Housing markets, expectation formation and interest rates
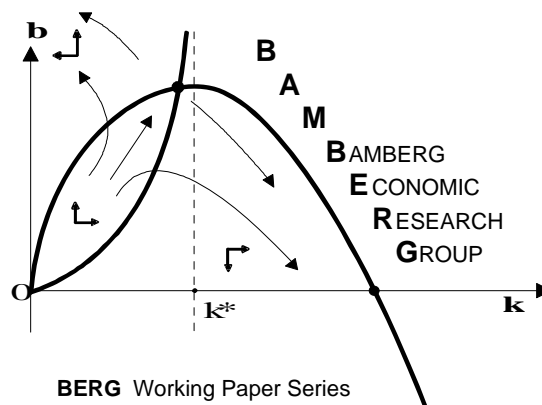
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Housing markets, expectation formation and interest rates[☆]

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Abstract

Based on a behavioral stock-flow housing market model in which the expectation formation behavior of boundedly rational and heterogeneous investors may generate endogenous boom-bust cycles, we explore whether central banks can stabilize housing markets via the interest rate. Using a mix of analytical and numerical tools, we find that the ability of central banks to tame housing markets by increasing the base (target) interest rate, thereby softening the demand pressure on house prices, is rather limited. However, central banks can greatly improve the stability of housing markets by following an interest rate rule that adjusts the interest rate with respect to mispricing in the housing market.

Keywords: Housing markets, heterogeneous expectations, variance beliefs, endogenous boom-bust cycles, interest rates, nonlinear dynamics

JEL classification: D91, E58, R31

1. Introduction

The past has repeatedly demonstrated that the instability of housing markets may pose serious threats for the real economy. As discussed in Taylor (2009), Glaeser et al. (2013), Shiller (2015) and Piazzesi and Schneider (2016), the enormous boom-bust cycle of the U.S. housing market, which peaked in 2006, initiated one of the most harmful global recessions in history. As a matter of fact, the U.S. housing market boom was caused at

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least in part by the low interest rate policy adopted by the Federal Reserve System (Fed) in its efforts to combat financial and economic distress in the aftermath of the dot-com bubble. While Himmelberg et al. (2005) conclude that the major decline in interest rates during the early 2000s merely resulted in a (massive) fundamental house price increase, Taylor (2009) critically argues that the Fed's aggressive interest rate adjustments were responsible for the appearance of the U.S. housing market's boom-bust cycle and the consequent financial market turmoil. The intensity of the academic controversy in this line of research over the last couple of years should not be underestimated. Immediately before the crash of the U.S. housing market, Yellen (2005) stated that monetary policy is not the best tool for deflating housing market bubbles, and ventured that economies will be little affected by shrinking housing markets. Ten years later, Glaeser and Nathanson (2015) warn that policymakers should never again be so confident that a housing market crash would not have serious economic consequences. Against this backdrop, the goal of our paper is to explore how the interest rate setting of central banks may affect the stability of housing markets. In particular, we study the conditions under which central banks may prevent – or at least tame – boom-bust cycles in the housing market, and which policies may trigger the opposite effect.

As a workhorse, we use the behavioral stock-flow housing market model by Dieci and Westerhoff (2016). Their model reveals that nonlinear interactions between speculative and real forces can generate significant endogenous fluctuations in the housing market. The speculative forces in this model result from the expectation formation behavior of boundedly rational and heterogeneous investors. Inspired by Day and Huang (1990), de Grauwe et al. (1993) and Brock and Hommes (1998), investors switch between extrapolative and regressive expectation rules to forecast future house prices with respect to current market circumstances.[1] The real forces in this model are due to a standard housing market model (Poterba 1984, 1991, Wheaton 1999) with a rental market and a housing capital market, tying key relations between house prices, the rent level and the housing stock. Based on an empirically motivated parameter setting, the model is able

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[1] Deviations from a fully rational behavior are strongly supported by empirical and experimental evidence (Case and Shiller 2003, Case et al. 2012, Hommes 2011). Moreover, Glaeser (2013) and Hommes (2013) point out that simple and plausible rule-governed behavior seems to describe reality better than fully rational behavior.

to generate cyclical housing market dynamics with lasting periods of overvaluation and overbuilding, as observed in real markets.

We generalize the model by Dieci and Westerhoff (2016) along two important dimensions. First, we introduce a central bank that follows a simple leaning-against-the-wind interest rate rule (Taylor 2009, Lambertini et al. 2013), consisting of two components. Not only may the central bank autonomously adjust the base (target) interest rate, it may also decide to automatically change the interest rate with a view to mispricing in the housing market. In the latter case, the central bank increases (decreases) the interest rate if the housing market is overvalued (undervalued) in order to deflate (fuel) the housing market. Second, we endogenize investors' variance beliefs. In the model by Dieci and Westerhoff (2016), investors have constant variance beliefs. Since the central bank's interest rate setting shapes the dynamics of the housing market, we let investors learn (update) their variance beliefs (Gaunersdorfer 2000, Chiarella et al. 2007). While this model feature has interesting implications per se for the model dynamics, since it may amplify housing market crashes, for instance, it also influences the effectiveness of the central bank's interest rate policy.

Our main results may be summarized as follows. The dynamics of our model is driven by a four-dimensional nonlinear map. The model possesses a fundamental steady state in which the price of houses reflects their future risk-adjusted rent payments. However, the fundamental steady state may become unstable due to a Neimark-Sacker bifurcation, i.e. endogenous house price fluctuations arise if investors extrapolate house prices too strongly. Note that such fluctuations are characterized by short-run momentum, long-run mean reversion and excess volatility, important empirical features of actual housing market dynamics (Glaeser 2013). Moreover, the fundamental steady state may also become unstable due to a Pitchfork bifurcation. In such a scenario, two locally stable nonfundamental steady states – surrounding the unstable fundamental steady state – emerge, implying that the housing market is either permanently overvalued or undervalued. The Pitchfork scenario occurs if the housing supply is rather sluggish and if investors use the extrapolative expectation rule too strongly. Finally, there is also the (theoretical) possibility that a Flip bifurcation compromises the stability of the housing market. Interestingly, a certain extrapolative strength of investors is then needed to

ensure stability of the fundamental steady state. From an empirical perspective, the Neimark-Sacker bifurcation scenario seems to be the most realistic one. For instance, the calibrated housing market models by Wheaton (1999), Dieci and Westerhoff (2016) and Glaeser and Nathanson (2017) as well as the estimated housing market models by Kouwenberg and Zwinkels (2014, 2015) produce endogenous house price oscillations. However, Bolt et al. (2014) detect empirical evidence of multiple steady states.

As it turns out, the central bank has a limited ability to increase the parameter domain that guarantees stability of the fundamental steady state by autonomously increasing the base (target) interest rate. Economically, higher interest rates reduce investors' demand pressure on house prices. From a quantitative perspective, the additional gain in the stability-enforcing parameter domain seems to be negligible. Moreover, high interest rates decrease the fundamental house price (and may lead to further adverse effects outside the scope of our model). Simulations also reveal that a decrease in the base (target) interest rate can spark a temporary bubble or even create permanent house price oscillations – a situation reminiscent of the start of the aforementioned U.S. housing market bubble. Central banks should keep this in mind when planning to adjust the interest rate.

Fortunately, the central bank has a great ability to control housing market fluctuations by dynamically adjusting the interest rate with a view to mispricing in the housing market. By increasing (decreasing) the interest rate in periods of overvaluation (undervaluation), such a leaning-against-the-wind policy smoothes investors' expectation-driven housing demand. Most importantly, this policy allows the central bank to prevent (or at least reduce) the instability of the housing market arising from the Neimark-Sacker bifurcation, i.e. the housing market remains stable or its oscillations are characterized by a lower amplitude. The stabilizing effect of the central bank's dynamic interest rate setting is also present in the Pitchfork bifurcation scenario, i.e. the central bank has an effective tool to prevent the appearance of nonfundamental steady states. The Flip bifurcation boundary only becomes more relevant if the central bank reacts very aggressively to the housing market's mispricing (though this possibility requires some more extreme parameter constellations).

Finally, we would like to stress that our insights are based on a mix of analytical

results and extensive numerical simulations, also including exogenous shocks and alternative model specifications, such as investors' endogenous variance beliefs, and may thus be regarded as relatively robust.[2] The remainder of our paper is organized as follows. In Section 2, we survey some related literature. In Section 3, we extend the housing market model by Dieci and Westerhoff (2016). We present our analytical and numerical results in Sections 4 and 5, respectively. In Section 6, we conclude our paper. Proofs and model extensions are presented in the Appendix.

2. Related literature

The important yet intricate relationship between house prices, interest rates and expectations has received increasing academic attention in the recent past. Unfortunately, no clear consensus about their interplay has been reached so far. For instance, Himmelberg et al. (2005) argue that the rapid price growth in the U.S. housing market in the 2000s was primarily caused by fundamental economic factors, especially by low interest rates. The relevance of interest rates for the formation of house prices, already articulated by Poterba (1984, 1991) to explain housing market fluctuations in the 1970s and 1980s, is, more recently, also stressed by Landvoigt (2017). However, Glaeser et al. (2013) conclude that interest rate changes cannot account for more than one-fifth of the U.S. housing market boom. Instead, they conjecture that overly optimistic expectations and mass psychology, as put forward by Case and Shiller (2003), Case et al. (2012) and Piazzesi and Schneider (2009), are major drivers of house price dynamics. Glaeser (2013) and Shiller (2015) sketch a typical boom-bust cycle as follows. While a decrease in interest rates may set in motion a fundamentally justified increase in house prices, the behavior of optimistic momentum investors can transform the initial price increase into a serious boom, resulting, of course, in an inevitable bust at a later stage.

For this reason, the expectation formation behavior of boundedly rational investors is a crucial factor in the housing market model by Dieci and Westerhoff (2016), forming the core of our model, and a number of related housing market models, e.g. by Dieci

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[2]We will also discuss some more subtle issues associated with the central bank's interest rate setting. For instance, the central bank may also manipulate the basins of attraction of coexisting steady states in a nontrivial yet stabilizing manner. Such important issues are often overlooked.

and Westerhoff (2012), Bolt et al. (2014), Kouwenberg and Zwinkels (2014), Eichholtz et al. (2015), Burnside et al. (2016), Diks and Wang (2016), Chia et al. (2017), Glaeser and Nathanson (2017) and Ascari et al. (2018). Overall, these models demonstrate that investors' expectation formation behavior can induce significant endogenous house price oscillations. Although this line of research is still at an early stage, it is worth noting that it is deeply rooted in the heterogeneous agent asset-pricing literature, a rather powerful research strand that convincingly explains the dynamics of financial markets, see, e.g. Day and Huang (1990), de Grauwe et al. (1993), Lux (1995), Brock and Hommes (1998), Farmer and Joshi (2002), Huang and Zheng (2012) and Franke and Westerhoff (2012). See Dieci and He (2018) for an insightful survey.

