increase of the interest rate may not be enough to achieve pricking bubbles without reasonable increase in the interest rate, in other words, the interest rate can rise, but the bubble can continue to exist. These effects are widely discussed in the literature as a part of the "clean" versus "lean" debate.[4]

[4] See, for example, Mishkin (2011) or Brunnermeier and Schnabel (2015) for the literature review on the "clean" versus "lean" debate.

Tab. 1. The Main Results for the Case Without Liquidity Flows from the Real Sector to the Financial Market.

$sensitivity_2 = 0$						
	$\Delta W_{average}$,%					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	-6.09***	-5.07***	-4.10***	-3.10***	-2.22***	-1.62***
$IPparam$	-3.68***	-2.79***	-2.08***	-1.46***	-1.07***	-0.69***
$IPparam$	-1.96***	-1.15***	-0.62***	-0.27***	-0.11	0.06
$IPparam$	-0.73***	-0.01	0.42***	0.62***	0.61***	0.66***
$IPparam$	0.27	0.86***	1.14***	1.30***	1.11***	1.15***
$IPparam$	1.21***	1.63***	1.78***	1.76***	1.61***	1.59***
	$\Delta Var_{average}(y)$, %					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	96.67***	74.68***	53.01***	35.86***	23.05***	15.24***
$IPparam$	64.99***	45.87***	28.93***	18.50***	11.13***	6.89***
$IPparam$	42.44***	25.17***	13.51***	6.66***	2.89***	1.68***
$IPparam$	24.11***	10.30***	1.83	-1.65	-2.99***	-2.27***
$IPparam$	9.27***	-1.33	-6.29***	-7.69***	-6.94***	-4.76***
$IPparam$	-2.47	-9.99***	-12.82***	-12.44***	-9.36***	-6.33***
	$\Delta Var_{average}(\pi)$, %					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	80.24***	53.91***	31.55***	16.64***	8.03***	3.44***
$IPparam$	46.16***	24.47***	8.68***	0.72	-1.96***	-2.88***
$IPparam$	23.36***	4.80***	-5.69***	-9.91***	-9.51***	-7.41***
$IPparam$	5.39***	-9.12***	-15.83***	-17.24***	-13.64***	-10.45***
$IPparam$	-8.41***	-19.57***	-23.25***	-20.96***	-16.68***	-12.46***
$IPparam$	-18.67***	-27.21***	-28.91***	-25.30***	-18.97***	-13.94***

*Notes:****,**, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Growth in the effectiveness of information policy causes welfare losses to decrease for all levels of $levCB$. When $IPparam = 1000$ pricking bubbles have the highest social welfare gains for all values of $levCB$ with the maximum at 1.78% of the steady state consumption level in the case when $levCB = 1.4$. Similar dynamics are observed for the decrease in the volatility of output and inflation; the maximum reductions also occur in the case $levCB = 1.4$ and have the following values: -12.82% for the volatility of output and -28.91% for the volatility of inflation.

Tab. 2. The Main Results for the Case With Liquidity Flows from the Real Sector to the Financial Market.

$sensitivity_2 = 0.075$						
	$\Delta W_{average}$,%					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	-5.51***	-4.80***	-4.18***	-3.53***	-2.98***	-2.42***
$IPparam = 200$	-2.48***	-1.84***	-1.22***	-0.80***	-0.51***	-0.36**
$IPparam = 400$	-0.31	0.43***	0.90***	1.27***	1.39***	1.31***
$IPparam = 600$	1.14***	1.79***	2.22***	2.43***	2.49***	2.34***
$IPparam = 800$	2.30***	2.83***	3.13***	3.26***	3.42***	3.08***
$IPparam = 1000$	3.23***	3.63***	3.74***	4.04***	3.89***	3.74***
	$\Delta Var_{average}(y)$, %					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	33.74***	27.31***	22.58***	18.77***	15.05***	12.15***
$IPparam = 200$	10.40***	5.53***	1.29	-0.56	-1.73	-1.16
$IPparam = 400$	-6.39***	-10.53***	-12.23***	-12.90***	-12.44***	-11.71***
$IPparam = 600$	-19.48***	-23.09***	-22.95***	-22.23***	-19.42***	-17.75***
$IPparam = 800$	-29.84***	-32.01***	-30.60***	-28.45***	-25.87***	-21.74***
$IPparam = 1000$	-37.08***	-38.93***	-37.37***	-33.89***	-30.39***	-25.47***
	$\Delta Var_{average}(\pi)$, %					
$levCB$	1	1.2	1.4	1.6	1.8	2
$IPparam = 0$	13.54***	5.79***	0.98	-2.17***	-4.05***	-4.88***
$IPparam = 200$	-10.32***	-15.86***	-19.27***	-19.73***	-19.03***	-17.00***
$IPparam = 400$	-25.92***	-30.73***	-31.94***	-30.16***	-27.98***	-25.08***
$IPparam = 600$	-37.08***	-41.09***	-40.65***	-37.99***	-34.12***	-30.10***
$IPparam = 800$	-45.08***	-47.92***	-47.01***	-43.42***	-38.83***	-33.69***
$IPparam = 1000$	-51.55***	-54.04***	-52.39***	-47.71***	-42.45***	-36.79***

*Notes:****,**, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

According to Table 2, when the joint model includes endogenous liquidity flows the main results are very similar. In comparison to Table 1, the maximum value of social welfare gains of 4.04% of the steady state consumption with $IPparam = 1000$ are achieved when $levCB =$

1.6, but the maximum value of the decrease in the volatilities of output and inflation are obtained when $levCB = 1.2$.

