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Lengnick, Matthias

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Agent-based macroeconomics - a baseline model

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Department of Economics

Economics Working Paper
No 2011/04

agent-based macroeconomics - a baseline model -

by Matthias Lengnick



Agent-Based Macroeconomics

– A Baseline Model –

Matthias Lengnick*

March 13, 2011

Abstract

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. It does not depend on the strict assumption of rationality and allows for aggregate behavior that is more than simply a replication of microeconomic optimization decisions. At the same time it allows for absolutely consistent micro foundations. 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.

JEL classification: B4, E1, E50

Keywords: Agent-based modeling, complex adaptive systems, microfoundations of macroeconomics

* *E-mail:* matthias.lengnick@vwl.uni-mannheim.de

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 been motivated by the desire of grounding macroeconomics in the economic behavior of individual economic entities.¹ 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. As a result, the 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 is very different from micro behavior. In such systems stable phenomena or relationships can occur on the macro level that can impossibly be deduced directly to micro decisions. These phenomena have come to be called "emergent"² in the literature 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.³

The most famous example of emergent phenomena is the degree of racial segregation in cities. Schelling (1969) showed that even 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) 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 without any reason that is visible on the macro level.⁴ 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.⁵ Another interesting property of traffic jams is the cyclical recurrence of stopping and driving phases⁶ observed for individual car drivers. This behavior can obviously not

¹ Janssen (2008)

² See for example Epstein (1999).

³ For a criticism of this way of microfoundation consult Kirman (1992), Gallegati et al. (2006), Colander et al. (2009), Kirman (2010), Gatti et al. (2010).

⁴ A bottleneck situation (road works, accident) for example would be a visible reason.

⁵ Phantom traffic jams have first been described by Treiterer & Taylor (1966) and been explained by means of agent-based simulation in Treiterer & Myers (1974).

⁶ See Zhang & Shen (2009). The analogy to the cyclical ups and down of the business cycle is obvious.

be reduced to individual car drivers in isolation and has to be explained by interaction (braking, accelerating and lane changing in this case).⁷ 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 can not 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.⁸ 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.⁹ 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.¹⁰ Assuming that markets are characterized by equilibria is therefore nothing more than a doubtful assumption. Real markets might be characterized by multiple equilibria, coordination problems, instability, perpetual novelty or even chaos.¹¹ 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 general equilibrium is typically a property that holds in every single period 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.¹² Time in such models has therefore no role other than dating commodities. If the Walrasian auctioneer – a clearly fictitious assumption – is removed, prices can not adjust anymore and transactions can not take place. All dynamics would ultimately break down.¹³ Questions like "who actually sets prices?" and "how is information processed and revealed by the market mechanism?" have to be addressed by macroeconomists in order to develop realistic models

⁷ A recent and easy to understand example can be found in Treiber et al. (2000).

⁸ Arthur (2006)

⁹ Kirman (2010)

¹⁰ Ackerman (2002), Kirman (2006), Gaffeo et al. (2008)

¹¹ Arthur (2006)

¹² Kirman (2006), Gaffeo et al. (2007), Gaffeo et al. (2008)

¹³ Gaffeo et al. (2008)

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.¹⁴ 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.¹⁵ The complexity property of economic systems suggests that they are characterized by aggregate, endogenous uncertainty that can not be expected rationally.¹⁶ 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.¹⁷

The assumptions of the *holy trinity of rationality, equilibrium and greed*¹⁸ 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.¹⁹

Some critics go even further and argue that the dominant methodological framework is not only false but even dangerous.²⁰ 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.

¹⁴ Akerlof (2002)

¹⁵ Gaffeo et al. (2008), Ackerman (2002), Kirman (2010)

¹⁶ Gatti et al. (2010)

¹⁷ De Grauwe (2010)

¹⁸ This expression is due to Robert Solow (see Gatti et al. (2008), p. 11).

¹⁹ Gatti et al. (2010)

²⁰ Colander et al. (2009), Kirman (2010), Gatti et al. (2010)

A method that seems well suited to respond to the raised criticism is agent-based computational (ABC) simulation and network analysis.²¹ ABC 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 price index or GDP could then easily be calculated. Instead of solving an equation system the model is simply run.

