Agent-based macroeconomics: A baseline model☆

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A B S T R A C T

This paper develops a baseline agent-based macroeconomic model and contrasts it with the common dynamic stochastic general equilibrium approach. Although simple, the model can reproduce a lot of the stylized facts of business cycles. The author argues that agent-based modeling is an adequate response to the recently expressed criticism of macroeconomic methodology because it allows for aggregate behavior that is more than simply a replication of microeconomic optimization decisions in equilibrium. At the same time it allows for absolutely consistent microfoundations, including the structure and properties of markets. Most importantly, it does not depend on equilibrium assumptions or fictitious auctioneers and does therefore not rule out coordination failures, instability and crisis by definition. A situation that is very close to a general equilibrium can instead be shown to result endogenously from non-rational micro interaction.

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1. Introduction

The debate on the methodological foundations of macroeconomic theory has gained new momentum during the recent worldwide economic crisis. One of the main building blocks that many scholars are unsatisfied with is the way microfoundation is provided. The quest for microfoundation has originally been motivated by the desire of grounding macroeconomics in the economic behavior of individual economic entities (Janssen, 2008). In most macroeconomic models, however, microfoundation is either obtained by setting the aggregate equal to a "representative" individual or by summing up over all individual decisions and confronting these sums on an aggregate level (the market). As a result, phenomena of the macro level are directly linked to individual behavior. Economists consider this a way to provide proper microfoundation although it is well known from a bunch of other disciplines that large systems composed of interacting units show aggregate behavior that cannot be directly inferred from micro behavior. In such systems stable phenomena or relationships can occur on the macro level that can impossibly be deduced directly from micro decisions. These phenomena have come to be called "emergent" in the literature (Epstein, 1999; Axtell, 2007) since they are endogenously emerging from micro interactions instead of being assumed on the micro level from the outset and then simply set equal (or summed up) to the macro level.[1]

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1 For a criticism of this way of microfoundation consult Kirman (1992, 2010), Gallegati et al. (2006), Colander et al. (2009), Delli Gatti et al. (2010).

The most famous example of emergent phenomena is the degree of racial segregation in cities. Schelling (1969) showed that even a small preference of individuals for living in a neighborhood that is dominated by other individuals of the same "color" can lead to total segregation on the macro level if interaction is taken into account. Therefore the aggregate shows a different (amplified in this case) behavior from that of the individuals. Other interesting examples can be found in traffic flow analysis. It has been puzzling to scientists that from time to time traffic jams occur seemingly without any causation.[2] Today it is known that such "phantom traffic jams" emerge out of the complex interaction of individual car drivers. They can easily be explained in models that take such interaction into account.[3] Another interesting property of traffic jams is the cyclical recurrence of stopping and driving phases[4] that each individual car driver typically experiences. This behavior can obviously not be reduced to individual car drivers in isolation and has to be explained by interaction (braking, accelerating and lane changing in this case).[5] Since the macroeconomy is obviously composed of interacting individuals it is natural to expect that it is also characterized by emergent phenomena. As a result macroeconomics cannot be reduced directly to the "fundamental parameters" of taste and technology and its methods should be able to allow for such phenomena. Unfortunately the dominant methods employed in mainstream macroeconomics don't.

Another critique aims at the equilibrium assumption. Mainstream economics is mainly concerned with situations that create no incentives for further change, i.e. equilibria (Arthur, 2006). As a justification for this practice it is often asserted, that an economy that is kicked out of equilibrium returns to that state quickly because of some adjustment processes (Kirman, 2010). It has often been shown, however, that under general conditions such adjustment processes do not exist and that general equilibria are neither unique nor stable (Ackerman, 2002; Kirman, 2006; Gaffeo et al., 2008). Assuming that markets are characterized by equilibria is therefore nothing more than a doubtable assumption. Real markets might be characterized by multiple equilibria, coordination problems, instability, perpetual novelty or even chaos (Arthur, 2006). Instead of assuming equilibria from the outset it should be shown that it is an emergent phenomenon of market economies.

A third line of criticism argues that the way dynamics are introduced into macroeconomic models is flawed. Since the general equilibrium is a property that holds in every single time step, the adjustment of prices toward the equilibrium price vector has to occur in meta time. The Walrasian auctioneer calculates and sets equilibrium prices before transactions take place. But real economies work the other way round. The market mechanism itself is needed to discover equilibrium. Price formation therefore has to be a result of transactions and not its precondition (Kirman, 2006; Gaffeo et al., 2007, 2008). Time in such models has therefore no role other than dating commodities. If the Walrasian auctioneer – a clearly fictitious assumption – is removed, prices cannot adjust anymore and transactions cannot take place. All dynamics would ultimately break down (Gaffeo et al., 2008) Questions like "who actually sets prices?" and "how is information processed and reveled by the market mechanism?" have to be addressed by macroeconomists in order to develop realistic models.

Another problem is the extreme rationality that agents are typically endowed with. First, it is often argued nowadays that agents decisions have to be modeled according to behavioral rules rather than rational choice or utility optimization. Instead of being the result of a sterile optimization problem based on – so-called – "fundamental parameters", reciprocity, fairness, identity, money illusion, loss aversion, herding, and procrastination should be included when explaining individual decisions (Akerlof, 2002). Second, the insistence on rational expectations is extremely unrealistic. Economies are complex insofar as they are composed of billions of interrelating decisions and interactions. Forming rational expectations would require every agent to know how everybody else would react in every possible situation and to calculate the resulting mean time paths in advance. It is unlikely that real world human beings (mere mortals like you and I) are employed with such implausibly large information processing capabilities (Ackerman, 2002; Gaffeo et al., 2008; Fair, 2011; Kirman, 2010). The complexity property of economic systems suggests that they are characterized by aggregate, endogenous uncertainty that cannot be expected rationally (Delli Gatti et al., 2010). Behaving according to simple, adaptive heuristics if "true dynamics" are uncomputable is therefore not irrational. It can instead be understood as the most rational way of dealing with an overwhelmingly complex world (Axtell (2007) and De Grauwe (2011)).

The assumptions of the *holy trinity of rationality, equilibrium and greed*[6] prohibits macroeconomists from recognizing the core of their discipline, namely the emergence of phenomena on the aggregate level as unintended and unplanned results of the interaction of individuals (Delli Gatti et al., 2010).

Some critics go even further and argue that the dominant methodological framework is not only false but even dangerous (Colander et al., 2009; Kirman, 2010; Delli Gatti et al., 2010). By assuming that agents are able to *ex ante* coordinate perfectly to continuous general equilibrium we have become blind to crisis. Unfortunately, the analysis of endogenous crisis has been crowded out of the profession. As a result we have been left without any theoretical guidance during the recent financial collapse. To protect us from straying in the dark in times of our greatest needs, we have to build models that allow for the occurrence of crisis. Contemporary macro rules out market instability by assumption and equate crisis with the occurrence of events that are exogenous to the market (i.e. stochastic shocks).

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[2] At least with non that is visible on the macro level like a bottleneck situation (road works, accident) for example.

[3] Phantom traffic jams have first been described by Treiterer and Taylor (1966) and been explained by means of agent-based simulation in Treiterer and Myers (1974).

[4] See Zhang and Shen (2009). The analogy to the cyclical ups and down of the business cycle that is not intended by any individual is self-evident.

[5] A recent and easy to understand example can be found in Treiber et al. (2000).

[6] This expression is due to Robert Solow (see Delli Gatti et al. (2008, p. 11).

A method that seams well suited to respond to the raised criticism is agent-based computational economics (ACE).[7] ACE models can be understood as the simulation of artificial worlds that are populated by autonomous interacting agents. Every agent is equipped with properties describing his internal state and with behavioral rules that guide his interaction with others. Once created the artificial economy is left alone and agents interact according to the defined rules. Aggregate statistics like the price index or GDP can then easily be calculated. Instead of solving an equation system the model is simply run.

One strength of the ACE method is that no assumptions about the macro level are necessary. The passage from micro to macro is by interaction and not by assuming a representative individual or by summing up individual decisions and equilibrating aggregate supply and demand on *the* labor market, *the* goods market and so on. All observed regularities of the aggregate variables are therefore endogenously emerging from micro assumptions and micro interactions. The method can help to shift the focus from calculating an equilibrium and proving its stability and uniqueness to the coordination of large decentralized economic systems. For example, one interesting question that can be answered in this context is: "How can agents, that are not endowed with unrealistically high information processing capacities and are not even aware of their mutual existence, coordinate so well through the market mechanism, that the aggregate outcome is near a full employment equilibrium (at least during normal times)?"

The major weakness of ACE models is that the modeler is left with enormous degrees of freedom in choosing the types of agents, their behavioral rules and the structure of markets. Consequently the few ACE macro models that exist are very different in nature since they start with very different assumptions. Additionally it is easy to deal with enormous complexity. ACE modelers are thus tempted to over-increase the level of complexity in their models (i.e. add more types of agents, behavioral rules, special cases for a certain interaction, etc.). Mainstream modeling, in contrast, includes the solving of a mathematical problem which puts a natural upper bound on the possible level of complexity. In order to keep his model tractable a DSGE modeler has to be much more disciplined in choosing his assumptions. As a result, the available ACE macro models are not only very different in nature, they are often so complex that it is unclear which macro patter is a result of what micro property.