It is worth noting, that the maximum social welfare gains from pricking bubbles in the case of endogenous liquidity flows is approximately 2.3 times larger than in the case without endogenous liquidity flow, but the maximum decrease in the volatility of output and inflation are approximately 3 and 1.9 times larger, respectively. This effect is caused by the fact that the volatility of output and inflation are higher in the case of endogenous liquidity flows.

6. Conclusion

In the paper, we develop the approach based on the synthesis of New Keynesian macroeconomics and agent-based models, which allows for the incorporation of behavioral and speculative factors in macroeconomic models. For this purpose, we construct a joint model that consists of a New Keynesian model with a financial accelerator, `a la Bernanke et al. (1999), which sets the real sector, and the agent-based model of the financial market, on which traders determine the market price of assets by selling and buying assets from each other. The model allows for the existence of bubbles on the financial market, and considers the cases when the central bank may try to prick asset price bubbles by raising the interest rate above the reaction from the Taylor rule, or by conducting its information policy, for example, by verbal interventions.

Using the model, we study the central bank's optimal strategy in pricking asset price bubbles. The results show that in some cases, the central bank pricking asset price bubbles can reduce the social welfare losses from asset price bubbles, as well as the volatility of output and the volatility of inflation. This effect is larger, especially in the cases when asset price bubbles are caused by credit expansion, or when the central bank conducts an effective information policy. Our results also demonstrate that pricking asset price bubbles only by raising the interest rate with the lack of the effectiveness of information policy leads to negative consequences for social welfare and financial stability.

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Appendix A. The Log-linearized New Keynesian Part of the Model

$$\lambda_t = -c_t \tag{A1}$$

$$\lambda_t + \pi_{t+1} = \lambda_{t+1} + r_t \quad \text{(A2}$$

$$y_t = a + \alpha * k_{t-1} + (1-\alpha) * \Omega * l_t \tag{A3}$$

$$w_t = y_t + mc_t - l_t \tag{A4}$$

$$r_t^k = y_t + mc_t - k_{t-1} \tag{A5}$$

$$q_{t+1} = \chi(i_t - k_{t-1}) \tag{A6}$$

$$\beta\pi_{t+1} = \pi_t - \frac{(1-\beta\theta_p)(1-\theta_p)}{\theta_p} mc_t \tag{A7}$$

$$c_t^e = f_t + k_t \tag{A8}$$

$$\frac{n_t}{\upsilon * \overline{R^q}} = \frac{\bar{K}}{\bar{N}} * r_t^q - \left(\frac{\bar{K}}{\bar{N}} - 1\right)(r_t - \pi_t) - \psi\left(\frac{\bar{K}}{\bar{N}} - 1\right)(k_{t-1} + q_{t-1} + u_{t-1}) + \left(\psi\left(\frac{\bar{K}}{\bar{N}} - 1\right) + 1\right) n_{t-1} \tag{A9}$$

$$b_t = \frac{\bar{K}}{\bar{B}}(q_t + k_t) - \frac{\bar{N}}{\bar{B}} n_t \tag{A10}$$

$$y_t = c_t^e \frac{\overline{C_e}}{\bar{Y}} + c_t \frac{\bar{C}}{\bar{Y}} + i_t \frac{\bar{I}}{\bar{Y}} + g_t \frac{\bar{G}}{\bar{Y}} \tag{A11}$$

$$r_t^q = r_t + \psi * (q_t + u_t + k_t - n_t) - \pi_{t+1} \tag{A12}$$

$$r_t = \rho_r r_{t-1} + (1-\rho_r)\left(\rho_\pi \pi_t + \rho_y y_t\right) + \Delta r_t^{Bubble} \tag{A13}$$

$$f_t - q_t = f_{t-1} - q_{t-1} + \varepsilon_t^F \tag{A14}$$

Appendix B. Model Parameters

Tab. B1. Calibrated Model Parameters

The New Keynesian part of the model		The agent-based part of the model	
Parameters	Values	Parameters	Values
β	0.99	S	10000
σ_l	1	$\overline{cash}$	1
α	0.35	$\overline{futures}$	1
Ω	0.99	$\underline{\Omega}$	40
A	1	C_1	1
υ	0.9728	C_2	20
lev	2	C_3	15
δ	0.025	$trend$	0.6
χ	0.25	$trendpar$	1.2
θ_p	0.75	σ^{fundam}	2
ϵ_y	6	$f1$	3
$\overline{R^F} - \bar{R}$	0.02	$f2$	750
ρ_r	0.7	$memory$	12
ρ_π	1.1	$share$	0.02
ρ_y	0.2	λ	0.05
Δr^{Bubble}	0.0025	$sensitivity_1$	0.06
ψ	0.02	$sensitivity_2$	0.075

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