Returning to the the interest rate setting of central banks, Taylor (2009) forcefully states that monetary excess caused the U.S. housing market bubble. It is clear that such a view − stressing a strong relation between interest rates and house prices − has straightforward policy implications. In fact, Taylor (2009) is convinced that a rule-based interest rate policy, moderately adjusting the interest rate with respect to inflation and output (the so-called Taylor principle, going back to Taylor 1993), would have considerably dampened the magnitude of the housing market's boom-bust cycle. In a similar vein, Agnello et al. (2018), exploring the dynamics of housing markets for 20 industrial countries between 1970 and 2012, find that housing market bubbles can be deflated by increasing the interest rate. Therefore, they argue that their work supports the idea that a leaning-against-the-wind monetary policy rule can help to stabilize the housing market. Related to this, Lambertini et al. (2013) show that an interest rate rule that responds to house price growth can foster welfare by reducing the volatility of house prices. In contrast, Iacoviello (2005), also using a model with rational and optimizing agents, concludes that an interest rate response to house prices does not yield significant welfare gains as it fails to improve market stability. Yellen (2005) is even more pessimistic, claiming that monetary policy should not be used to deflate housing market bubbles.

However, it is important to note that a related line of research underlines the role of the supply side for the stability of housing markets. In particular, Glaeser et al. (2008) show that housing market bubbles are more likely to occur in places where housing sup-

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ply is rather inelastic. They argue that policymakers need to make housing supply more elastic, e.g. by providing more building land or reducing construction costs, to obtain fewer and shorter bubbles with shorter price increases. Similar arguments are offered by Gyouroko et al. (2013), who argue that limitations in building land increase building costs, and by Glaeser and Gyourko (2018), who point out that overly regulated housing markets also exhibit higher building costs. Obviously, elementary laws of demand and supply imply that housing markets will exhibit stronger price reactions to shifts in housing demand, e.g. triggered by changes in interest rates or expectations, when housing supply is inelastic than when it is elastic. Such aspects should not be overlooked when it comes to explaining the dynamics of housing markets.

Our results may help to disentangle the intricate relationship between house prices, interest rates and expectations. On the one hand, our model reveals that interest rates affect the fundamental value of house prices, particularly if interest rates are already low. On the other hand, actual house prices heavily depend on investors' expectation formation behavior. Clearly, investors' expectations can induce endogenous house price fluctuations in which house prices significantly oscillates around their fundamental value, letting any (steady-state) response of the fundamental house price appear rather small. Moreover, a reduction in interest rates may spark a temporary housing market boom or, by increasing investors' demand for housing, permanently compromise the stability of housing markets. Naturally, an increase in the interest rate reduces house prices and enforces more stability, albeit with a rather small effect. The good news is that the central bank can stabilize housing markets by dynamically adjusting the interest rate with a view to mispricing in the housing market. Our analytical and numerical results suggest that, as long as the reaction parameter of the interest rate rule is not too strong, a leaning-against-the-wind interest rate policy substantially increases the parameter domain that ensures the stability of the housing market or, at least, significantly reduces the amplitude of house price cycles. While the supply side of the housing market influences the duration and magnitude of boom-bust cycles, the central bank can always control these effects by manipulating the demand side of the housing market by dynamically adjusting the interest rate. Indeed, it is the demand side of the housing market

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that is subject to the optimistic/pessimistic expectations of housing market investors.[3]

3. The housing market model

Dieci and Westerhoff (2016) combine a standard stock-flow housing market framework (Poterba 1984, 1991, Wheaton 1999), comprising explicit relations between house prices, the rent level and the housing stock, with a parsimonious approach that captures the expectation formation behavior of boundedly rational and heterogeneous investors (Day and Huang 1990, de Grauwe et al. 1993, Brock and Hommes 1998). According to the stock-flow housing market part of their model, the housing market consists of two interrelated markets: a rental (flow) market and a housing capital (stock) market. For a given housing stock, the demand for housing services determines the rent level in the rental market. House prices depend on investors' demand for housing stock relative to the existing housing stock. Investors' demand for housing stock is a function of their house price expectations, the rent level, the perceived housing market risk and the interest rate, while the housing stock evolves with respect to new housing construction and housing depreciation. The expectation formation part of their model assumes that investors rely on extrapolative and regressive expectation rules to forecast future house prices. In particular, investors increasingly turn to the regressive expectation rule as house prices disconnect from their fundamental values. We extend the model by Dieci and Westerhoff (2016) by introducing a central bank that adjusts the interest rate with a view to mispricing in the housing market. Since the central bank's interest rate setting may affect the (perceived) riskiness of the housing market, we also let investors update their variance beliefs. Technically, this turns the original two-dimensional framework into a four-dimensional model.

Let us start with the rental market. The market clearing condition for housing services implies that the demand for housing services D_t in each period t is equal to the

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[3]Martin and Westerhoff (2019) explore whether public housing construction programs may stabilize housing markets. As it turns out, it is difficult to counter expectation-driven demand changes via supply adjustments, due to the long durability of the housing stock. While the housing stock may grow during a boom to dampen the house price increase, the stock of housing remains high for a considerable amount of time, and may thus worsen the consequent bust.

supply (or flow) of housing services S_t in the same period, i.e.

$$D_t = S_t. \tag{1}$$

The demand for housing services is written as

$$D_t = a - bR_t. \tag{2}$$

Since parameters a and b are positive, (2) indicates that D_t depends negatively on rent level R_t, the price of housing services. The supply of housing services is proportional to the initial stock of housing H_t, and is described as

$$S_t = cH_t, \tag{3}$$

where $c > 0$. By inserting (2) and (3) in (1), rent level R_t is given by a decreasing function of the current housing stock

$$R_t = \alpha - \beta H_t, \tag{4}$$

where $\alpha = \frac{a}{b} > 0$ is a scaling parameter and $\beta = \frac{c}{b} > 0$ represents the sensitivity of the rent level with respect to the housing stock. Of course, α and β have to be such that $R_t \geq 0$.

As regards the capital market, the market clearing condition for housing stock

$$Z_t = H_t \tag{5}$$

indicates that the demand for housing stock Z_t is equal to the supply of housing stock H_t. The development of the housing stock is given by

$$H_t = I_t + (1 - \delta)H_{t-1}, \tag{6}$$

where $0 < \delta < 1$ is the housing depreciation rate and I_t denotes the amount of new housing construction. Since housing investments in period t depend positively on the

price of the previous period P_{t-1}, i.e.

$$I_t = \gamma P_{t-1}, \tag{7}$$

where $\gamma > 0$ represents an inverse cost parameter, we obtain

$$H_t = \gamma P_{t-1} + (1 - \delta)H_{t-1} \tag{8}$$

as the equation that describes the evolution of the housing stock. Note that the lower parameter γ is, the more sluggish the housing stock. Since Glaeser et al. (2008) argue that the duration and magnitude of housing bubbles crucially depends on the price-responsiveness of the supply side, parameter γ is a key parameter of our model.[4]

We model investors' demand for housing stock using a standard one-period mean-variance framework. More precisely, investor i faces a wealth allocation problem between housing capital and an alternative riskless asset over the time horizon from period t to $t+1$. For a hypothetical house price level P_t at time t, investor i's end-of-period wealth is given by

$$W_{t+1}^i = (1 + r_t)W_t^i + Z_t^i(P_{t+1} + R_t - (1 + r_t + \delta)P_t), \tag{9}$$

where W_t^i and Z_t^i stand for the wealth and the amount of housing units held by investor i at the beginning of the period. Note that variables indexed with $t + 1$ are random. We assume accordingly, that rent level R_t and interest rate r_t are determined at the beginning of the period.

The goal of housing market investors is to maximize the certainty equivalent of final wealth. For investor i, this results in the following mean-variance optimization problem

$$max_{Z_t^i}\left[E_t^i[W_{t+1}^i] - \frac{\lambda^i}{2}V_t^i[W_{t+1}^i]\right], \tag{10}$$

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[4]Investment function (7) is consistent with the behavior of risk-neutral firms, which maximize expected profits and face a quadratic cost function $C_t = \frac{1}{2\gamma}I_t^2$. Accordingly, an increase in parameter γ implies a decrease in the costs of building houses. Since the construction of new houses requires time, firms have to form price expectations. Apparently, (7) is in line with the assumptions of a one-period production lag and naive expectations. In a related framework, Dieci and Westerhoff (2012) study the case in which firms have perfect foresight expectations, while Campisi et al. (2018) elaborate on the case in which firms rely on a mix of perfect foresight and naive expectations.

where $E_t^i[W_{t+1}^i]$ and $V_t^i[W_{t+1}^i]$ represent investor i's conditional expectation and variance about his end-of-period wealth, while parameter $\lambda^i > 0$ reflects his (absolute) risk aversion.

As is well known, investor i's solution to the above maximization problem yields

$$Z_t^i = \frac{E_t^i[P_{t+1}] + R_t - (1 + r_t + \delta)P_t}{\lambda^i V_t^i[P_{t+1}]}. \tag{11}$$

Obviously, investor i's optimal demand (amount of housing units) increases in line with the expected future house price and the rent level, while it decreases in line with the interest rate, the (current) house price and the perceived housing market risk.

In our paper, we consider the case in which investors' beliefs about future house prices are heterogeneous, while their beliefs about the variance of future house prices are homogeneous yet time-varying. Let $E_t[P_{t+1}]$ stand for investors' average future house price expectation and $V_t[P_{t+1}]$ for their homogeneous variance beliefs. Normalizing the mass of investors to one and assuming the same risk aversion for all investors allows us to express investors' total housing demand as

$$Z_t = \frac{E_t[P_{t+1}] + R_t - (1 + r_t + \delta)P_t}{\lambda V_t[P_{t+1}]}. \tag{12}$$

From the market equilibrium condition (5), we then get

$$P_t = \frac{E_t[P_{t+1}] + R_t - H_t \lambda V_t[P_{t+1}]}{1 + r_t + \delta} + \epsilon_t, \tag{13}$$

where $\epsilon_t \sim N(0, \sigma^2)$ reflects additional exogenous noise affecting the housing market. Apparently, the house price depends positively on investors' house price expectations and the rent level, and negatively on the stock of housing, investors' risk perception and the interest rate.

Hommes (2013) argues that agents are boundedly rational and, when facing complex decision problems, rely on simple yet plausible heuristics. A similar view is offered by Glaeser (2013). To keep the model tractable, investors select only between two expectation rules to forecast future house prices: an extrapolative and a regressive expectation rule. Moreover, expectations formed in period t about the house price in period $t + 1$

rely on the last observable house price, namely the house price in period $t-1$. According to the extrapolative expectation rule, investors predict the next period's house price by

$$E_t^E[P_{t+1}] = P_{t-1} + \chi(P_{t-1} - P^*), \qquad (14)$$

where $\chi > 0$ denotes the rule's extrapolation strength and P^* stands for the housing market's fundamental price. Hence, the extrapolative expectation rule predicts a continuation of the current boom or bust period in the housing market. In contrast, the regressive expectation rule is based on the assumption that the house price reverts to its fundamental value. This rule is formalized by

$$E_t^R[P_{t+1}] = P_{t-1} + \phi(P^* - P_{t-1}), \qquad (15)$$

where $0 < \phi < 1$ stands for the rule's mean-reversion speed. Note that expectation rules (14) and (15) can be traced back to the seminal asset-pricing models by Day and Huang (1990) and Brock and Hommes (1998). Empirical support for these rules is provided by contributions such as Boswijk et al. (2007) and Westerhoff and Franke (2012).[5]

Investors' choice of prediction rules depends on current market circumstances. While investors seek to chase price trends, they also fear fundamental price corrections. Assuming that investors prefer the regressive expectation rule with increasing mispricing, the market share of investors that follow the extrapolative expectation rule can be expressed by

$$N_t^E = \frac{1}{1 + \eta(P^* - P_{t-1})^2}. \qquad (16)$$

Near the fundamental value, the market share of the extrapolative expectation rule is relatively high. In such an environment, the bulk of investors regard any price change away from the fundamental value as the start of an exploitable bull or bear market. However, the larger the switching parameter $\eta > 0$, the faster investors switch to the

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[5] Expectation rules (14) and (15), as well as the switching function (16) and the interest rate rule (22), imply that the fundamental house price is common knowledge. As we will see in more detail in Section 4, this is not a too strong assumption since the fundamental house price corresponds to the discounted value of future (risk-adjusted) rents and can thus be identified by investors and the central bank.

regressive expectation rule as mispricing in the housing market increases. Of course, the market share of the regressive expectation rule is given by $N_t^R = 1 - N_t^E$. The bell-shaped switching function (16) was originally proposed by de Grauwe et al. (1993) to explain the dynamics of foreign exchange markets. See He and Westerhoff (2005) for a more related application and Franke and Westerhoff (2012) for empirical support.