The aim of this paper is to take the most prominent ACE macro models and reduce them in complexity. Building such minimal models can be seen as a way to deal with the enormous degrees of freedom in a disciplined way. It also helps to reduce the black box character of models and to pin down the relationship between cause and effect more clearly. The presented model microfounds markets strictly in individual interaction and does not simply replace the central clearing mechanism (auctioneer) by a central matching or queuing mechanism. This paper thus provides a reasonable starting point for ACE modeling in macroeconomics by developing a minimal model that is able to reproduce some stylized facts of market economies, such as endogenous business cycles, a Phillips curve, a Beveridge curve, long run neutrality and short run non-neutrality of money.

The model is developed and compared to other ACE macro models in Section 2. Section 3 provides simulation results which prove that the model is capable of reproducing a number of empirical facts about business cycles. Section 4 analyzes the influence of monetary shocks, Section 5 shows that the model generates true complexity results while Section 6 demonstrates that the general equilibrium is a robust and endogenously emerging result of market economies. Section 7 concludes.

2. The model

ACE models divide into two categories.[8] The first tries to mimic real world economies in a highly detailed way. The largest and most complete agent-based model developed to date is the EURACE project that models the European economy.[9] Started in 2006 it is developed by a team of economists and computer scientists and runs on massively parallel computing clusters (Van der Hoog et al., 2008). While models of this category clearly allow for very deep insights, its huge complexity makes it difficult to isolate and explain the obtained results (Chan and Steiglitz, 2008). At the same time, the need for massive computational power and the high demand of computational skills generate practical problems for economists to replicate or advance models like EURACE. The second category consists of stylized models that abstract from real economies in a number of ways. They contain only a small number of different agent types and interaction rules. Such models can be programed more easily and run on ordinary desktop PCs.

The model presented in this paper belongs to the second category.[10] The most influential models of this category are those of Wright (2005), Russo et al. (2007), Dosi et al. (2008) and Gaffeo et al. (2008). Wright (2005) builds on the economic writings of Marx (1887). His model contains only two types of agents: workers and capitalists. His agents are of the "zero intelligence" type and act in a basically random fashion. As outlined above, the high rationality requirements on the individual level that are common in modern macroeconomics are not very realistic. On the other hand, since real human beings seem to employ at least some basic logic or heuristics when making economic decisions, the complete opposite (zero intelligence) seems not very satisfying either.

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[7] Some of the authors who argue for ACE in macroeconomics are Axtell (2007), Colander et al. (2008), Keen (2009), Kirman (2010), Delli Gatti et al. (2010)

[8] For another classification that consists of one more category consult Chan and Steiglitz (2008).

[9] The EURACE model is described among others in Cincotti et al. (2010) or Dawid et al. (2011).

[10] The model is programmed in Java. All source code is available upon request.
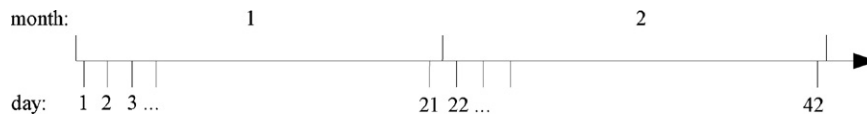
Fig. 1. Time scale as indexed by days and months.

The models of Dosi et al. (2008) and Gaffeo et al. (2008) (which is an extension of Russo et al. (2007)) consists of three different types of agents who employ simple behavioral rules that are either derived from survey studies or based on common-sensical reasoning. The approach seems very promising because its aggregate outcomes already show remarkable similarities to real world data. At the same time its assumptions about micro behavior are a reasonable compromise between full and zero rationality. The use of such simple adaptive rules has also proven to be very successful in the context of artificial ACE financial market models.[11]

The model presented in this paper follows Dosi et al. (2008) [D2008] and Gaffeo et al. (2008) [G2008] in a number of aspects. The main similarities are, first, that prices and wages are chosen according to simple adaptive rules. Second, no central market clearing mechanism is introduced, the economy is allowed to self-organize toward a spontaneous order. Third, households can only buy from a subset of all firms.

The most important differences are the following. Both D2008 and G2008 analyze growth as a result of R&D. The aim of this paper, instead, is to define a simpler minimal ACE model that is concerned with basic macroeconomic relations in a non-growth environment. It makes use of only two different types of agents: households and firms. Both, D2008 and G2008, distinguish between three types of agents.[12] The indexation of time in D2008 and G2008 is given by periods only, while in this paper, time is indexed by days and months to allow different actions to take place in different time intervals. The model at hand also follows the ACE methodology more rigorously: the agents's rules are depending on purely local knowledge and not on any aggregate statistic (like the price index or a minimum wage as in G2008). All transactions that occur in the model are explicitly taking place between individuals: there is always one particular agent being the buyer and one being the seller. In contrast, D2008 have parts of their transactions carried out at the aggregate level. Individual firms, for example, do not encounter demand from individual households but simply are assigned a fraction of the aggregate demand, which itself is a function of aggregate employment. The authors thus deviate from a purely ACE method because the aggregate is (at least partly) modeled directly and not emerging from individual interaction.[13]

2.1. Basic properties

In order to exclude growth, households and firms are fixed in number and infinitely lived. Households are index by $h = 1$, $2, \ldots, H$ and firms by $f = 1, 2, \ldots, F$. Production technology is also fixed. For now the model shall cover a pure market economy without a government or a central bank to generate only the generic properties of markets lacking any central policy maker. In reality, different goods are typically traded in different time intervals. This operation on different time horizons is a crucial feature of market economies and an important possible source of coordination problems.[14] Therefore we allow for such a distinction in our model from the outset, and define the fundamental time unit to represent days while 21 coherent days[15] are called month (Fig. 1). Consumption goods are bought daily while labor is bought monthly.

In G2008 the agents are characterized by loyalty to trading partners of former periods. The present model advances this feature by explicitly stating a network of relationships among agents (illustrated in Fig. 2). All transactions are performed between individual agents throughout this network. It is assumed that households are not able to buy from any firm. They only have trading relations with 7 different firms (type A connections) that are used for buying consumption goods. At the same time each household has a trading relation to the one firm for which he works (type B connection). An unemployed household does not have such a connection. Firms on the other hand are not limited in their number of trading connections. They can have an unlimited amount of both types of trading relations. It is also allowed that a type A and a type B connection exist between the same household–firm-pair, i.e. a household can buy goods from his employer. The aggregate of all agents is thus connected by a bipartite[16] network of trading relationships. In the short run this network is fixed, but over time, agents cut unsatisfying trading connections to create other more beneficial ones. Thus the network is allowed to change over the medium run.

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[11] For an introduction into ACE financial market modeling see, e.g. Samanidou et al. (2006), Hommes (2006) or LeBaron (2006). Outstanding examples of such models are Kirman (1993), Brock and Hommes (1998), and Lux and Marchesi (2000).

[12] D2008 distinguish between households and two types of firms: producers of capital and producers of consumption goods. The model of G2008 includes households, firms and banks.

[13] The intension of the authors of course was to show how investment decisions and R&D can lead to endogenous business cycles. Modeling this part in great detail almost automatically leads to the need of simplifying assumptions somewhere else.

[14] Consult De Vany (1996) for a very vivid description.

[15] Since economic action does take place on working days, we exclude holidays and weekends.

[16] The nodes of a bipartite network can be divided into two types. Each node is only connected to nodes of the opposite type.
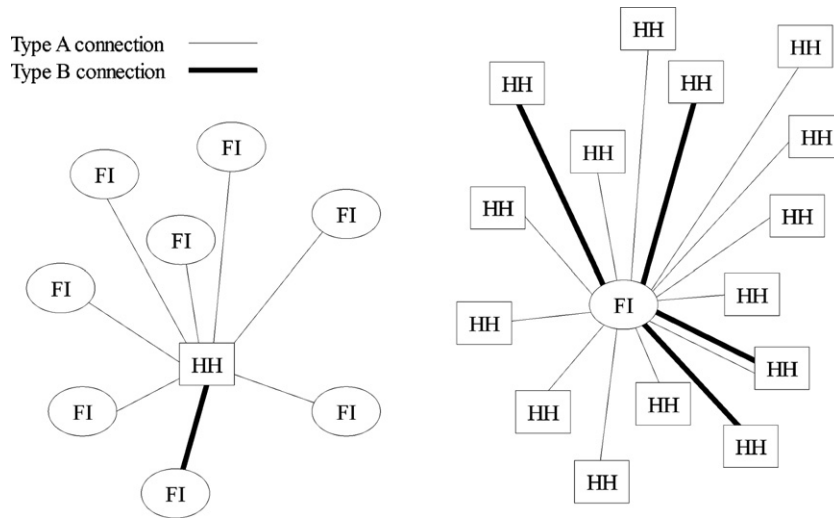
Fig. 2. Example of the trading relation structure of a household (left) and firm (right).

Each household has two properties: first, the reservation wage ω_h which defines a minimal claim on his labor income. In contrast to the typical use of reservation wages in economics, households might work for less than ω_h under specific circumstances (a detailed description follows below). Second, the liquidity m_h that determines the amount of monetary units the household currently possesses. It is changed, each time the household performs a transaction: if he buys a consumption good, m_h is decreased by the amount of the purchasing costs. If he receives income, m_h is increased by that amount. Thus at the beginning of day t his liquidity is given by:

$$m_{h,t} = m_{h,t-1} + \text{income}_{t-1} - \text{spendings}_{t-1} \tag{1}$$

$$= m_{h,t-k} + \sum_{i=1}^{k} \text{income}_{t-i} - \sum_{i=1}^{k} \text{spendings}_{t-i} \qquad k = 1, 2, \dots \tag{2}$$

Setting k equal to $t-1$, Eq. (2) states that current liquidity equals the sum of all past income minus the sum of all past spendings plus the initial endowment with liquidity $m_{h,1}$.

$$m_{h,t} = m_{h,1} + \sum_{i=1}^{t-1} \text{income}_{t-i} - \sum_{i=1}^{t-1} \text{spendings}_{t-i} \tag{3}$$

The liquidity property denotes the financial position of the household. By restricting it to positive values we can make sure that the household obeys the budget constraint, i.e. he can only spend if he has previously gained enough income.

$$m_{h,t} \geq 0 \quad \Leftrightarrow \quad m_{h,1} + \sum_{i=1}^{t-1} \text{income}_{t-i} \geq \sum_{i=1}^{t-1} \text{spendings}_{t-i} \tag{4}$$

Firms also have the liquidity property m_f, inventory i_f measuring the amount of produced consumption goods that are stored and ready to be sold, a goods price p_f and a wage rate w_f.[17] Following D2008 and G2008 we assume that every household inelastically supplies one unit of labor ($l_h = 1$). It is assumed, that households have limited knowledge. They only know the prices of those firms they have type A connections with and the wage rate of their employer. Prices and wages of other firms have to be uncovered by a search mechanism. Firms do not know prices or wages of any competitor. Thus all knowledge is purely local and the law of one price does not necessarily apply.

2.2. Beginning of a month

At the beginning of a month each firm has to decide on how to set its wage rate. This decision is based on past success or failure to find workers at the offered wage rate. The firm increases w_f if a free position was offered during the last month, but no worker was found to accept it. It is decreased if all positions have been filled with workers throughout the last γ

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[17] The subscripts h and f point out that all values are individual specific.

months. Following G2008, wage adjustment is performed by multiplying the current wage w_f^{old} with a growth rate μ that is idiosyncratic and drawn from a uniform distribution with support $[0, \delta]$:

$$w_f^{new} := w_f^{old} \cdot (1 \pm \mu) \qquad \mu \sim U_{\{0,\delta\}} \tag{5}$$

The decision whether the price or the number of employees should be changed is based on a comparison of the current level of inventories with the most recent demand. An upper and lower bar value for inventories is given by:

$$\overline{i_f} = \overline{\phi} \cdot d_f^{old} \tag{6}$$

$$\underline{i_f} = \underline{\phi} \cdot d_f^{old} \tag{7}$$

where d_f^{old} is the demand for consumption goods of the most recent month and the parameters satisfy $0 < \underline{\phi} < \overline{\phi}$. If the inventory has fallen below $\underline{i_f}$ a new open position is created in order to raise production. If, vice versa, inventories are above $\overline{i_f}$, a randomly chosen worker is fired, i.e. the corresponding type B connection is cut.[18] It is further assumed that hiring decisions lead to an immediate offering of a new position, while firing decisions are implemented with a lag of one month. This assumption reflects the fact, that most workers are protected against immediate firing by job protection laws.

Next the decision on changing the goods price has to be reached. It is assumed that a change of prices is only considered if the firm is confronted with an unsatisfying level of inventories. If current inventories are below the critical lower bound ($i_f < \underline{i_f}$) the firm considers to increase its price. In the opposite case of high inventories ($i_f > \overline{i_f}$) a decrease of p_f is considered.

Similar to the hiring/firing-decision critical upper and lower bar values for p_f are calculated. Prices are raised as long as they are not exceeding the upper bar value $\overline{p_f}$ and decreased as long as they are above a lower bar value $\underline{p_f}$. The critical upper and lower bar values for prices are given relative to marginal costs.

$$\overline{p_f} = \overline{\varphi} \cdot mc_f \tag{8}$$

$$\underline{p_f} = \underline{\varphi} \cdot mc_f \tag{9}$$

where the parameters satisfy $1 < \underline{\varphi} < \overline{\varphi}$. In analogy to the adjustment of w_f, prices are adjusted according to:[19]

$$p_f^{new} = p_f^{old} \cdot (1 \pm \nu) \qquad \nu \sim U_{\{0;\vartheta\}} \tag{10}$$

where the growth rate ν is again idiosyncratic and drawn from a uniform distribution with support $[0, \vartheta]$. Similar to Calvo (1983) firms set the newly determined price p_f^{new} only with a probability $\theta < 1$. The firms decisions are illustrated in Fig. 3.

After all firms have formed decisions in the described way, it is the households turn to search for more beneficial trading connections. Households are picked in a random order to seek for new network connections that are more beneficial than existing ones. First, with a probability of $\psi_{Price} < 1$ each household picks one randomly determined firm from the subset of all firms he has a type A connection with and one randomly determined firm from those he has no such connection with. The probability of picking the latter out of the set of all possible firms is proportional to the firm's size, measured in employees. If the price of the latter is at least $\xi \cdot 100$ percent lower than that of the former, the existing connection is removed and the new one is established. This procedure represents the search of households for cheaper places to buy.

The household might have been demand constrained during the last month, i.e. one or more of the firms he wanted to buy from were not able to satisfy his demand fully. If this is the case, the household randomly determines one of those firms with a probability proportional to the extend of the restriction. He cuts the type A connection to this firm and replaces it with a connection to a new one. This procedure represents the search for firms that are able to satisfy the demand fully. In analogy to the above search mechanism, this procedure is only executed with a probability of $\psi_{Quant} < 1$. Similar to D2008 the goods demand that one individual firm encounters, is therefore negatively correlated with its price and with its failure to satisfy past demand.

If the household is unemployed he visits a randomly chosen firm to check whether there is an open position. If the firm indeed offers an open position and pays a wage that is higher than the households currently received wage, the position is accepted and a new type B connection between the household and the firm is created. If the firm offers no vacancy or the wage it pays is too small, the search process is repeated until a total of β firms have been visited.

As mentioned above, an employed household might end up working for less than his reservation wage if his employer has decided to decrease wages. In such a case we assume that households do not quit immediately, but instead intensify their search effort for another job that satisfies $w_f \geq \omega_h$. As a result we have three different intensities to search for vacancies: employees who are satisfied with their job ($w_f \geq \omega_h$) show the least search effort in the labor market. With a probability of $\pi < 1$, they visit one randomly determined firm per month to ask for an open position. The position is accept if the offered wage payment exceeds that of their current position. An employee who is unsatisfied ($w_f < \omega_h$) shows higher search effort.

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[18] The assumption that each firm is allowed to hire/fire at most one worker per month seems restrictive. But on the aggregate level it implies that up to 10 percent of the whole population can be hired/fired each month.

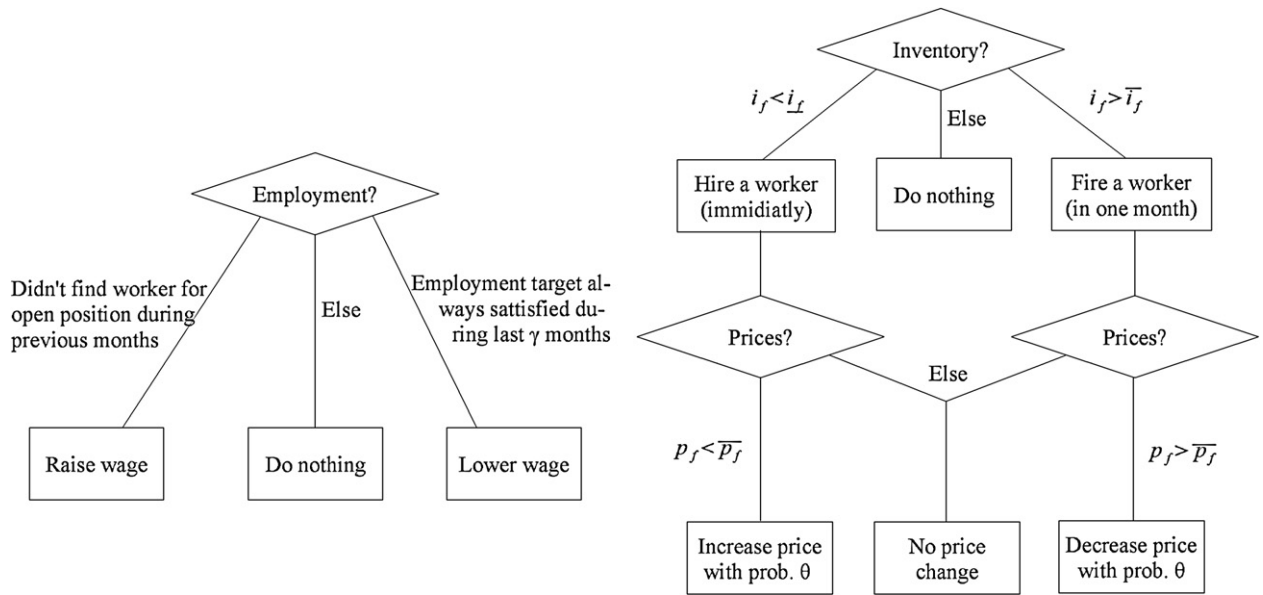[19] This rule is, like that for wage adjustment, also inspired by Gaffeo et al. (2008).

Fig. 3. Flow chart of firms's decision procedure.

He performs the same searching mechanism with a probability of 1. As described above, unemployed households show the highest search effort since they visit more than one firm per month.