Investors' average house price expectations are defined by

$$E_t[P_{t+1}] = N_t^E E_t^E[P_{t+1}] + N_t^R E_t^R[P_{t+1}].$$ (17)

Combining (14)-(17) reveals that

$$E_t[P_{t+1}] = \frac{P_{t-1} + \chi(P_{t-1} - P^*) + P_{t-1}\eta(P^* - P_{t-1})^2 + \phi\eta(P^* - P_{t-1})^3}{1 + \eta(P^* - P_{t-1})^2},$$ (18)

i.e. investors' expectation formation behavior adds a strong nonlinearity to our housing market model.

Following Chiarella et al. (2007, 2013), investors' variance beliefs depend on a fundamental and a speculative component, so that we can write

$$V_t[P_{t+1}] = \Omega + \kappa V_t^S.$$ (19)

The fundamental variance component Ω is constant and captures investors' perceived risk associated with owning a house (e.g. damages to the house, not receiving the rent, unforeseen regulations connected with buying and selling houses or other fundamental disturbances).[6] The speculative variance component V_t^S is time-varying and depends on housing market volatility, where parameter $\kappa \geq 0$ measures investors' sensitivity with respect to the latter component. Note that $\kappa = 0$ implies that investors' variance beliefs are constant, as is the case in the original housing market model by Dieci and Westerhoff (2016) and almost all other related heterogeneous agent asset-pricing models (see, for

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[6]Piazessi and Schneider (2016) point out that the volatility of house prices depends more strongly on idiosyncratic shocks than the volatility of stocks. Since houses are indivisible (they are sold in their entirety and not in small pieces), idiosyncratic shocks to housing are difficult to diversify. Furthermore, real housing markets are usually not very liquid, and are characterized by high transaction costs, aspects that add to the risk of owning a house.

instance, the recent survey by Dieci and He 2018).

We model investors' speculative variance component using a learning rule introduced by Gaunersdorfer (2000), that is

$$V_t^S = \nu V_{t-1}^S + (1 - \nu)(P_{t-1} - U_{t-1})^2 \tag{20}$$

and

$$U_t = \mu U_{t-1} + (1 - \mu)P_{t-1}, \tag{21}$$

where $0 < \nu, \mu < 1$ are memory parameters. Accordingly, investors update their speculative variance beliefs by computing a weighted average of their past speculative variance beliefs and the most recent observable squared deviation between the house price and an average house price. Obviously, the average house price is also updated in the form of a weighted average.[7]

Inspired by Taylor (2009), Lambertini et al. (2013) and Agnello et al. (2018), we consider the case in which the central bank sets the interest rate with a view to the fundamental condition of the housing market. More precisely, the central bank tries to stabilize the housing market by using the following interest rate rule

$$r_t = r_0 + \rho \left(\frac{P_{t-1} - P^*}{P^*} \right), \tag{22}$$

where r_0 is the central bank's base (target) interest rate. Furthermore, $\rho \geq 0$ is a parameter that controls how strongly the central bank reacts to mispricing in the housing market. Naturally, $r_t \geq 0$, i.e. the interest rate cannot become negative.[8] Note that (22) suggests increasing (decreasing) the interest rate if the housing market is overvalued (undervalued). In fact, recall from (12) and (13) that higher (lower) interest rates −

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[7]In the Appendix, we study an alternative learning rule proposed by Chiarella et al. (2007, 2013). While their learning rule may affect our model's global behavior, it does not affect the fundamental steady state's stability domain. Further learning rules with fixed memory length are studied by Chiarella and He (2002).

[8]While the interest rate is always positive in the analytical part of our paper (Section 4), it may hit the zero-lower bound when we simulate our model's out-of equilibrium dynamics (Section 5). In fact, (22) then implies that the model's map is piecewise defined, an aspect that may cause interesting side effects. See Avrutin et al. (2019) for an overview of possible implications of such maps, and tools to explore them, and Schmitt et al. (2017) for economic examples.

accomplished by adjusting the base (target) interest rate or reacting to the fundamental condition of the housing market – decrease (increase) investors' demand for housing stock, and therefore depress (elevate) house prices. In the next sections, we use a mix of analytical and numerical tools to explore the extent to which the interest rate rule (22) allows the central bank to control the dynamics of housing markets.

4. Analytical insights

By combining our equations, we can easily express the model by the four-dimensional nonlinear map

$$
S : \begin{cases}
P_t = \frac{E_t[P_{t+1}] + \alpha - (\beta + \lambda V_t[P_{t+1}])\gamma P_{t-1} - (\beta + \lambda V_t[P_{t+1}])(1-\delta)H_{t-1}}{1 + r_0 + \rho\left(\frac{P_{t-1} - P^*}{P^*}\right) + \delta} \\
H_t = \gamma P_{t-1} + (1-\delta)H_{t-1} \\
V_t^S = \nu V_{t-1}^S + (1-\nu)(P_{t-1} - U_{t-1})^2 \\
U_t = \mu U_{t-1} + (1-\mu)P_{t-1}
\end{cases}
, \tag{23}
$$

where

$$
E_t[P_{t+1}] = \frac{P_{t-1} + \chi(P_{t-1} - P^*) + P_{t-1}\eta(P^* - P_{t-1})^2 + \phi\eta(P^* - P_{t-1})^3}{1 + \eta(P^* - P_{t-1})^2}
$$

and

$$
V_t[P_{t+1}] = \Omega + \kappa V_t^S.
$$

As can be seen, the dynamics depends on 14 parameters: α, β, γ, δ, λ, ν, μ, r_0, ρ, χ, η, ϕ, κ and Ω. Nevertheless, we are able to prove the following results:

Proposition 1. *The dynamical system (23) always gives rise to the fundamental steady state $FSS = (P^*, H^*, V^{S*}, U^*) = \left(P^*, \frac{\gamma}{\delta}P^*, 0, P^*\right)$ with $P^* = \frac{\alpha\delta}{(r_0+\delta)\delta + (\beta+\lambda\Omega)\gamma}$. Moreover, the FSS is locally asymptotically stable if and only if*
(i) $\chi > \frac{4 + 2r_0 - 2\rho - \delta(\delta + r_0 - \rho) - \gamma(\beta+\lambda\Omega)}{\delta - 2}$, (ii) $\chi < \frac{\gamma(\beta+\lambda\Omega)}{\delta} + \delta + r_0 + \rho$ and (iii) $\chi < \frac{2\delta + r_0}{1-\delta} + \rho$.

Proof. A steady-state solution $(\overline{P}, \overline{H}, \overline{V}^S, \overline{U})$ of the dynamical system (23) necessarily

satisfies the conditions

$$\overline{P} = \frac{E_t[\overline{P}] + \alpha - (\beta + \lambda(\Omega + \kappa\overline{V}^S))\gamma\overline{P} - (\beta + \lambda(\Omega + \kappa\overline{V}^S))(1-\delta)\overline{H}}{1 + r_0 + \rho\left(\frac{\overline{P}-P^*}{P^*}\right) + \delta},$$

$$\overline{H} = \gamma\overline{P} + (1-\delta)\overline{H},$$

$$\overline{V}^S = \nu\overline{V}^S + (1-\nu)(\overline{P}-\overline{U})^2$$

and

$$\overline{U} = \mu\overline{U} + (1-\mu)\overline{P},$$

where $E_t[\overline{P}]$ denotes the price expectations at the steady state. Let us define the fundamental steady state $FSS = (P^*, H^*, V^{S*}, U^*)$ as a steady-state solution to (23) in which $E_t[\overline{P}] = \overline{P}$ and $r_t = r_0$, i.e. $P^* = \overline{P}$. Therefore, expectations are realized at the steady state and the central bank does not change its base (target) interest rate, since prices mirror their fundamental values. It follows that the price at the fundamental steady state is given by

$$P^* = \frac{\alpha\delta}{(r_0+\delta)\delta + (\beta+\lambda\Omega)\gamma},$$

while $H^* = \frac{\gamma}{\delta}P^*$, $U^* = P^*$ and $V^{S*} = 0$. However, the dynamical system (23) may also give rise to further nonfundamental steady states $(\overline{P}, \overline{H}, \overline{V}^S, \overline{U})$, such that $E_t[\overline{P}] \neq \overline{P}$. While these steady states cannot be expressed analytically, we will numerically encounter them in Section 5.

From the Jacobian of the fundamental steady state, i.e.

$$J(FSS) = \begin{pmatrix} \frac{1-\rho+\chi-\gamma(\beta+\lambda\Omega)}{1+\delta+r_0} & \frac{(\delta-1)(\beta+\lambda\Omega)}{1+\delta+r_0} & -\frac{\alpha\gamma\kappa\lambda\nu}{(1+\delta+r_0)(\delta(\delta+r_0)+\gamma(\beta+\lambda\Omega))} & 0 \\ \gamma & 1-\delta & 0 & 0 \\ 0 & 0 & \nu & 0 \\ 1-\mu & 0 & 0 & \mu \end{pmatrix},$$

we immediately see that two eigenvalues are given by $z_1 = \nu$ and $z_2 = \mu$. Since $0 <$

$\nu, \mu < 1$, we have $|z_{1,2}| < 1$. The two further eigenvalues are the ones of the 2-D block

$$Q = \begin{pmatrix} \frac{1-\rho+\chi-\gamma(\beta+\lambda\Omega)}{1+\delta+r_0} & \frac{(\delta-1)(\beta+\lambda\Omega)}{1+\delta+r_0} \\ \gamma & 1-\delta \end{pmatrix}$$

from which we obtain the characteristic polynomial $P(z) = z^2 - zTr(Q) + Det(Q)$ with $Tr(Q) = \frac{1-\rho+\chi-\gamma(\beta+\lambda\Omega)}{1+\delta+r_0} + 1 - \delta$ and $Det(Q) = \frac{(\delta-1)(\rho-\chi-1)}{1+\delta+r_0}$. Necessary and sufficient conditions (Gandolfo 2009, Medio and Lines 2001) for $z_{3,4}$ to be smaller than one in modulus, which implies local asymptotic stability of the fundamental steady state, are given by $1 + Tr(Q) + Det(Q) > 0$, $1 - Tr(Q) + Det(Q) > 0$ and $1 - Det(Q) > 0$. Rewriting these inequalities in terms of the parameters reveals

$$\chi > \frac{4 + 2r_0 - 2\rho - \delta(\delta + r_0 - \rho) - \gamma(\beta + \lambda\Omega)}{\delta - 2},$$

$$\chi < \frac{\gamma(\beta + \lambda\Omega)}{\delta} + \delta + r_0 + \rho,$$

and

$$\chi < \frac{2\delta + r_0}{1 - \delta} + \rho.$$

$\square$

As shown above, the model has a fundamental steady state where the house price equals its fundamental value, i.e. $\overline{P} = P^* = \frac{\alpha\delta}{(r_0+\delta)\delta+(\beta+\lambda\Omega)\gamma}$, while the corresponding values for the housing stock, the speculative variance component and the average house price are given by $H^* = \frac{\gamma}{\delta}P^*$, $V^{S*} = 0$ and $U^* = P^*$, respectively. Note that P^* is independent of any behavioral parameters, such as χ, ϕ or η, and depends only on fundamental parameters. In particular, if the central bank increases the base (target) interest rate r_0, the fundamental house price decreases, which, in turn, implies decreasing values for the housing stock and higher rent levels (and vice versa).