Households also have to decide how much liquidity to spend for the purchase of consumption goods and how much to save. Following G2008 the interest on savings is normalized to 0. According to the empirical evidence of Souleles (1999) and the theory of consumption under uncertainty Carroll and Kimball (1996), consumption expenditure increases with personal wealth but at a decaying rate.[20]

$$c_h^r = \left(\frac{m_h}{P_h^I} \right)^\alpha \tag{11}$$

where P_h^I is the average goods price of all firms that household h has a type A connection with. And the parameter α satisfies $0 < \alpha < 1$. Note that consumption (and thus also savings) depends only on wealth and not on the interest rate.[21] Savings are thus due to a precautionary motive. Since households receive income on a monthly basis, the decision of dividing it on consumption and savings is also performed monthly. Accordingly c_h^r denotes planned real expenditures for the current month. If $m_h/P_h^I > 1$, Eq. (11) results in planned consumption expenditures that the household could not afford given the current amount of liquidity $c_h^r > m_h/P_h^I$. To avoid such inconsistent planning behavior that violates the budget constraint, we change the equation to:

$$c_h^r = \min \left\{ \left(\frac{m_h}{P_h^I} \right)^\alpha, \frac{m_h}{P_h^I} \right\} \tag{12}$$

2.3. The lapse of a day

After the above steps have been performed, the transactions of the first day begin. Households are picked in a random order to execute their goods demand. Since planned demand c_h^r has been determined for a complete month, but transactions are taking place daily, we have to bring c_h^r from a monthly to a daily basis. The most simple and straightforward way to do so, is to assume that c_h^r is distributed equally over the days of the month. Each household visits one randomly determined firm of those he has a type A connection with. If that firm's inventories are high enough to satisfy his daily demand of $c_h^r/21$ and the household's liquidity is high enough to pay the goods ($m_h \geq p_f(c_h^r/21)$) the transaction will be performed: the household's liquidity is reduced by the purchasing costs of $p_f(c_h^r/21)$, the firm's liquidity is raised by the same amount while its inventories are reduced by $c_h^r/21$.

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[20] A related approach is also used in Gaffeo et al. (2008).

[21] Simplifying assumptions for the consumption decision are not unusual in ACE models. For example in D2008 and G2008 consumption also depends only on income.

If the household cannot afford to buy the planned amount of goods ($m_h < p_f(c_h^r/21)$), his demand is reduced to the highest possible amount (m_h/p_f). If the firms inventories are lower than the households demand, the transaction is performed at the highest possible amount of i_f. Thus inventories can never become negative. The household tries to satisfy the remaining demand by repeating the buying process with another firm. This process is stopped after n firms have been asked or at least 95 percent of the planned demand have been satisfied. Eventually remaining demand vanishes.

Next, each firm produces according to the production function:

$$f(l_f) = \lambda \cdot l_f \quad \lambda > 0 \tag{13}$$

where l_f is the number of workers the firm employs and λ is a positive technology parameter. Following G2008 we assume a production technology that is a linear function of labor input. The firms inventory is increased by the produced goods:

$$i_f^{new} := i_f^{old} + \lambda \cdot l_f \tag{14}$$

After all households and firms have performed their daily actions, the next day starts.

2.4. The end of a month

After all 21 working days are performed, the month ends. Firms use the liquidity they own at the end of a month for three different purposes: pay wages, build a buffer for bad times, pay profits. First, all firms pay their workers a wage of w_f: the firm's liquidity is reduced by $w_f \cdot l_f$ while the liquidity of each household employed by that firm is raised by w_f. Second, if the firm has liquidity remaining after the payout of wages, it keeps a fraction as a buffer for possibly negative future profits. Since such negative profits would be a result of unaffordable high labor costs, we assume that this liquidity buffer ($m_{f,t}^{buffer}$) is given relative to labor costs:

$$m_{f,t}^{buffer} := \chi \cdot w_f l_f \tag{15}$$

Third, all remaining liquidity of the firm is distributed as profit among all households. Following Haber (2008), we assume that rich households have higher claims on firms' profits than poor ones. Therefore each household receives a share of aggregate profits that is proportional to his current liquidity.[22] For simplicity reasons, we do not introduce a third network structure for the allocation of profits. The method can be seen as a proxy for stock ownership. The wealthy own more stock than the poor, consequently they receive more profits.[23]

In some cases it might happen that the firm made losses during the month. As a first option the firm bridges this problematic situation by not paying any profit and reducing the liquidity buffer while keeping the wage payments unchanged. However, in some rare cases, the losses might be so large, that even with a reduction of $m_{f,t}^{buffer}$ down to zero, the labor costs are unaffordable. In this situation we assume that the firm's employees accept an immediate wage cut that is sufficient to keep the firm operating. While one finds empirical evidence for this assumption especially during recessions, it shall be emphasized that such wage cuts happen only very rarely.[24] This simplification allows to keep the number of firms constant and neglect firm entry and exit.

As a next step households adjust their reservation wage depending on their currently received labor income. If the labor income exceeds a households reservation wage, ω_h is raised to the level of the received labor income. If the labor income is lower than ω_h, the reservation wage is not changed.[25] Instead, the household intensifies his search for a better paid job (compare Section 2.2). If a household has been unemployed during the last month, his reservation wage for the next month is reduced by 10 percent. The month ends and the next one begins.

2.5. Properties of the model

Before performing some numerical simulations, let us reflect on the assumptions we used and the model properties they imply. Note that the model is not an equation system, an optimal control problem or some similar mathematical problem. Hence it cannot be "solved". Instead, we will simply calibrate the parameters, set all properties to initial values, and let the agents interact in the predefined way. Agents have a unique internal state (e.g. price, wage, stock, money, etc.). They also have a unique set of connections to agents of the opposite type. Therefore, agents are heterogeneous with respect to their properties, their positioning in the network and their information set.

We did not assume any direct relationship of aggregates with one another or with individual agents. All aggregates are emerging from individual interaction. They are statistical quantities only that do not lead a live of there own. Of course that does not mean, for example, that a rising GPD cannot have any influence on an unemployed household. But this influence

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[22] E.g. if household A owns twice as much money as household B ($m_A = 2m_B$), his share of the distributed profit is twice as large as B's.

[23] The same mechanism is used in Salle et al. (2012).

[24] A wage cut of 5 (10) or more percent occurs only with a probability of 0.01 (0.006).

[25] Recall that at the point in time when the households accepts a given job offer, the received wage rate is always above his reservation wage. A situation in which this is not the case anymore ($w_f < \omega_h$) can thus only be the result of a firm decreasing its wage payments.

Table 1
Calibration of the model.

Households	Firms
$\phi = 0.25$	$\gamma = 24$
$\xi = 0.01$	$\delta = 0.019$
$\beta = 5$	$\overline{\phi} = 1$
$\pi = 0.1$	$\underline{\phi} = 0.25$
$\alpha = 0.9$	$\overline{\overline{\varphi}} = 1.15$
$n = 7$	$\underline{\varphi} = 1.025$
$\psi_{Price} = 0.25$	$\overline{\vartheta} = 0.02$
$\psi_{Quant} = 0.25$	$\theta = 0.75$
	$\lambda = 3$
	$\chi = 0.1$

Table 2
Main equations.

Consumption function[b,e]	$c_h^r = \left(\frac{m_h}{p_h^r} \right)^{\alpha}$
Labor supply[a,b,d]	$l_h = 1$ (inelastic)
Production function [a,b,d]	$f(l_f) = \lambda \cdot l_f$
Wage adjustment [c]	$w_f^{new} := w_f^{old} \cdot (1 \pm \mu)$
Price adjustment [b,d]	$p_f^{new} := p_f^{old} \cdot (1 \pm \nu)$
	Random variables: μ, ν

[a] Consult Dosi et al. (2008).
[b] Consult Gaffeo et al. (2008).
[c] Consult Gaffeo et al. (2008), who additionally assume a minimum wage.
[d] Consult Russo et al. (2007).
[e] Consult Russo et al. (2007), where marginal propensity to consume is one.

is brought about by a concrete interaction of individuals (e.g. a job offer by an individual firm that faces rising demand) and not by the aggregate interfering directly.

Note also that we did not explicitly assume the existence of markets with predefined properties (like monopolistic competition, equilibrium or trade at one price). Trade of goods and labor is not performed at the aggregate level by a central mechanism. It is performed at the micro level through the network of trade relationships. We can interpret the total of all these connections as markets: the total of all type A trading connections as goods market and the type B ones as labor market. Since the network of connections evolves endogenously, markets – and hence their properties like existence and stability of equilibria or the degree of competition – are themselves endogenous objects.

The Walrasian auctioneer has been criticized for being an unrealistic central mechanism (Section 1). We have replaced the auctioneer (i.e. equilibrium) assumption by a straight *bottom up* approach. Therefore we model markets in a fully *individual-based* way and do not rely on any central mechanism (queuing list, matching mechanism, etc.).

We did also not assume the existence of a money market in the common way, i.e. *money supply = money demand*. Every agent has the *liquidity* property m_h or m_f that measures how much liquidity units the agent possesses. If we define the money amount as the sum of individual liquidities, the role of money is simply to circulate commodities: if a commodity is exchanged between two agents, liquidity (i.e. money) is exchanged in the opposite direction. Instead of introducing money (by means of an additional market) on top of a working model that is defined in real terms, the ACE model is stated as an exchange economy and therefore assigns an explicit and natural role to money (i.e. paying for goods) from the outset.[26] An illustration of the circulation of money through the economy is given in the next section.

Note, that for the ease of exposition, we did not explain how money originally came into existence.[27] Thus, when analyzing the impact of monetary policy, we are restricted to changes of the exogenous quantity $\sum_h m_h + \sum_f m_f$.

3. Numerical simulation

Now that the model is defined, we check weather it can match some of the stylized facts of aggregate dynamics. All simulations are performed with 1000 households and 100 firms. The calibration is given in Table 1. Table 2 summarizes the main equations.

The model is run for a period of 500 years (6000 months) plus a burn-in of 1000 months to get rid of the influence of arbitrary starting conditions. Since we did not assume market clearing, we should first check weather or not the artificial
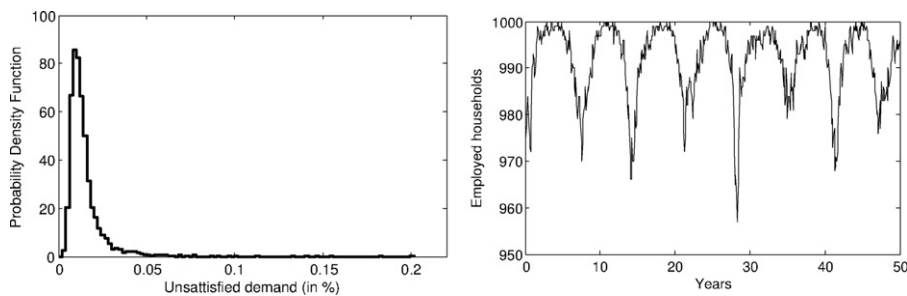
Fig. 4. Excess demand (left) and employment (right).

economy arrives at a general equilibrium state or not. Fig. 4 displays a probability density function of the goods demand that households are not able to satisfy relative to their planned demand. This relative unsatisfied demand is very small: in 95 percent of all periods it has been smaller than 0.03 percent. The course of aggregate employment for a subperiod of 50 years is illustrated in Fig. 4.[28] The number of employed households ranges between 957 and 1000. Since the total work force consists of 1000 individuals, this corresponds to an unemployment rate between 4.3 percent and 0 percent. We can thus conclude that the artificial economy is able to self-organize to a state that is very close to a general equilibrium but shows a realistic amount of unemployment.

Although the agents in our model are using simple adaptive rules they are able to coordinate to a situation that is very close to a general equilibrium and shows a small percentage of unemployment of a realistic size. Real world economies show higher unemployment rates of course, but since we did not model structural unemployment, for example, our model necessarily produces lower unemployment rates. We did not assume the agents to have high computational capabilities or to make use of sophisticated learning algorithms. Therefore we showed that the inter-action of agents who employ simple behavioral rules can lead to an almost fully efficient allocation on the aggregate level.

This result fits nicely into the history of economic thought. Vilfredo Pareto (and later Friedrich Hayek) pointed out, that it is the market as a whole that works out equilibrium (Hayek, 1945; Al-Suwailem, 2010). No individual possesses the information or the computational power to calculate it. The same is true for the ACE model: collectively, agents face the problem of allocating goods in an efficient way. But no agent (and no auctioneer) posses the information or the computa-tional abilities to calculate the efficient allocation. It is known that the most crucial instrument to facilitate such allocation is the correct setting of prices. Individual firms set individual prices, wages and quantities according to personal knowl-edge about their own production possibilities and the willingness of households to accept a given price. Households, in turn, perform a local search based on the price and wage signals they receive from firms. By cutting and rewiring trade connections in an individually beneficial way, they provide feedback to firms whether their currently set prices and wages are acceptable compared to those of other firms. Competition drives the economy to a point where prices are set in such a way that they reflect the true relative scarcity of commodities and hence lead to an efficient allocation of resources (i.e. an equilibrium). Such an equilibrium is brought about by the interplay of agents although no individual agent even has an idea about what an equilibrium is. The equilibrium is therefore an emergent property of the aggregate (Epstein, 1999).

One empirical fact that has fascinated macroeconomists since decades is the cyclical up and downturn of aggregate production. Models of the DSGE class have addressed this empirical fact by imposing exogenous shocks (technology shocks, cost shocks, news shocks, etc.) on the economy. In the ACE model, however, this feature is endogenously occurring (Fig. 4). Removing the assumption of perfect ex ante coordination and continuous market clearing automatically gives rise to an endogenous business cycle. Note that no state, central bank or monopolistic labor union is yet present in the model that can be blamed for creating it, hence the cycle is a generic property of the market itself.[29] Aggregate production is not plotted since it is a linear function of employment and has therefore qualitatively the same shape.

Business cycles in standard macro are often understood as stochastic deviations *around* a trend. In the ACE model it is a cyclical deviation *below* the full employment level that is due to coordination failure of the interacting agents. This difference is crucial when concerning stabilization policy. For example, Lucas (2003) has argued that stabilizing the business cycle is barely useful at best. His argument, however, depends on the assumption that stabilization means dampening both, recessions as well as booms. In the ACE model there are no stochastic peaks above potential output. Therefore it is generally possible to fill the troughs without shaving the peaks.[30] Stabilization policy might thus generally perform much better in ACE models than in DSGE ones.

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[28] The rest of the simulated periods show similar patterns but have been excluded for visual convenience.

[29] The cyclical up and down of production has also been reproduced in a number of different agent-based macro models. See for example Dosi et al. (2006), Bruun (2008) and Westerhoff (2010).

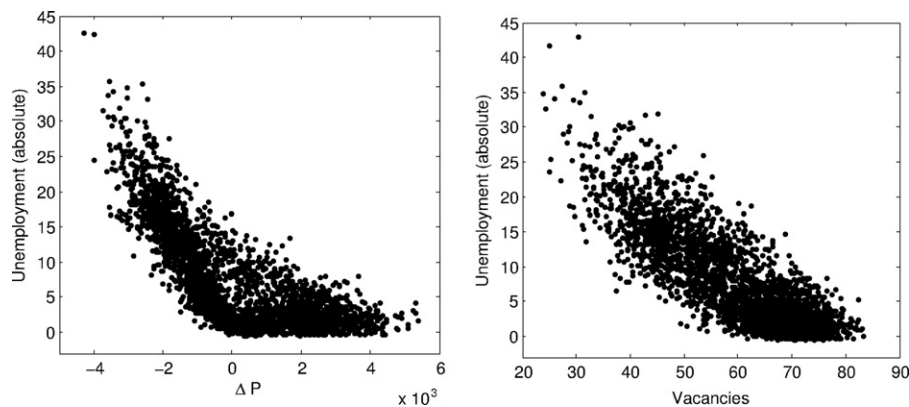[30] This idea is not new for behaviorally oriented economists. See for example Yellen (2007).

Fig. 5. Empirical trade-offs between unemployment and inflation/vacancies.
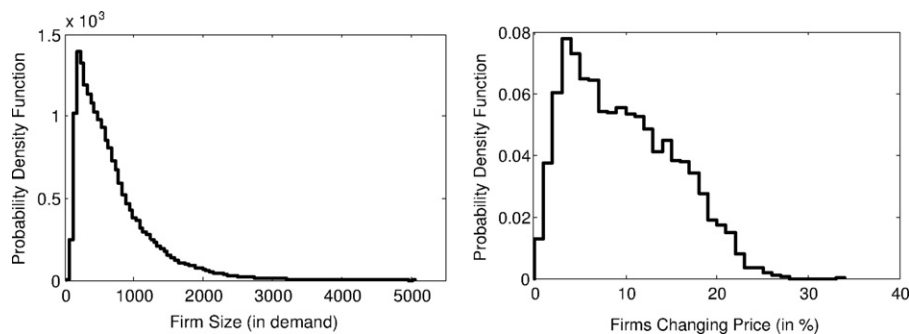

Fig. 6. Firm size distribution (left) and frequency of price changes (right).

G2008 and Delli Gatti et al. (2008, p. 14) have suggested to judge an ACE macro model by its ability to reproduce aggregate empirical "laws" like the Phillips curve or the Beveridge curve. As shown in Fig. 5 the model is able to reproduce both of these empirical laws.[31] Another stable empirical finding mentioned by the authors is that the distribution of firm size is right skewed. Again the ACE model can mimic this fact quite well (compare Fig. 6; sample skewness is about 1.88). The firm size distribution, however, does not feature fat tails.[32] The frequency of price changes is endogenous in the ACE model. We can therefore check weather it is comparable to empirical findings. Nakamura and Steinsson (2008) have found that the frequency of price changes follows a right skewed distribution with median between 9 percent and 12 percent per month. The ACE model also matches this aspect of the data and generates a distribution of price change frequencies that is also right skewed (sample skewness of about 0.47) with a median of 9 percent.

Another empirical fact, that is of special importance when analyzing the short run effects of monetary policy, concerns the correlation structure of inflation and output. According to Walsh (2010) inflation tends to be below trend when GDP is above trend and increases in GDP tend to be followed by increases in prices. Fig. 6 displays the correlation structure of output with lagged prices. The solid line displays results of simulated time series while broken lines represent US data including and excluding the recent financial crisis.[33] The basic ACE model obviously captures the empirical correlations qualitatively quite well. As in real data, the correlation is below zero for negative lags. The positive correlation for lags greater or equal to 2 indicates that a rise in GDP is followed by a rise in the price index. Quantitatively, most of the model generated values are within a bootstrapped 95 percent confidence band. Only for negative lags below −3 correlations are too strong. This may indicate that the model produces aggregate cycles that are too regular (compare also Fig. 4) and that real markets contain some disturbing forces which are not included in the model.

The mentioned correlation structure of real data have led economists to speculate about whether it might be demand shocks or supply shocks that drive the business cycle (Kydland and Prescott, 1990; Judd and Trehan, 1995; Ball and Mankiw, 1994). The ACE model suggests a very different implication. The simulation run has not been subject to any shock. Therefore

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[31] Since unemployment and vacancies are integer values, a lot of points in the shown scatter plots would lie at the exactly same position. Hence such a graph would not provide a good impression of the spread and frequency of data points. To avoid this problem and allow for more visual convenience a very small pseudo random number $\sim U[-0.5\,;0.5]$ is added to unemployment and vacancies before plotting them in Fig. 5.