Since the rent level at the fundamental steady state is given by $R^* = \alpha - \beta H^*$, it follows that $P^* = \frac{R^* - \lambda\Omega H^*}{r_0+\delta}$. By defining risk-adjusted rents as $\hat{R}^* = R^* - \lambda\Omega H^*$ (see Dieci and Westerhoff 2016 for more details), the fundamental house price can be expressed as the discounted value of future risk-adjusted rents, i.e. $P^* = \frac{\hat{R}^*}{r_0+\delta}$, where

the term $r_0 + \delta$ reflects the user cost of housing. This is a key property of Poterba's (1984, 1991) seminal housing market model inspired by asset pricing. As pointed out by Himmelberg et al. (2005), the nonlinearity in the discounting of risk-adjusted rents can cause sharp fundamental house price changes with respect to interest rate changes. In fact, the sensitivity of the fundamental house price to changes in the interest rate is higher at times when interest rates are already low. In a low interest rate environment, for instance, a given decrease in the interest rate induces a larger increase in house prices than the same decrease in the interest rate that would initiate starting from a high interest rate. Of course, the reverse is also true. An increase in interest rates in a low interest rate environment would cause a disproportionally large decline in house prices, especially if risk-adjusted rents remain constant, or adjust only slowly.

To illustrate the stability domain of the fundamental steady state, we plot in Figure 1 the stability conditions in (χ, γ)-parameter space. The depiction is stylized and based on $\rho = 0$. The first, second and third conditions are represented by the red, blue and green line, respectively. Accordingly, the fundamental steady state is locally asymptotically stable for the parameter space that is bounded by the three bifurcation curves (highlighted in gray). For $0 < \gamma < A1$, an increase in investors' extrapolation behavior may violate the second stability condition, which is associated with a Pitchfork bifurcation, i.e. the fundamental steady state becomes unstable and two additional nonfundamental steady states are created. The housing market then remains permanently either overvalued or undervalued. Note that this scenario may occur if the housing supply is rather sluggish. If $A1 < \gamma < A2$, an increase in χ may cause a Neimark-Sacker bifurcation, and thus the onset of a quasi-periodic motion.[9] If the housing supply reacts more strongly to the past house price, i.e. if $A2 < \gamma < A3$, the local asymptotic stability of the fundamental steady state requires that investors' extrapolation behavior is neither too low (violation of the Flip bifurcation boundary) nor too high (violation of the Neimark-Sacker bifurcation boundary). Hence, there are scenarios where a modest extrapolative behavior of investors is beneficial for the stability of housing markets. Finally, the fun-

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[9]Several empirical papers indicate that the cyclical nature of housing markets is due to a Neimark-Sacker bifurcation, e.g. Wheaton (1999), Kouwenberg and Zwinkels (2014, 2015), Dieci and Westerhoff (2016) and Glaeser and Nathanson (2017). However, Bolt et al. (2014) detect empirical evidence for coexisting attractors due to a Pitchfork bifurcation.

damental steady state is always unstable if $\gamma > A3$, i.e. if the price-responsiveness of the housing stock becomes very large. Overall, an intermediate value of γ seems to be needed to generate endogenous house price cycles.[10]
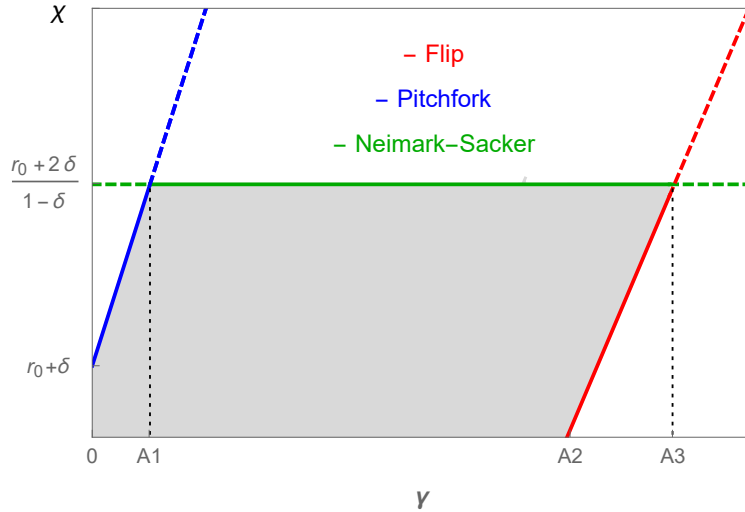

Figure 1: Stability domain of the fundamental steady state in (χ,γ)-parameter space. Since the blue, red and green lines represent the three stability conditions, the parameter space highlighted in gray illustrates the region for which the fundamental steady state is locally asymptotically stable. Note that $\rho = 0$.

The central bank may be able to influence the stability domain of the fundamental steady state by varying r_0 and ρ. If the central bank increases the base (target) interest rate, all three stability conditions become relaxed, and the region for which P^* is locally asymptotically stable becomes larger. From an empirical perspective, however, this effect seems to be rather limited. This can be explained by the following example. For quarterly data, $r_0 = \delta = 0.005$ is a reasonable assumption, implying that $\chi^{NS} \approx 0.015$. Since γ seems to be much larger empirically, say $\gamma^{emp} = 0.15$ (see Section 5 for more details), extremely high (and unrealistic) base (target) interest rates may be needed to stabilize housing markets. In contrast, the stabilizing effect of an increase in the central bank's reaction parameter ρ appears to be much stronger. While an increase in ρ makes the presumably not so important Flip bifurcation boundary more binding, it

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[10]Clearly, the violation of the first, second and third stability conditions is a necessary condition for the emergence of a Flip, Pitchfork and Neimark-Sacker bifurcation. Combined with numerical evidence indicating that such bifurcations occur, they constitute strong evidence (Medio and Lines 2001).

relaxes the highly relevant Pitchfork and Neimark-Sacker bifurcation boundaries. Given $r_0 = \delta = 0.005$ and $\chi^{emp} = 0.15$, for instance, we need $\rho \approx 0.135$ to ensure stability of the fundamental steady state, which seems to be reasonable.

To sum up: investors' extrapolation behavior may destabilize housing markets. In particular, a violation of the Neimark-Sacker bifurcation can set endogenous house price cycles in motion. While the central bank has a limited ability to tame housing markets by increasing the base (target) interest rate, it has a strong potential to stabilize housing markets by following a leaning-against-the-wind interest rate rule. In this sense, our local stability results support the view of Taylor (2009), Agnello et al. (2018) and Lambertini et al. (2013).

5. Numerical insights

Equipped with our analytical insights, we are now ready to explore the model's out-of-equilibrium behavior. In Section 5.1, we first introduce our base parameter setting and explain the basic functioning of our model. In Section 5.2, we investigate in more detail the extent to which the central bank can stabilize housing markets by adjusting the interest rate with a view to mispricing of the housing market, paying special attention to the Neimark-Sacker bifurcation scenario (Section 5.2.1), the Pitchfork bifurcation scenario (Section 5.2.2) and the Flip bifurcation scenario (Section 5.2.3). In Section 5.3, we discuss how the central bank influences the housing market by adjusting the base (target) interest rate.

5.1. Base parameter setting and functioning of the model

Table 1 shows the base parameter setting of our simulations. A time period in the calibrated model is equivalent to one quarter of a year. The real parameters, such as the base (target) interest rate and the depreciation rate, are grounded on empirical observations. The remaining model parameters, in particular those that include agents' expectation formation, are set such that the model dynamics reflects a number of important characteristics of real housing markets. In particular, we will see that our model is able to produce boom-bust cycles with short-run momentum, long-run mean reversion and excess volatility, crucial features of actual housing market dynamics (Glaeser and

Nathanson 2015, Piazzesi and Schneider 2016). In addition, a small amount of exogenous noise is added to the house price equation, which is normally distributed with zero mean and standard deviation σ. See Dieci and Westerhoff (2016) for more details.

Table 1: Parameter setting used in the simulations (quarterly data)

$\alpha = 62$	scaling parameter	rental market
$\beta = 0.06$	sensitivity of rental market	
$\gamma = 0.06$	sensitivity of home building	supply side of housing market
$\delta = 0.005$	depreciation rate	
$r_0 = 0.005$	base (target) interest rate	central bank
$\rho = 0.1$	reaction parameter of central bank	
$\chi = 0.15$	extrapolative parameter	price expectations
$\phi = 0.125$	regressive parameter	
$\eta = 0.1$	switching intensity	
$\lambda = 0.00025$	risk aversion	risk aversion and
$\Omega = 4$	base fundamental risk	variance beliefs
$\kappa = 0.25$	sensitivity to speculative risk	
$\nu = 0.5$	memory parameter variance	
$\mu = 0.5$	memory parameter mean	
$\sigma = 2$	standard deviation of noise	exogenous shocks

The calibrated model parameters imply that the FSS is given by $P^* = E[\overline{P}] = U^* = 100$ and $H^* = 1000$. Since the rent level at the FSS amounts to $R^* = 2$, it follows that the (annual) price-rent ratio is $\frac{P^*}{4R^*} = 12.5$. Furthermore, the steady state level of investors' variance beliefs and the interest rate is $V^*[P^*] = 4$ and $r^* = 0.005$, respectively. At the FSS, all agents form extrapolative expectations, i.e. $N^{E^*} = 1$. Note that the Neimark-Sacker condition is violated while the Flip and the Pitchfork conditions hold. Hence, the fundamental steady state is unique but unstable.

To start, Figure 2 shows the functioning of a restricted version of our model. In the depicted simulation run, the parameter of agents' sensitivity to speculative risk κ and the central bank's reaction parameter ρ are set to zero, i.e. investors' variance beliefs are constant and $r_t = r_0$. Note that this setup is close to that of Dieci and Westerhoff (2016), who show that their model can produce realistic housing market dynamics with lasting periods of overbuilding and overvaluation. The 200 observations represent a time span of 50 years. The panels show, from top left to bottom right, the evolution of house prices, the housing stock, the market share of regressive expectations, the rent level, investors' variance beliefs, and the interest rate, respectively. The gray lines shown in

the panels depict the fundamental values. For comparability, we also use this design for Figures 3-5. Obviously, investors' extrapolative behavior causes significant housing market fluctuations. The functioning of the restricted model can be summarized as follows. Initially (at $t = 1$), the housing market is strongly overvalued, which means that the market share of regressive expectations is relatively high. Since regressive expectations have a stabilizing effect, house prices return towards their fundamental value. Moreover, high house prices induce substantial new housing construction, which leads to an expansion of the housing stock and a depression of the rent level. Once house prices drop below their fundamental value, investors with extrapolative expectations become pessimistic. Since their market share is relatively high, prices drop even further until shortly after period $t = 50$. At this point, the situation starts to change. If house prices are very low, more and more investors switch to the regressive expectation rule and predict an increase in house prices. Since the housing stock is still relatively small, the rent level recovers and the story repeats itself until the next crash occurs.