[32] In this respect the simple ACE model cannot catch up with Dosi et al. (2008) who generate tails that are even fatter than those empirically observed

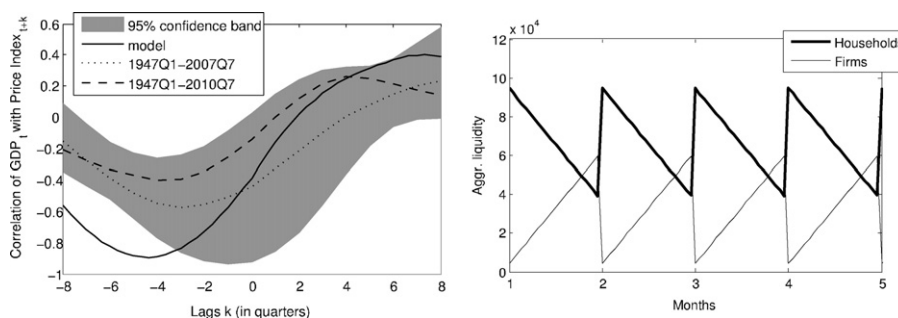[33] Empirical time series have been detrended using an HP-filter.

Fig. 7. Correlation of GDP with prices (left) and aggregate liquidity (right).
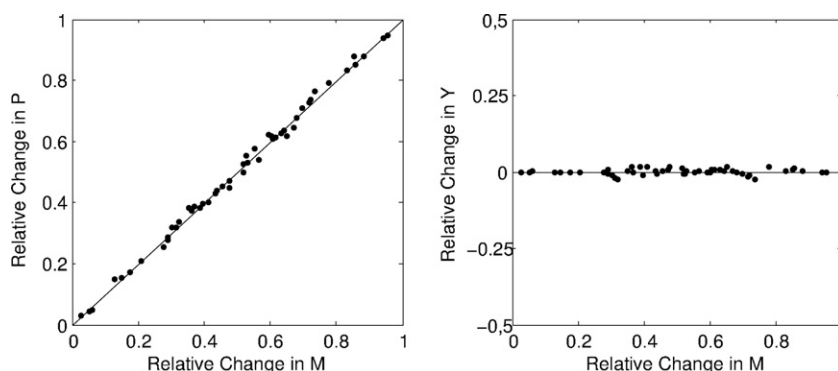

Fig. 8. Long run effects of an increase in the money amount.

the correlation structure might be a generic property of market economies and not the result of any kind of exogenous shocks.

This role of money as the medium of exchange is visualized in Fig. 7 (right panel) which shows the aggregate liquidity of households and firms over time. The aggregate liquidity of households decreases over the lapse of each month. This effect is due to the daily purchases of consumption goods. It does not fall to zero because households save part of their liquidity. At the same time the aggregate liquidity of firms rises by the same amount since firms are constantly selling goods and thus receiving payments. At the end of each month, firms pay wages and profits to the households. Their liquidity immediately falls sharply, while that of households rises. The next month begins and the pattern repeats. Therefore, while time goes by, money constantly changes hands between different agents and thus circulates commodities between them. Now that the role of money has been clarified, we can turn to the analysis of monetary policy.

4. Monetary policy

The effect of monetary policy in the short run crucially differs from that in the very[34] long run. It is widely accepted today[35] that a relative growth in money supply in the very long run creates only inflation and has no influence on the level of production. To check weather this property holds in the ACE model, we run another 50 simulations. In each simulation the money amount is raised randomly by an amount between 0 percent and 100 percent. Practically this is done by multiplying the liquidity value of all agents by a factor between 1 and 2 (helicopter drop).

Fig. 8 (left panel) shows a scatter plot of the relative change of the money amount against the induced relative change in the price level after 50 years. The induced relative difference in production after 50 years is given in the right panel. Since all points in the left panel closely follow a 45° line while all points in the right are located at a horizontal line, we can conclude that the classical dichotomy of the monetary and real sector holds for the very long run. The ACE model is thus in line with empirical evidence.

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[34] In Sections 4 and 5 we have to deal with time horizons that lie far beyond what macroeconomics typically call *the long run*. To avoid confusion with the length of different time spans we call time periods of 50 and more years the *very* long run.

[35] The long run neutrality of money is empirically confirmed in e.g. McCandless and Weber (1995) and Berentsen et al. (2011).
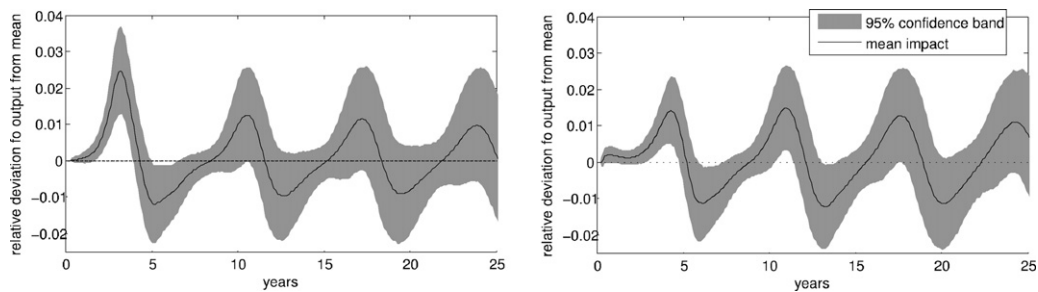
Fig. 9. Short run effects of a 5 percent increase of the money amount during recession (left) or boom (right).

The effect of monetary policy in the short run is somewhat more controversial in the literature.[36] It is, however, widely accepted that it is not neutral with respect to real variables (Sims, 1992; Cover, 1992). To analyze the short run effects of monetary policy via impulse response functions, we use the method described in Lengnick and Wohltmann (2013):

1. Generate the model dynamics for one simulation run.
2. Generate the same dynamics with identical realizations of the pseudo random numbers, but with an increase of the money amount by 5 percent in one particular period.
3. Calculate the differences of the trajectories of step 1 and 2 which gives the isolated impact of the monetary shock. Note that the realizations of all stochastic terms are identical in both runs.
4. Repeat steps 1–3 2500 times with different seeds for the random number generator from the shock period on.

The results of this experiment are shown in Fig. 9 for two different settings. The left panel illustrates the mean impact on production if the positive monetary shock hits during a recession. In contrast, the right panel shows the same response if the shock hits during a boom. Both graphs have in common that after a period of about five years, the economy falls back into a cyclical up and down around the mean, where the amplitude of the mean impact slowly decreases over time while the variance increases, i.e. it dies out. The maximum amplitude during this time is around 4.5 percent. For comparison: the maximum amplitude of US business cycle for the last two decades is between 3.7 percent and 5.0 percent for HP-filtered real GDP data.

The key differences are found in the short- and medium run (up to five years). During a recession, monetary stimuli have a strong positive impact on production that lasts for four years. The maximum of 2.5 percent is reached after 3 years. If the stimulus is applied during a boom, it has a much smaller impact. In fact, for the first 3 years there is no significant effect at all. The maximum of 1.4 percent is reached after four years. This positive impact, however, is not distinguishable from the cycles to come while in the left panel the short run impact is obviously above. Expansionary monetary policy therefore has a much stronger short- and medium run effect if it is applied during a recession than during a boom. Similar asymmetric impacts are also found empirically (Cover, 1992). In DSGE models, shocks are typically additive which implies that they have the same effect regardless of the current economic situation.

The confidence bands imply that (in the left panel) we are unable to reject the neutrality of money with respect to output from $6\frac{1}{2}$ years after the shock onward. In the right panel neutrality starts much later, i.e. 14 years after the shock. It can thus not be significantly rejected that the long run dichotomy, found in the previous analysis, sets in between $6\frac{1}{2}$ and 14 years after the shock.

5. The large impact of small shocks

Can a single person change the course of the business cycle significantly by spending €5 more or less at one particular day? – Yes, he can!

Economists typically assume that individual persons actions average out in the aggregate and do therefore not matter for aggregate dynamics. It is well known however that complex systems are critically dependent on initial conditions. Changing a little seemingly unimportant detail might lead to very different development in the distant future. We run the experiment of the previous section again. Instead of performing a "big" shock that hits on the aggregate level, we perform a very "small" one on the micro level: at one day in the middle of one particular month we reduce the demand of one household by 5 percent.

Fig. 10 illustrates the mean impact of this shock as the mean difference between the trajectories including the shock and those excluding it (thin line). The mean impact is practically zero for all periods following the shock. Therefore the micro shock does not make a significant difference to the aggregate dynamics *on average*. The bold lines illustrate the mean of the

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[36] A nice overview on the contradicting views about the short run impact of money on real variables can be found in Walsh (2010).
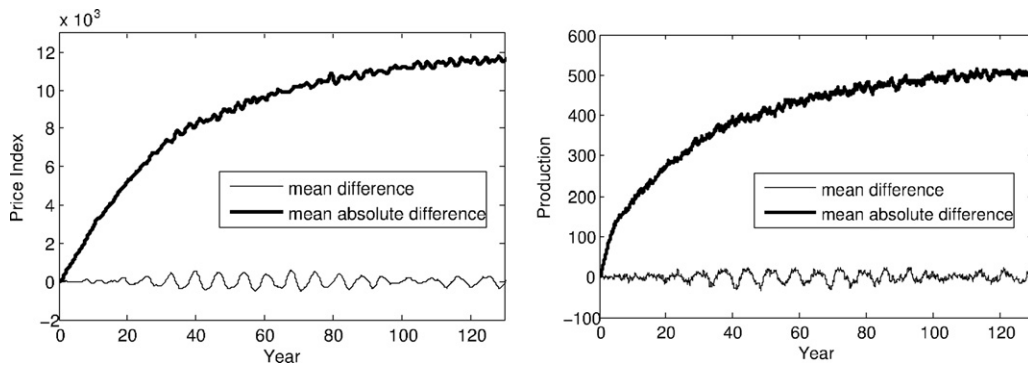
Fig. 10. Effect of a tiny shock on prices (left) and production (right).
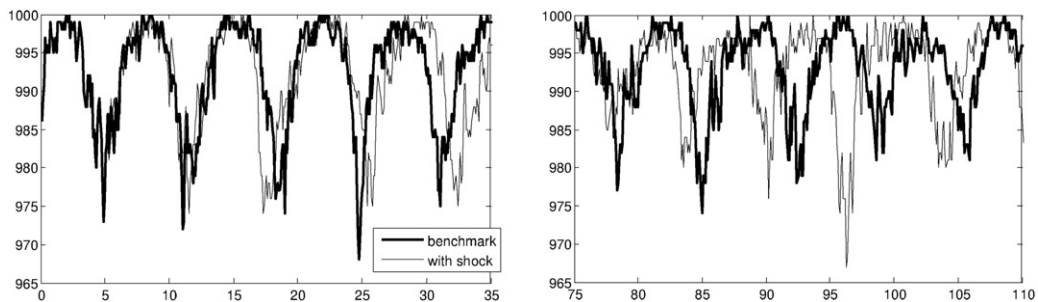

Fig. 11. Change of the business cycle in the short and medium run (left) and very long run (right).

same differences in absolute value. Since it is significantly[37] unequal from zero after the shock, it indicates that the mean difference of zero is only due to a balancing of positive and negative differences. The absolute differences gradually rise over an interval of 120 years after the shock.

The shock is extremely small in relation to the aggregate.[38] But since the decisions of all individuals are interrelated it can propagate through the network structure and create huge changes to the aggregate developments some decades later. A simple statistical test (details in footnote 37) proves, that the tiny change somewhere on the individual level leads to a completely unsystematic phase shift of the business cycle after some years (e.g. turn a peak into a trough). The provocative statement at the beginning of this section is therefore true.

An example of how the business cycle is effected by the micro shock is given in Fig. 11. The bold line illustrates the level of employment in the benchmark simulation while the thin line refers to the case in which the economy has been subject to a shock performed in year zero. Obviously, the shock does not change the general structure of the cycle: amplitude, duration and average level are not affected. Comparing the short and medium run difference (left panel) to that in the very long run (right panel) reveals, however, that the business cycle is subject to a phase shift that slowly builds up over time: directly after the shock, both trajectories are practically identical. About 100 years later, they are completely different. E.g. without the occurrence of the shock, the economy encounters a boom in year 96. The shock, however, turns it into a bust.

Such effects are common for complex systems and known as butterfly effects.[39] They show that huge effects can be the result of very small shocks. This result is in stark contrast to the transmission of shocks in DSGE models. In such models responses are typically proportional to the implied shock and die out gradually over time.[40] This significant dependence

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[37] To evaluate if the value of production in the simulation with the shock is completely decoupled from the simulation without the shock (i.e. a significant unsystematic phase shift), one can check if the mean absolute difference between production with and without the shock (at a certain point in time) is equal to the mean absolute difference of each value of production in a given benchmark trajectory to each other point weighted with its probability of occurrence. For aggregate production after 120 years we get a value of 508 (compare Fig. 10(b)) while the benchmark is given by 559. In a few simulations the shock does not create any difference at all. This is the case if it hits an unemployed household who does not have any money. Since such a household cannot demand anything, a shock that reduces his demand can obviously not impact the economy. Removing these zero-trajectories results in a value of 569 which is even a bit higher than the benchmark. We can thus conclude that small shocks lead to a complete decoupling of aggregate production in the very long run.

[38] Only one of 1000 households reduces the demand at only one of 21 days by only 5 percent.

[39] Lorenz (1972) argued that correct whether predictions are impossible because events like the flap of a butterfly can change the course of weather forever. What applied to the weather in his model, also applies to the course of the business cycle in our model.

[40] The second point does also apply for some complex adaptive systems. The impulse response functions in the macroeconomic model of De Grauwe (2010, 2011) for example clearly show decreasing volatility in the response to a given shock. Accordingly the shocks do not set a complex and irreversible chain of events in motion but monotonically die out over time.
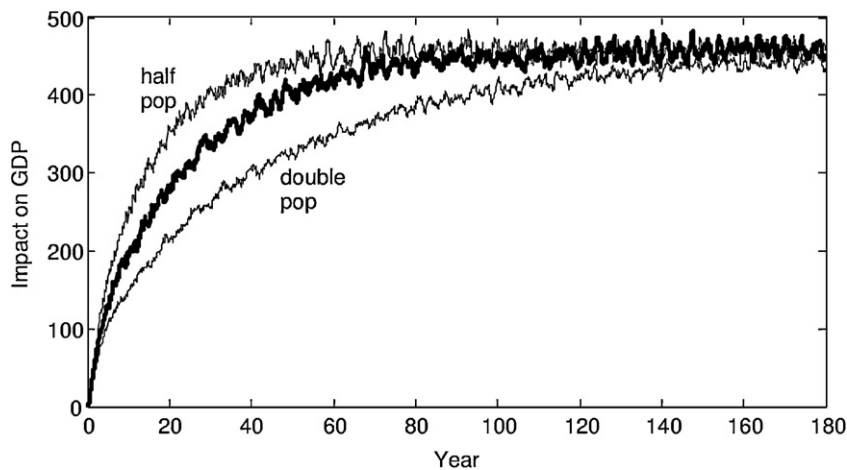
Fig. 12. Impact on production: different population sizes.

on initial conditions also justifies *a posteriori* the assumption of simple adaptive rules of behavior, because individuals can impossibly expect the future rationally if all tiny changes that occur somewhere on the individual level can change the aggregate in such a tremendous way.

The time it takes the business cycle to undergo a complete phase shift depends on the population size. Fig. 12 compares the impact of the micro shock on aggregate production for different population sizes. The bold line shows the response of the above experiment, the thin lines refer to cases with a half-sized and a double-sized population. To allow for comparison between the three cases, the values of production are given per 1000 households. If the population is only of half size compared to the benchmark case, the impact on aggregate production builds up much quicker and reaches its maximum some decades earlier. The opposite holds for a population of double size. In this case the effect builds up slower and reaches its maximum about 60 years later. The economic rational behind this effect is that one individual has a much higher influence on the aggregate if the economy is small. A change in his demand can therefore more quickly pulse through the network, if the economy is small. After 180 years the absolute difference in all three cases is equal. Therefore, the result, that the business cycle is subject to a complete phase shift in the very long run, still holds and is independent of the population size. The concave pattern also sheds light on the speed with which the shock pulses through the economy. The impact obviously builds up much faster shortly after the tiny shock than in the distant future.

6. Robustness checks

In this section we will check the robustness of some of the most important findings against the change of important parameters. One of the most profound differences – compared to DSGE macroeconomics – is, that equilibrium is not simply assumed but shown to emerge endogenously. One interesting question to ask in this context is whether the potential of the economy to self-organize onto such an equilibrium is robust against several parameters. Important in this respect is the willingness of households to accept a reduction in wages. To test its influence on the aggregate system, we perform the following experiment. In the above simulations, unemployed households adjust there reservation wage ω_h downwards by 10 percent after having unsuccessfully searched for a new job (compare Section 2.4). We run the model again, with downward adjustments of ω_h ranging from 0 percent to 50 percent.

The results of this experiment[41] are shown in Fig. 13. The resulting level of unemployment (left panel) and unsatisfied demand (right panel) are plotted as dashed lines with respect to the relative reduction of ω_h that an unemployed household is willing to accept. If the unemployed are less willing to reduce their reservation wage (low values on abscissa), unemployment is relatively high. Increasing their willingness to reduce ω_h monotonically leads to lower unemployment up to wage cuts of about 20 percent. Increasing it further does not result in a significantly better market clearing of the labor market. This experiment has shown that the labor market can more easily self-organize to an equilibrium if the unemployed are willing to accept wage cuts more easily. The model is thus generally consistent with classical economic reasoning. But increasing wage flexibility alone cannot eliminate unemployment completely. At the same time, an increase of wage flexibility seams to worsen the potential of the goods market to self-organize onto an equilibrium. If reservation wages are cut by more than 10 percent, the average unsatisfied demand increases. Thus, while increasing the self-organization ability of the labor market, higher wage flexibility worsens conditions for self-organization of the goods market. If we assume that wage cuts are never

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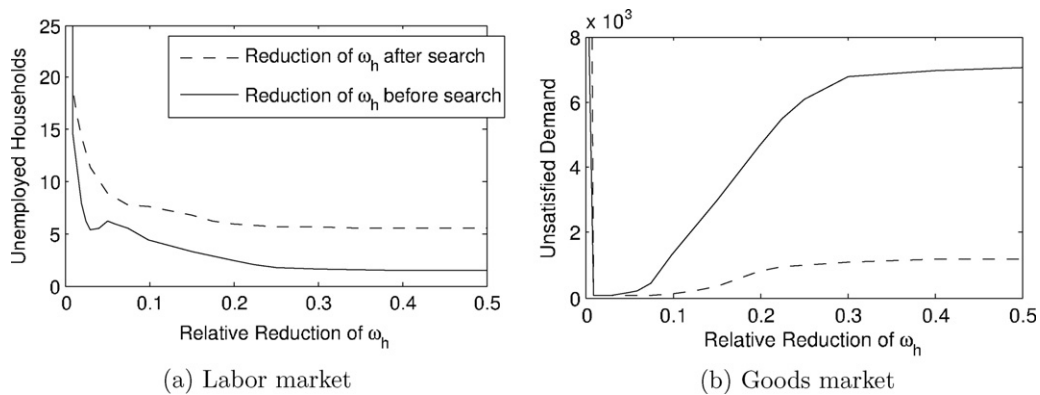[41] 2500 repetitions have been performed for each parameterization.