To investigate how endogenous variance beliefs change the dynamics of the housing market model, we now set the parameter of agents' sensitivity to speculative risk to $\kappa = 0.25$ instead of $\kappa = 0$. The dynamics of the model with endogenous variance beliefs and constant interest rates (i.e. $\rho = 0$) is illustrated in Figure 3. As can be seen from the bottom left panel, investors' variance beliefs fluctuate slightly above the fundamental value $V^*[P^*] = 4$, except around period $t = 65$, where variance beliefs increase to over $V_t = 20$. According to equations (13) and (19), a rapid drop in house prices leads to an increase in V_t^S, and thus an increase in variance beliefs V_t. In fact, this is exactly what we observe. Around period $t = 65$, house prices fall sharply due to the high level of the housing stock and the low rent level, causing a rapid increase in investors' variance beliefs. Put differently, the sharp drop in house prices makes the housing market appear more risky. Investors then retreat, amplifying the crash, and house prices drop below $P_t = 75$. This gives the model a slightly asymmetric nature, i.e the level of the housing stock decreases and the rent level increases. As house prices rise, investors' uncertainty recedes and their housing demand increases, which further strengthens the upward trend. Glaeser and Nathanson (2015) remark that while real housing markets are excessively volatile, house prices do not display a constant level of volatility. Instead,
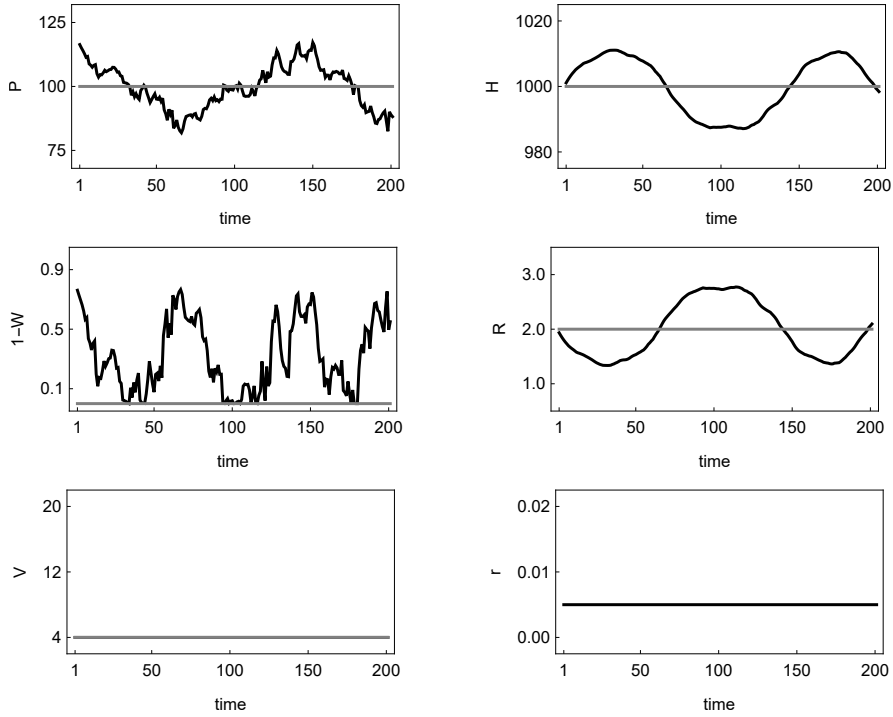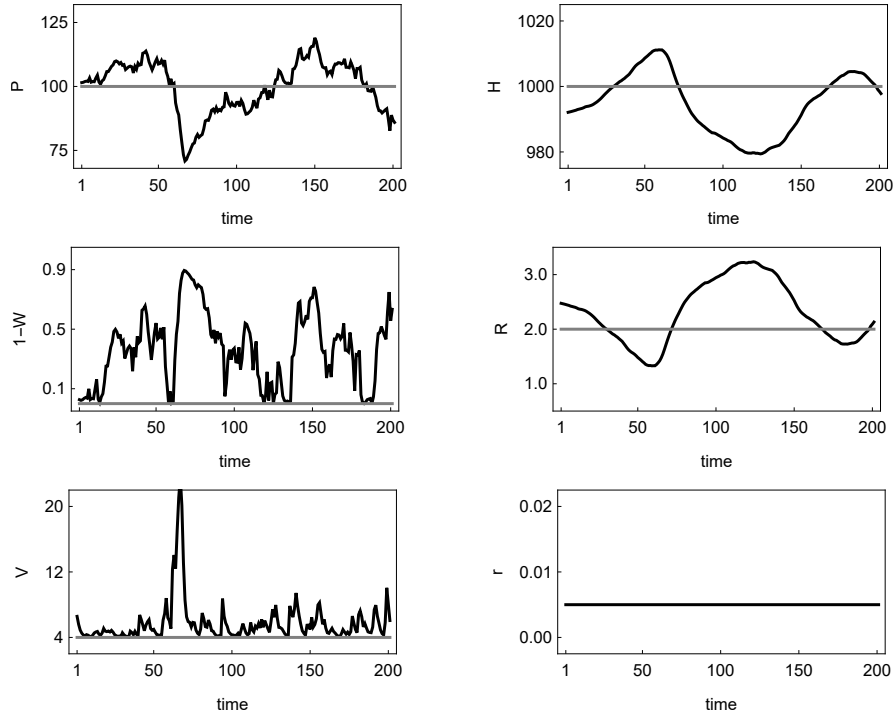
Figure 2: The functioning of the model with constant variance beliefs and a constant interest rate. The panels show, from top left to bottom right, the evolution of house prices, the housing stock, the market share of regressive expectations, the rent level, investors' variance beliefs, and the interest rate, respectively. Base parameter setting, except that $\kappa = 0$ and $\rho = 0$.

house prices experience brief moments of extreme variance that interrupt longer periods of lower variance. Note that our model with endogenous variance beliefs can replicate this empirical property.

In Figure 4, we examine the dynamics of the housing market with endogenous variance beliefs and with a constant, yet high interest rate. As can be seen, an increase in the base (target) interest rate has a weakly stabilizing effect on the housing market, since both house prices and the housing stock, as well as the rent level, fluctuate slightly closer around their fundamental values. To be able to visualize these weak effects, here we set the base (target) interest rate to $r_0 = 0.04$, i.e. we increase the annual interest rate from 2% (Figure 3) to 16% (Figure 4). In line with Himmelberg et al. (2005), the fundamental values of house prices and the housing stock decrease to $P^* = 94.66$ and $H^* = 946.57$, respectively, and the fundamental value of the rent level increases to
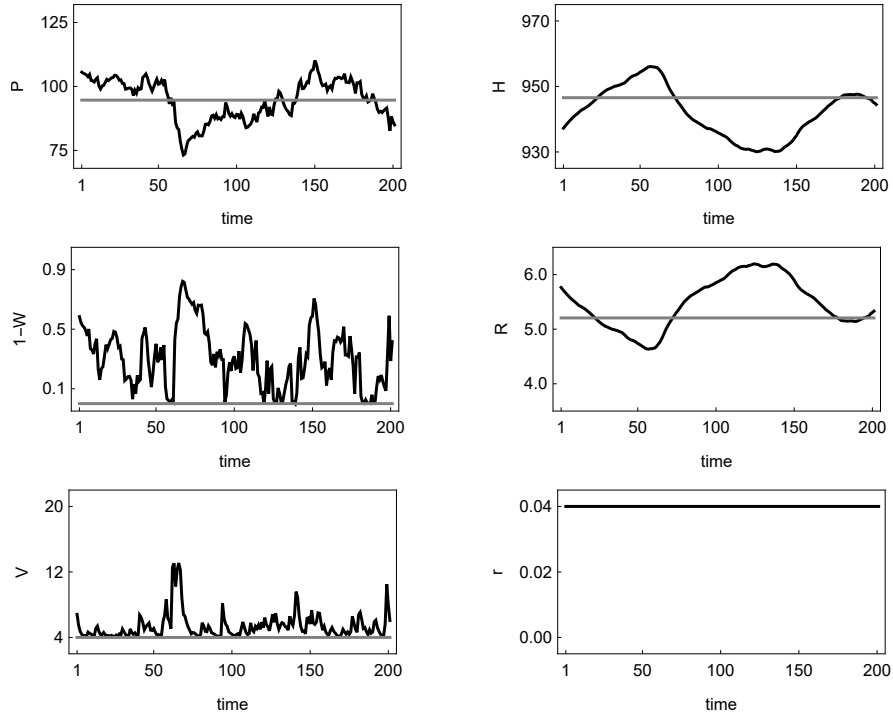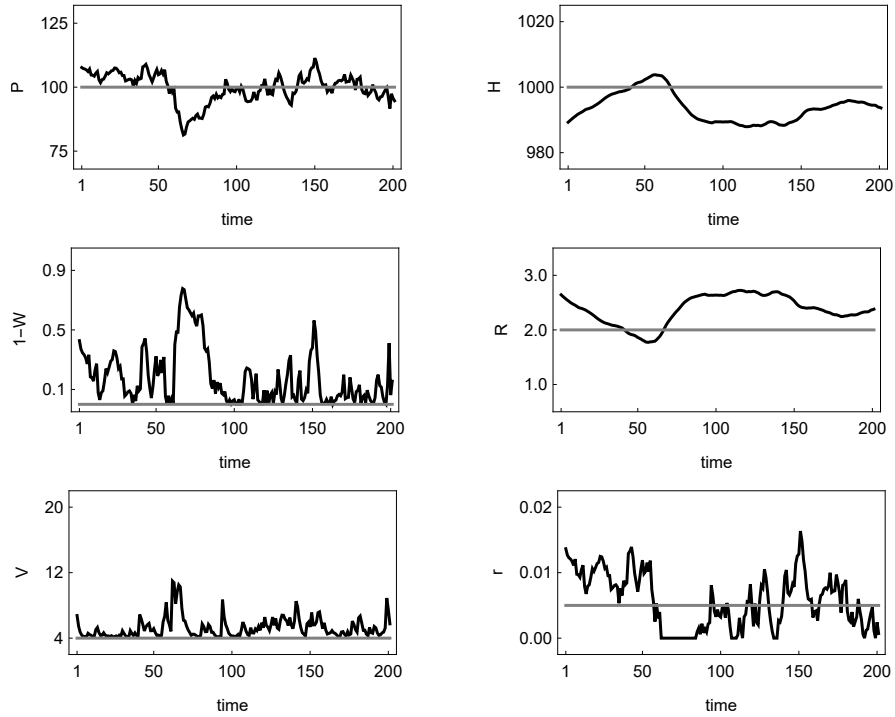
Figure 3: The functioning of the model with endogenous variance beliefs and a constant interest rate. The panels show, from top left to bottom right, the evolution of house prices, the housing stock, the market share of regressive expectations, the rent level, investors' variance beliefs, and the interest rate, respectively. Base parameter setting, except that $\rho = 0$.