Fig. 13. Influence of willingness to accept wage cuts on labor market (left) and goods market (right).

accepted (zero on the abscissa), the situation on both markets turns into extreme disequilibria: the unsatisfied demand is above 10 percent and unemployment rates above 50 percent.[42]

In the above experiment, it was assumed that unemployed households reduce their reservation wage after having searched at least one month for a new job. Now, we increase wage flexibility of the unemployed even further and assume that they also reduce it (by the same relative amount) immediately after they have been fired and thus before starting to searching for a new job. Results are given in Fig. 13 (solid line). For all levels of wage flexibility, unemployment falls compared to the former experiment. At the same time unsatisfied demand rises. The general result of the former experiment is therefore confirmed: an increase in wage flexibility has a positive impact on the self-organization of the labor market but a negative on the goods market.

We will now turn to the goods market and analyze the impact of different price change flexibilities by changing the parameter θ. Recall, that a high value of θ referrers to a scenario in which firms change prices often while low values are associated with less frequent price changes. Fig. 14 (top row) illustrates the influence of θ on the self-organization capacity of the two markets. The scaling of the ordinates is identical to those of Fig. 13 to allow for better comparability of the two experiments. For most values of θ the economy is very close to an equilibrium situation on average. The value of θ, however, does not have a significant influence on the disequilibrium measures. As long as $\theta > 0.25$ the average number of unemployed households is almost constant at about 8. The same result holds for the unsatisfied demand of goods which is almost constant at 0.0002. Similar to our findings from the above experiments, the equilibrium breaks down only if price flexibility becomes too low. The economic explanation for this finding is straight forward: as explained in Section 3, the self organization to an equilibrium is performed via a search for the correct price vector. Of course, when price or wage adjustment is prohibited, the search mechanism breakers down and the equilibrium cannot be reached. At the same time, however, there is a slight negative impact on the labor market if θ becomes larger than 0.25. Increasing flexibility of the goods market therefore worsens self-organization conditions on the labor market.

One new aspect of the model is that markets are modeled as endogenous networks. For the goods market we have assumed that household are connected to only 7 firms. This assumption reflects the fact that the information set of households about the goods market is limited. In the next robustness check we vary the number of these connections, where a higher number of type A connections can be interpreted as a larger set of information. As shown in Fig. 14 (bottom row) a higher information set implies better self-organization capabilities of the goods market. For 5 and more connections unsatisfied demand becomes so small that we can classify the situation as a quasi equilibrium. For less than 5 connections, however, the self-organization brakes down completely. The impact on the labor market is ambiguous: while a minimum of 5 connections is again needed to facilitate self-organization, there is a small negative effect if the information set in increased above 15. We can therefore conclude that information has an ambiguous impact on the economy: while a minimum of information is needed to allow for self-organization, too much of it has the opposite effect.

In this section we have shown that the emergence of close-to-equilibrium situations simultaneously on all markets is a remarkably stable result of the market mechanism. Disequilibrium measures are small for a wide set of parameters. For some extreme parameterizations, however, the market fails to self-organize close to an equilibrium. We have also found that increasing flexibility or information on one market often has a small negative effect on the other market.

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[42] Both values have not been shown in the plot because the variation on the (economically more interesting) interval [0.01, 0.5] would not be visible any more.
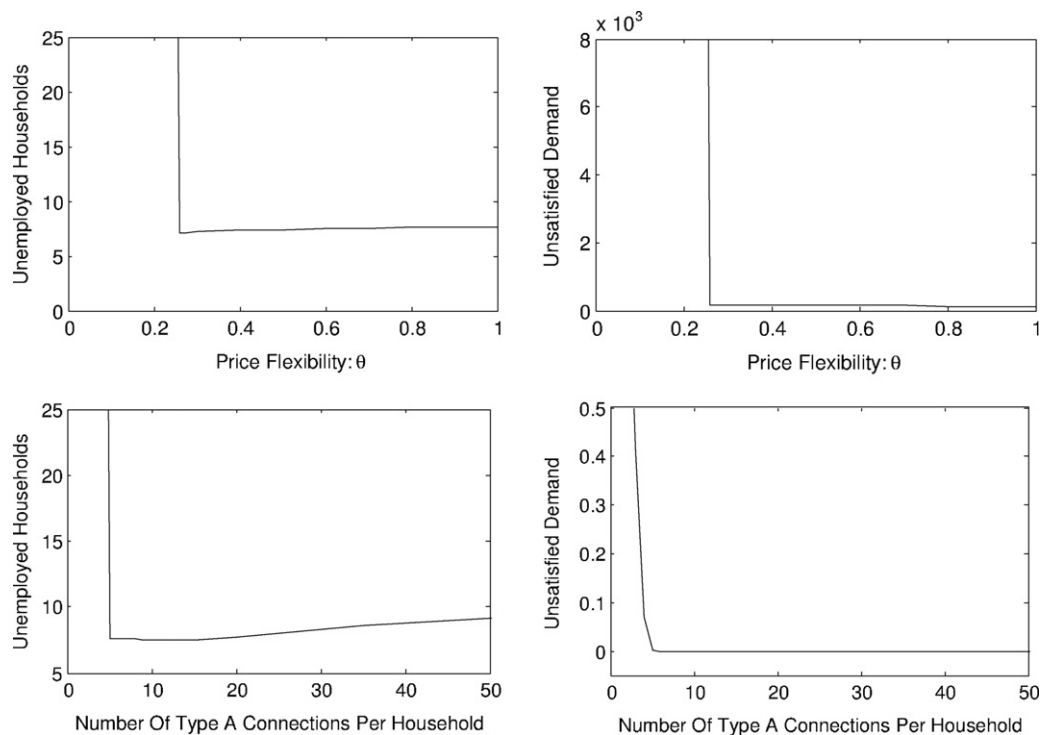
Fig. 14. Influence of price flexibility (top panels) and information set (bottom panels).

7. Conclusion

We have developed a baseline ACE macroeconomic model that is simpler than other ACE models and employs the bottom-up approach rigorously. The only economic agents it consists of are households and firms, both of which are described by simple, adaptive rules of behavior. Despite its simplicity, the model can already mimic a number of empirical facts: cyclical swings in the level of aggregate production (with empirically reasonable amplitude) that emerge endogenously from interaction, reasonable levels of unemployment, empirical laws like the Phillips or Beveridge curve, right skewed firm size distribution, a median value of price change frequency between 9 percent and 12 percent, dynamic correlation structure between output and inflation, long run neutrality and short run non-neutrality of the money amount. The model also possesses properties of a complex system like a butterfly effect. We have shown that a single person can change the business cycle forever just by cutting demand by 5 percent at one day. Finally, we demonstrated that the equilibrium is a robust result of the ACE economy for all markets. It does only break down, if either price or wage adjustment is turned off completely.

At the same time, the criticism often raised recently among macroeconomists does not apply to the presented model. First, all actions take place on the micro level. The passage from micro to macro is not by adding up individual decisions but by interaction. Hence, the ACE method (in contrast to DSGE) truly deserves the attribute *microfounded*. This aspect is especially interesting because behavioral and experimental economics provide us with ever more insights into the decisions of real human beings. ACE macro is a method for bringing these empirically observed individual behavior to the aggregate level in a 100 percent consistent way.[43] Second, the model does not rely on the assumption of equilibrium. Instead, equilibrium is shown to be an endogenously emerging result of the market. Consequently disequilibrium and coordination failure are not ruled out by assumption, a property that makes ACE models interesting for the analysis of crises. Third, time plays an active role in the model. Price adjustments are not outsourced into meta time. They are the result and not the precondition of market activity. Fourth, we did not require the agents to be super rational but employed behavioral rules which are so common-sensical, that real world human beings might actually be employing them. Nonetheless we have shown that these agents managed to self-organize close to an efficient full employment state.

The recent global economic collapse has brought a critical discussion about the methodological foundations of macroeco-nomics on the agenda. It has been shown in this paper, that ACE modeling is a promising new tool to answer this criticism. On the one hand it allows founding macro consistently in micro and therefore protecting macro against the criticism of being *ad hoc*. On the other hand it allows for emergent macro phenomena that are no direct replications of summed up micro behavior.

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[43] Consult Duffy (2006) on the relation of human subject experiments and ACE modeling.

The aggregate economy has its own patterns and properties that cannot be deduced directly to utility optimization calculus. Thus it allows for a re-emancipation of macro from micro dominance without neglecting microfoundations.

In this paper, empirical remarks have only been used to validate the ACE model, while the confrontation with DSGE has been done on a theoretical level. Although this confrontation is important because most of the currently expressed criticism is concerned with theoretical problems, the research project should not stop at this point. Future research needs to be done which compares ACE and DSGE modeling in quantitative terms like forecasting accuracy.

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