$R^* = 5.21$ (the scaling of H, R and r has been adjusted accordingly). Since a higher interest rate increases the opportunity cost of buying a house, housing demand becomes depressed, pushing house prices down. As a result, housing construction and thus the housing stock decrease, resulting in higher rent levels. While the higher interest rate may slightly stabilize the dynamics of the housing market, decreased house prices and housing stock may result in undesirable consequences that may not be justified by marginally more stable markets.[11]

Finally, we investigate the complete model with endogenous variance beliefs and

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[11]The drop in house prices and the housing stock may have negative effects on wealth, income and financial markets. Since there is a positive relationship between housing wealth and consumption, households may spend less than usual when house prices fall. Furthermore, the decline in aggregate expenditure may cause a reduction in income and employment, i.e. a negative income effect. Since the drop in house prices also reduces the construction of new houses, the construction industry faces a decline in demand and experiences a direct loss of income.

Figure 4: The functioning of the model with endogenous variance beliefs and a constant, yet high interest rate. The panels show, from top left to bottom right, the evolution of house prices, the housing stock, the market share of regressive expectations, the rent level, investors' variance beliefs, and the interest rate, respectively. Base parameter setting, except that $r_0 = 0.04$ and $\rho = 0$.

interest rates. Figure 5 reveals that the dynamic part of the interest rate rule manages to stabilize housing markets. On average, we observe a decrease in house price distortion, i.e. a decrease in the average distance between house prices and the fundamental value, and, hence, a more efficient housing market. Since house prices fluctuate significantly closer around their fundamental value, no strong bubbles or crashes occur. The same can be observed for the housing stock and the rent level, both of which move closer to their fundamental values. A further stabilizing effect of the interest rate rule is that investors' variance beliefs are less extreme. This can be explained as follows. In boom periods, i.e. if $P_t > P^*$, the interest rate is relatively high, leading to a decline in housing demand. This causes house prices to fall. But since the drop in house prices is less extreme, investors' variance beliefs, and thus their demand, remain more balanced. Moreover, new housing construction, the housing supply and the rent level also benefit

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from more stable house prices. This becomes apparent between periods $t = 1$ and $t = 50$. In the other case, if $P_t < P^*$, the interest rate decreases, which can be observed between periods $t = 50$ and $t = 100$. As housing demand increases, so do house prices. Note that the interest rate fluctuates mainly between 0 and 0.01, which seems to be reasonable. Furthermore, the stability condition is still violated, i.e. the deterministic model still produces endogenous cycles, albeit with a much lower amplitude.

Figure 5: The functioning of the model with endogenous variance beliefs and endogenous interest rates. The panels show, from top left to bottom right, the evolution of house prices, the housing stock, the market share of regressive expectations, the rent level, investors' variance beliefs, and the interest rate, respectively. Base parameter setting.

5.2. Endogenous interest rate adjustments

In this section, we discuss in more detail how the endogenous component of the central bank's interest rate rule may affect the dynamics of the housing market.

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5.2.1. The Neimark-Sacker bifurcation scenario

In Figure 6, we use bifurcation diagrams to relate the house price to the extrapolative parameter χ in the Neimark-Sacker scenario. The parameter setting is as in Table 1, except that $\kappa = 0$, $\rho = 0$, $\sigma = 0$ in the top left panel, $\rho = 0$, $\sigma = 0$ in the top right panel, $\kappa = 0$, $\sigma = 0$ in the center left panel, $\sigma = 0$ in the center right panel and $\kappa = 0$ in the bottom left panel. The top panels of Figure 6 reveal that the stronger investors' extrapolation is, the larger the amplitude of house price fluctuations. Furthermore, the bifurcation route evolves from a stable steady state to quasi-periodic dynamics as χ increases from 0 to 0.4. To be more precise, for small values of χ, the model's fundamental steady state is stable, but becomes unstable when the extrapolative parameter exceeds $\chi = 0.015$, as predicted by our analytical results. To explore the effect of endogenous variance beliefs, we repeat our simulations from the top left panel in the top right panel, but now with the base setting $\kappa = 0.25$. The corresponding bifurcation route shows that the amplitude of house price swings is biased downwards for high values of parameter χ, an outcome which is due to the crashes induced by variance beliefs.

The stabilizing impact of an endogenous interest rate on house price swings is shown in the two center panels. As can be seen, the amplitude of house price fluctuations can be significantly reduced in both cases, with constant and endogenous variance beliefs. Moreover, the housing market remains stable for larger values of χ, namely up to about $\chi = 0.15$. Again, this observation is in line with our analytical results. Thus the central bank's dynamic interest rate rule has a significant stabilizing effect on the housing market's dynamics by reducing instability, which arises from the Neimark-Sacker bifurcation. The two bottom panels repeat our simulations in a noisy environment. As it turns out, the distorting effect of endogenous variance beliefs is robust with respect to additional exogenous noise – at least with a view to the amplitude of price fluctuations.

Figure 7 illustrates how the dynamics change with respect to the central bank's reaction parameter ρ. The extrapolative parameter in the top left panel is set to $\chi = 0.4$, i.e. investors extrapolate house prices quite strongly. Note that if the central bank reacts more aggressively to mispricing in the housing market, the amplitude of house price fluctuations decreases. Moreover, a convergence to the steady state sets in when ρ exceeds 0.385. In the center left panel, we repeat these simulations for the base setting,
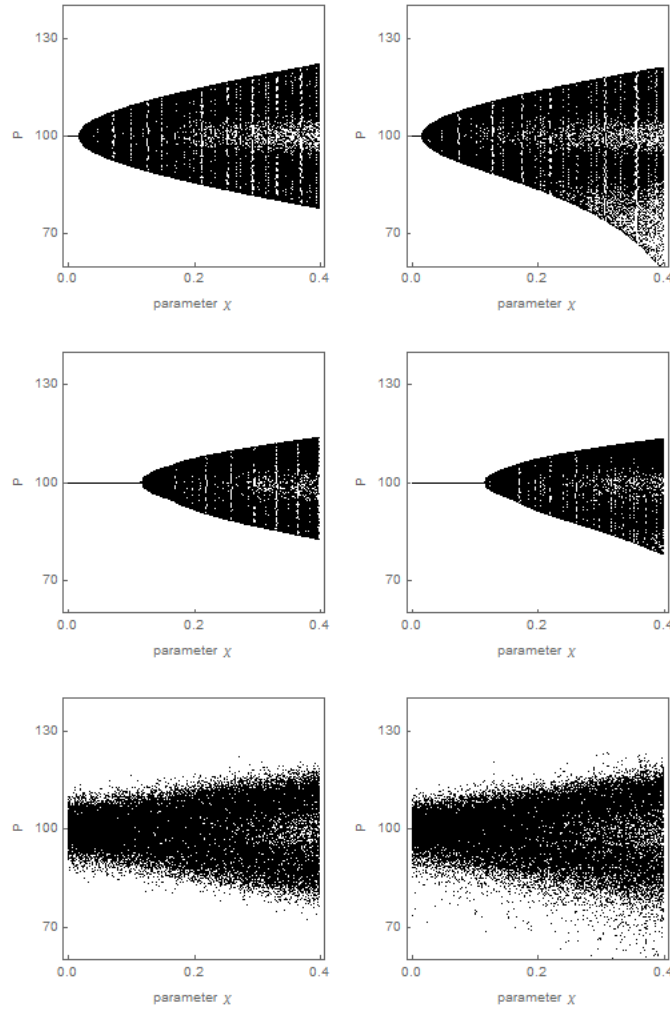
Figure 6: The destabilizing effect of extrapolative expectations in the Neimark-Sacker scenario. The panels show bifurcation diagrams for the house price versus extrapolative parameter χ. Base parameter setting, except that $\kappa = 0$, $\rho = 0$, $\sigma = 0$ (top left), $\rho = 0$, $\sigma = 0$ (top right), $\kappa = 0$, $\sigma = 0$ (center left), $\sigma = 0$ (center right), $\kappa = 0$ (bottom left). Moreover, parameter χ is varied between 0 and 0.4.

and again observe a stabilizing effect: the steady state is reached for a lower value of the central bank's reaction parameter, namely for $\rho = 0.13$. In addition, house price fluctuations are significantly more dampened for increasing values of ρ. According to the top right and the center right panel, the stabilizing effect of an increasing parameter ρ holds with respect to exogenous noise, which, in turn, is further supported by the two bottom panels in which we compute the distortion of a housing market as the average

relative distance between the house price and its fundamental value. Note that both the distortion for $\chi = 0.4$ (bottom left panel) and the distortion for $\chi = 0.15$ (bottom right panel) decrease strongly as parameter ρ increases from 0 to 0.5.
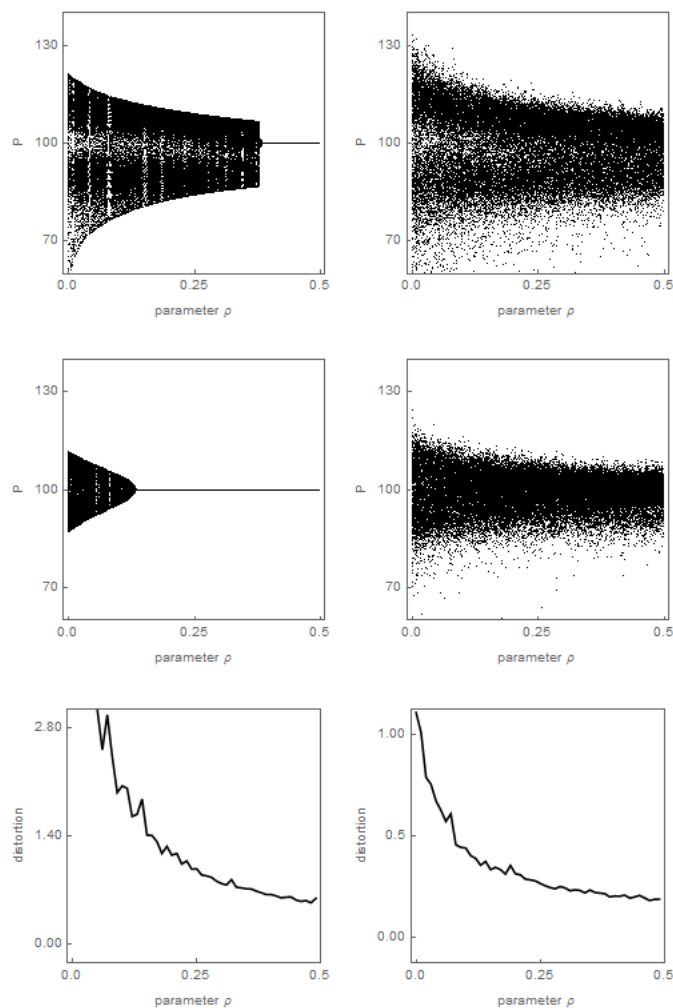
Figure 7: The stabilizing effect of the endogenous part of the interest rate rule in the Neimark-Sacker bifurcation scenario. The first four panels show bifurcation diagrams for the house price versus the central bank's reaction parameter ρ. The bottom two panels show the distortion of the housing market versus the central bank's reaction parameter ρ. Base parameter setting, except that $\chi = 0.4$, $\sigma = 0$ (top left), $\chi = 0.4$ (top right), $\sigma = 0$ (center left), $\chi = 0.4$ (bottom left).

5.2.2. The Pitchfork bifurcation scenario

In Figure 8, we analyze the Pitchfork bifurcation scenario. The panels show how extrapolative expectations (top panels) and the endogenous part of the interest rate rule (center and bottom panels) affect the dynamics of our model. Recall that the Pitchfork bifurcation scenario occurs if the housing supply is relatively sluggish. It becomes apparent from the top left panel (base parameter setting, except that $\sigma = 0$, $\beta = 0.0005$ and $\rho = 0$) that if investors use the extrapolative expectation rule too strongly, the steady state becomes unstable and two locally stable nonfundamental steady states emerge, surrounding the unstable fundamental steady state. The housing market then remains permanently overvalued (red line) or undervalued (blue line). Furthermore, mispricing in the housing market increases with the extrapolative parameter χ. The bifurcation route in the top right panel (base parameter setting, except that $\sigma = 0$ and $\beta = 0.0005$) shows that an endogenous interest rate causes the bifurcation to occur for a higher value of the extrapolative parameter, namely for $\chi = 0.128$ instead of $\chi = 0.028$, as can be verified analytically. A comparison of the two top panels also reveals that mispricing in the housing market is – for a given value of χ – lower if the central bank dynamically adjusts the interest rate.

To illustrate these results in more detail, we present three bifurcation diagrams in which we vary the central bank's reaction parameter ρ between 0 and 0.5. In the center left panel (base parameter setting, except that $\sigma = 0$, $\beta = 0.0005$ and $\chi = 0.4$), investors strongly extrapolate prices, and the corresponding bifurcation route undoubtedly reveals that mispricing in the housing market decreases with ρ. As depicted in the center right panel (base parameter setting, except that $\sigma = 1$, $\beta = 0.0005$ and $\chi = 0.4$), this result is robust with respect to noise, but we observe attractor switching (for more details, see Figure 9). This attractor switching occurs more frequently with higher noise, which is illustrated in the bottom left panel (base parameter setting, except that $\sigma = 5$, $\beta = 0.0005$ and $\chi = 0.4$). Here again, the amplitude of house price fluctuations decreases as ρ increases. Further evidence of this result is provided by the bottom right panel (base parameter setting, except that $\sigma = 5$, $\beta = 0.0005$ and $\chi = 0.4$), which reveals that distortion decreases with ρ. Thus, the central bank's dynamic interest rate setting is an effective instrument for preventing the appearance of nonfundamental steady states.
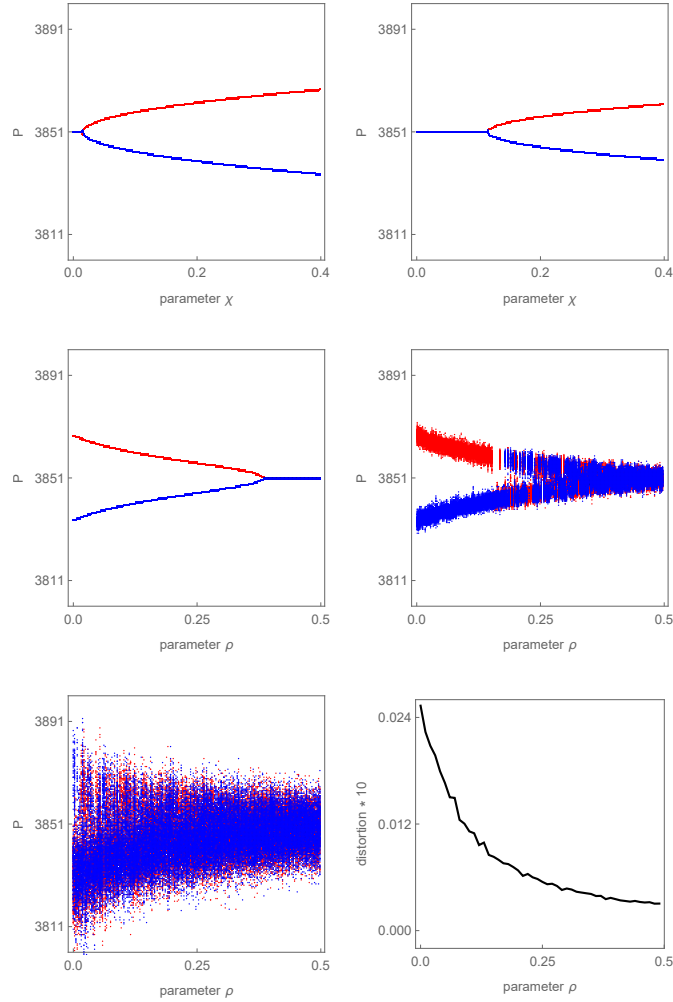
Figure 8: The destabilizing (stabilizing) effect of extrapolative expectations versus the endogenous part of the interest rate rule. The top left panel shows a bifurcation diagram for the house price versus the extrapolative parameter χ for the base parameter setting, except that $\sigma = 0$, $\beta = 0.0005$ and $\rho = 0$. The top right panel shows the scenario, except that $\sigma = 0$ and $\beta = 0.0005$. The center left panel shows a bifurcation diagram for the house price versus the endogenous part of the interest rate ρ for the base parameter setting, except that $\sigma = 0$, $\beta = 0.0005$ and $\chi = 0.4$. The center right panel shows the scenario, except that $\sigma = 1$, $\beta = 0.0005$ and $\chi = 0.4$. The bottom left panel shows the scenario, except that $\sigma = 5$, $\beta = 0.0005$ and $\chi = 0.4$. The bottom right panel shows the scenario, except that $\sigma = 5$, $\beta = 0.0005$ and $\chi = 0.4$.

In Figure 9, we analyze coexisting attractors and basins of attraction in the Pitchfork bifurcation scenario in more detail. The top left panel (base parameter setting, except

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that $\beta = 0.0005$, $\sigma = 1$ and $\rho = 0$) shows a time series for constant interest rates. As can be seen, house price P_t fluctuates around the lower nonfundamental steady state (blue line), and hence the average price is below P^* (gray line). An increase in ρ from 0 to 0.13 brings the nonfundamental steady states closer towards P^*, as depicted in the bottom left panel. As a result, we may observe attractor switching and thus a price correction towards the fundamental price P^*, which is in accordance with the center right panel of Figure 8. The corresponding change in the basins of attraction is visualized in the right panels of Figure 9. In fact, compared to the top right panel (with $\rho = 0$), the basin of the upper nonfundamental steady state (red area) becomes smaller and the basin of the lower nonfundamental steady state (blue area) becomes larger due to the introduction of an endogenous interest rate. In the bottom right panel, however, nonfundamental steady states (red and blue dot) are closer to the borders of their basins of attraction, which explains attractor switching (a nontrivial effect of ρ).

Coexisting attractors may have interesting policy implications. Suppose that the price has converged towards the model's lower nonfundamental steady state in a constant interest rate environment. As long as exogenous shocks are not too large, the system does not leave the steady state's basin of attraction (blue area), and endogenous forces drive the price back towards its equilibrium value. While endogenous interest rates cause the blue area to increase, nonfundamental steady states move closer to the boundary of their basins of attraction. Policymakers may thus have the opportunity to drive back nonfundamental steady states towards P^* by increasing ρ, reducing mispricing in the housing market.

5.2.3. The Flip bifurcation scenario

Figure 10 illustrates how extrapolative expectations (top panels) and an endogenous interest rate (center and bottom panels) affect the dynamics of our model in the Flip bifurcation scenario. The left (right) panels show the dynamics of house prices (interest rates). As can be seen in the top panels (parameter setting, except that $\sigma = 0$ and $\rho = 2.5$), the Flip bifurcation value is $\chi = 0.4915$, hence this extrapolative strength is needed to ensure housing market stability. For $\chi < 0.4915$, the steady state is unstable and the system tends to explode until interest rates hit the zero lower bound at which the map becomes piecewise defined (Avrutin et al. 2019). The destabilizing impact
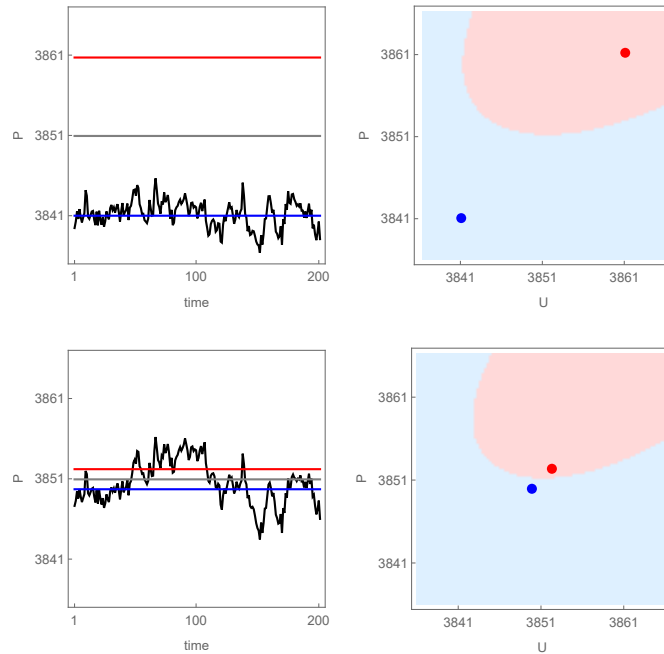
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Figure 9: Coexisting attractors and basins of attraction in the Pitchfork bifurcation scenario. The top left panel shows a simulation run of house prices for the base parameter setting, except that $\beta = 0.0005$, $\sigma = 1$ and $\rho = 0$. The nonfundamental and fundamental steady states are given in red, blue and gray. The bottom left panel shows the same for $\rho = 0.13$. The right panels visualize the corresponding basins of attraction for initial conditions of P and H, abstracting from exogenous noise.

of endogenous interest rates is depicted in the second line of panels (base parameter setting, except that $\sigma = 0$ and $\chi = 0.01$. If the central bank reacts very aggressively to mispricing in the housing market (from a value of $\chi = 0.01$), the steady state becomes unstable, and chaotic dynamics emerges. This finding also holds in a noisy environment, as is witnessed in the bottom left panel (base parameter setting, except that $\sigma = 0.2$ and $\chi = 0.01$). The corresponding distortion (bottom right panel) further supports our findings. Clearly, the distortion increases with ρ.

5.3. Exogenous interest rate adjustments

Finally, we investigate the extent to which the autonomous part of the interest rate rule is able to tame housing markets in the Neimark-Sacker bifurcation scenario. The left (right) panels of Figure 11 rely on our base parameter setting, except that $\chi = 0.014$ and $\sigma = 0$ ($\sigma = 0$). In the top left (center left) panel of Figure 11, we increase (decrease) the

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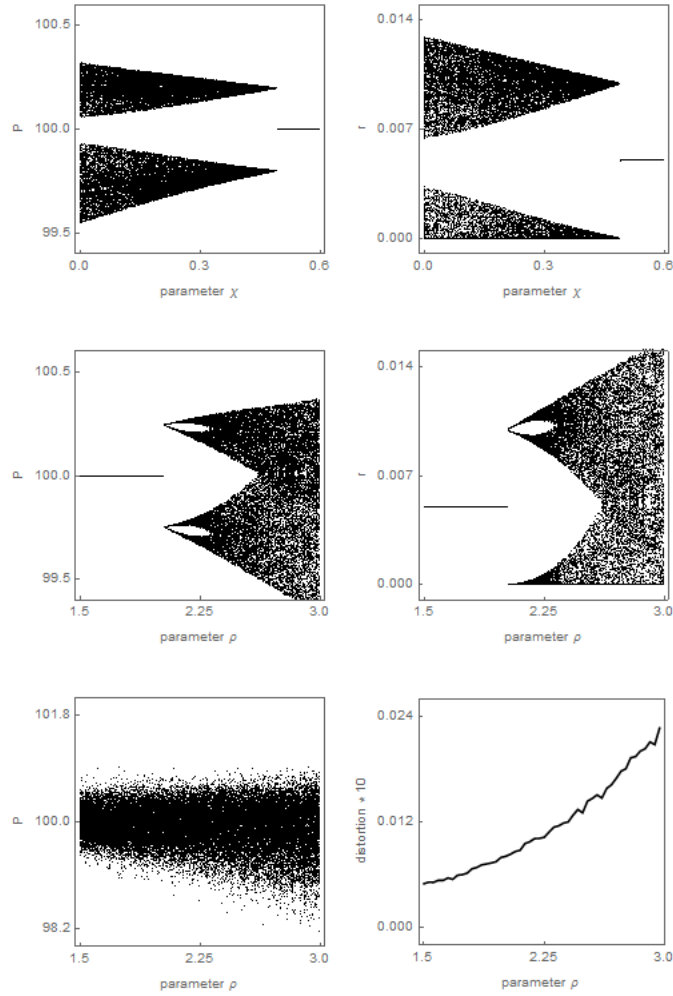
Figure 10: The stabilizing (destabilizing) effect of extrapolative expectation (endogenous interest rates) in the Flip bifurcation scenario. The first line of the panels shows bifurcation diagrams for house prices and the interest rate versus parameter χ for the base parameter setting, except that $\sigma = 0$ and $\rho = 2.5$. The second line of the panels shows bifurcation diagrams for house prices and the interest rate versus parameter ρ for the base parameter setting, except that $\sigma = 0$ and $\chi = 0.01$. The third line of the panels shows bifurcation diagrams for house prices and distortion versus parameter ρ, except that $\sigma = 0.2$ and $\chi = 0.01$.

base (target) interest rate r_0 in period 100 from 0.005 to 0.010 (0.0005). Before $t = 100$, the house price is equal to the fundamental steady state. The increase in r_0 in $t = 100$ makes the system more stable, but creates an adjustment process with strong house price fluctuations towards a lower steady-state house price level. While our main focus is on

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endogenous housing dynamics, the relevance of temporary housing dynamics should not be underestimated. For instance, Glaeser and Nathanson (2017) discuss in detail how exogenous shocks may cause temporary fluctuations in a housing market model in which agents form extrapolative expectations. Moreover, Taylor (2009) argues that the Fed's strong interest rate adjustments between 2001 and 2006 have greatly contributed to the instability of the U.S. housing market. Note that a decrease in r_0 can create permanent house price oscillations around an increased steady-state price level. We may observe similar effects of the increase (decrease) in the interest rate in period 500 from 0.005 to 0.05 (0) in the top right (center right) panel. While an increase in r_0 leads to smaller amplitudes of house price fluctuations around a lower steady-state level, a decrease in r_0 enlarges the amplitude of house price oscillations. Further evidence of these results is provided by the bottom panels, which show the model dynamics for increasing r_0. It can be seen that, with increasing base (target) interest rates, the amplitude of house price fluctuations becomes smaller up to the bifurcation value $r_0 = 0.00393$ (bottom left panel) and $r_0 = 0.13925$ (bottom right panel), respectively. At this point, the quasi-periodic dynamics segues into a stable fundamental steady state. However, the fundamental house price P^* decreases with parameter r_0, which may have further unfavorable effects. All in all, the central bank's ability to reduce the dynamics on housing markets by increasing the base (target) interest rate, weakening the demand pressure on house prices, is rather limited.

6. Conclusions

Shiller (2015), Glaeser (2013) and Piazzesi and Schneider (2016) demonstrate that, while the U.S. housing market bubble between 1998 and 2012 may seem extreme, it was hardly unique. In fact, history is replete with dramatic housing market instabilities that have had dire economic consequences. Unfortunately, the economics of housing market bubbles is still in its infancy. According to Glaeser and Nathanson (2015), many important questions remain unresolved, e.g. why did the U.S. boom-bust cycle occur and what are its policy implications? The goal of our paper is to shed light on the intricate relationship between house prices, expectations and interest rates, also keeping in mind the supply side of the housing market.
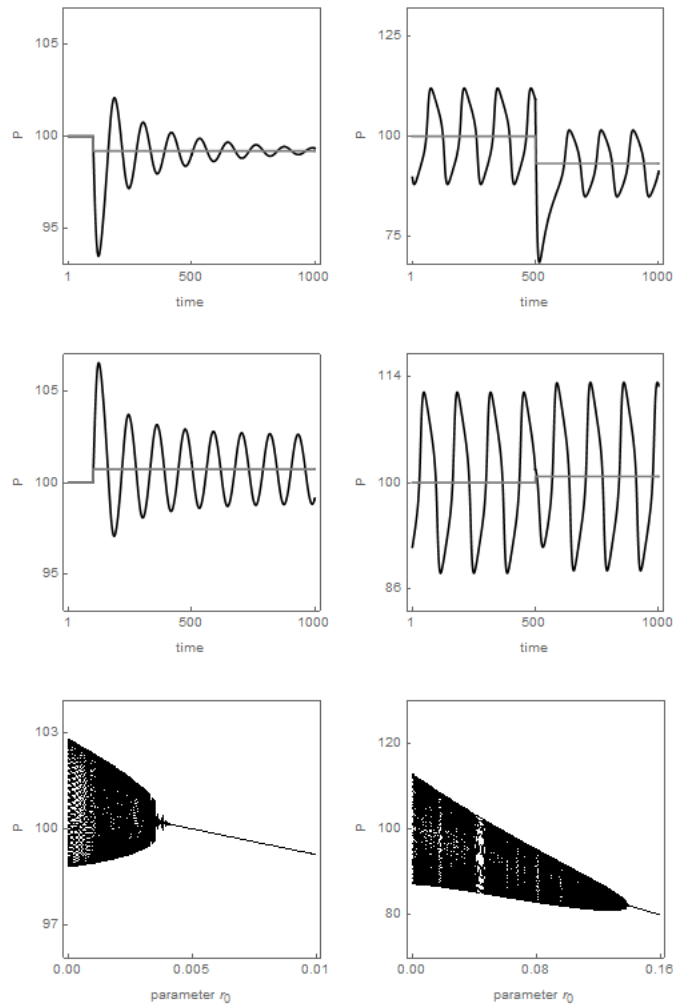
Figure 11: Some effects of the autonomous part of the interest rate rule in the Neimark-Sacker bifurcation scenario. The left panels rely on the base parameter setting except that $\chi = 0.014$ and $\sigma = 0$. Moreover, in the top left (center left) panel, the interest rate increases (decreases) in period 100 from 0.005 to 0.010 (to 0.0005). The right panels rely on the base parameter setting, except that $\sigma = 0$. In addition, in the top right (center right) panel, the interest rate increases (decreases) in period 100 from 0.005 to 0.050 (to 0).

For this reason, we generalize the behavioral stock-flow housing market model by Dieci and Westerhoff (2016). Our analysis reveals that interactions between investors' expectations, their variance beliefs and the supply side of housing markets may give rise to substantial boom-bust dynamics. Since the setup of our model is able to explain a number of stylized facts of housing market dynamics, including short-run momen-

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tum, long-run mean reversion and excess volatility, it seems ideally suited for exploring whether the central bank may stabilize the housing market via interest rates. Using a mix of analytical and numerical tools, we find that the central bank has only a limited ability to tame housing markets by increasing the base (target) interest rate. Moreover, any change in the base (target) interest rate causes at least temporary housing market fluctuations. However, we are also able to show that a leaning-against-the-wind interest rate rule, which adjusts the interest rate with a view to mispricing in the housing market, can significantly improve the stability of housing markets. Within our model, and in line with empirical evidence (Case and Shiller 2003 and Case et al. 2012), housing market bubbles are driven by investors' optimistic expectations, an aspect that greatly destabilizes the demand for housing. An interest rate policy that counters these demand fluctuations may effectively stabilize housing markets.

We hope that our paper fosters our understanding of the functioning of housing markets and enables us to design better tools that reduce damage arising from bursting bubbles. More work is undoubtedly needed in this important research direction.

Appendix

By following Chiarella et al. (2007, 2013), we can express the investors' speculative variance component as

$$V_t^S = mV_{t-1}^S + m(1-m)(P_t - U_{t-1})^2,$$

where

$$U_t = mU_{t-1} + (1-m)P_t.$$

Note that $0 < m < 1$ also represents a memory parameter. The higher m is, the higher the weight given to past prices. Considering this alternative learning rule yields the

following dynamical system

$$S : \begin{cases} P_t = \dfrac{E_t[P_{t+1}]+\alpha-(\beta+\lambda V_t[P_{t+1}])\gamma P_{t-1}-(\beta+\lambda V_t[P_{t+1}])(1-\delta)H_{t-1}}{1+r_0+\rho\left(\frac{P_{t-1}-P^*}{P^*}\right)+\delta} \\[2ex] H_t = \gamma P_{t-1} + (1-\delta)H_{t-1} \\[2ex] V_t^S = mV_{t-1}^S + m(1-m)(P_t - U_{t-1})^2 \\[2ex] U_t = mU_{t-1} + (1-m)P_t \end{cases} ,$$

where

$$E_t[P_{t+1}] = \frac{P_{t-1} + \chi(P_{t-1} - P^*) + P_{t-1}\eta(P^* - P_{t-1})^2 + \phi\eta(P^* - P_{t-1})^3}{1 + \eta(P^* - P_{t-1})^2}$$

and

$$V_t[P_{t+1}] = \Omega + \kappa V_{t-1}^S.$$

Straightforward computations reveal that the fundamental steady state is also given by $FSS = \left(P^*, H^*, V^{S*}, U^*\right) = \left(P^*, \frac{\gamma}{\delta}P^*, 0, P^*\right)$, where $P^* = \frac{\alpha\delta}{(r_0+\delta)\delta+(\beta+\lambda\Omega)\gamma}$. The Jacobian can be written as

$$J(FSS) = \begin{pmatrix} \frac{1-\rho+\chi-\gamma(\beta+\lambda\Omega)}{1+\delta+r_0} & \frac{(\delta-1)(\beta+\lambda\Omega)}{1+\delta+r_0} & -\frac{\alpha\gamma\kappa\lambda}{(1+\delta+r_0)(\delta(\delta+r_0)+\gamma(\beta+\lambda\Omega))} & 0 \\[2ex] \gamma & 1-\delta & 0 & 0 \\[2ex] 0 & 0 & m & 0 \\[2ex] \frac{(m-1)(\beta\gamma+\rho-\chi-1+\gamma\lambda\Omega)}{1+\delta+r_0} & -\frac{(\delta-1)(m-1)(\beta+\lambda\Omega)}{1+\delta+r_0} & \frac{(m-1)\alpha\gamma\kappa\lambda}{(1+\delta+r_0)(\delta(\delta+r_0)+\gamma(\beta+\lambda\Omega))} & m \end{pmatrix},$$

revealing that two eigenvalues are given by $z_{1/2} = m$. Since $0 < m < 1$, the local stability of the fundamental steady state only depends on the two eigenvalues of the remaining 2-D block

$$Q = \begin{pmatrix} \frac{1-\rho+\chi-\gamma(\beta+\lambda\Omega)}{1+\delta+r_0} & \frac{(\delta-1)(\beta+\lambda\Omega)}{1+\delta+r_0} \\[2ex] \gamma & 1-\delta \end{pmatrix}.$$

As it is the same 2-D block as in the other case, we have the same stability conditions for $|z_{3,4}| < 1$.

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