One strength of the ABC 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. 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 ABC models is that the modeler is left with enormous degrees of freedom in choosing the types of agents and their behavioral rules. Consequently the few ABC macro models that exist start with very different assumptions and it is not always clear which macro pattern is a result of what micro property. The aim of this paper is, first, to provide a reasonable starting point for ABC modeling in macroeconomics by developing a minimal model that is able to reproduce some stylized facts of market economies. And second, to demonstrate the differences of ABC and DSGE modeling with a simple example

The model is developed and compared to other ABC macro models in section 2. Section 3 provides simulation results which prove that the model can well reproduce a number of empirical facts about business cycles. Section 4 analyzes the influence of monetary shocks while section 5 shows that the model generates true complexity results. Section 6 concludes.

²¹ Colander et al. (2008), Keen (2009), Kirman (2010), Gatti et al. (2010)

2 The Model

ABC models divide into two categories.²² 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. Started in 2006 it is developed by a team of economists and computer scientists and runs on massively parallel computing clusters. While models of this category clearly allow very realistic insights, its huge complexity makes it difficult to isolate and explain the obtained results.²³ At the same time, the need for massive computational power generates 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 run on ordinary desktop PCs.

The model presented in this paper belongs to the second category.²⁴ The two most influential models of this category are those of Wright (2005) 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. The model of Gaffeo et al. (2008) consists of three different types of agents: Households, Firms and Banks who employ simple behavioral rules that are either derived from survey studies or based on common-sensical real world experience. 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 already proven to be very successful in the context of artificial ABC financial market models.²⁵

The model presented in this paper follows 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.

²² For another classification that consists of one more category consult Chan & Steiglitz (2008).

²³ Chan & Steiglitz (2008)

²⁴ The model is programmed in Java. All source code is available upon request.

²⁵ For an introduction into ABC financial market modeling see, e.g., Samanidou et al. (2006), Hommes (2006) or LeBaron (2006). Outstanding examples of such models are Kirman (1993), Brock & Hommes (1998), and Lux & Marchesi (2000).

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 of the two models are the following. G2008 analyzes growth as a result of investment in R&D. The aim of this paper, instead, is to define a simpler model that is concerned with basic macroeconomic relations in a non-growth environment. It also makes use of only two different types of agents: Households and firms (G2008 also include banks). The agents's rules are depending on purely local knowledge and not on any aggregate statistic (like the price index or a minimum wage). The indexation of time in G2008 is given by quarters, while in the paper at hand, time is indexed by days and months to allow different actions to take place in different time intervals.

2.1 Basic Properties

In order to exclude growth, households and firms are fixed in number and infinitely lived. Production technology and the capital stock are 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. 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.²⁶ 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 are called month (fig. 1). Consumption goods are bought daily while labor is bought monthly.

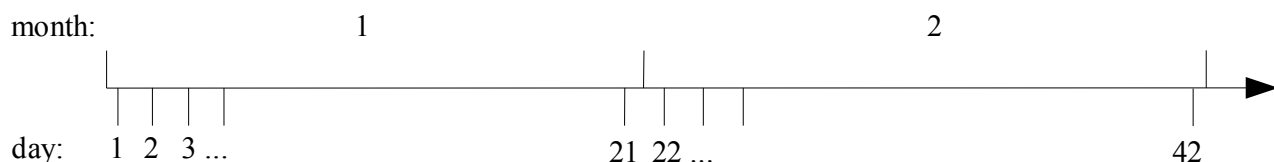


Figure 1: Time scale as indexed by days and months

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. 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

²⁶ Consult De Vany (1996) for a very vivid description.

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 connections of individual households and firms are exemplified in figure 2. The aggregate of all agents is thus connected by a bipartite²⁷ network of trading relationships that is fixed in the short. Over time, agents cut unsatisfying trading connections to create other more beneficial ones. Thus the network is allowed to change in the medium run.

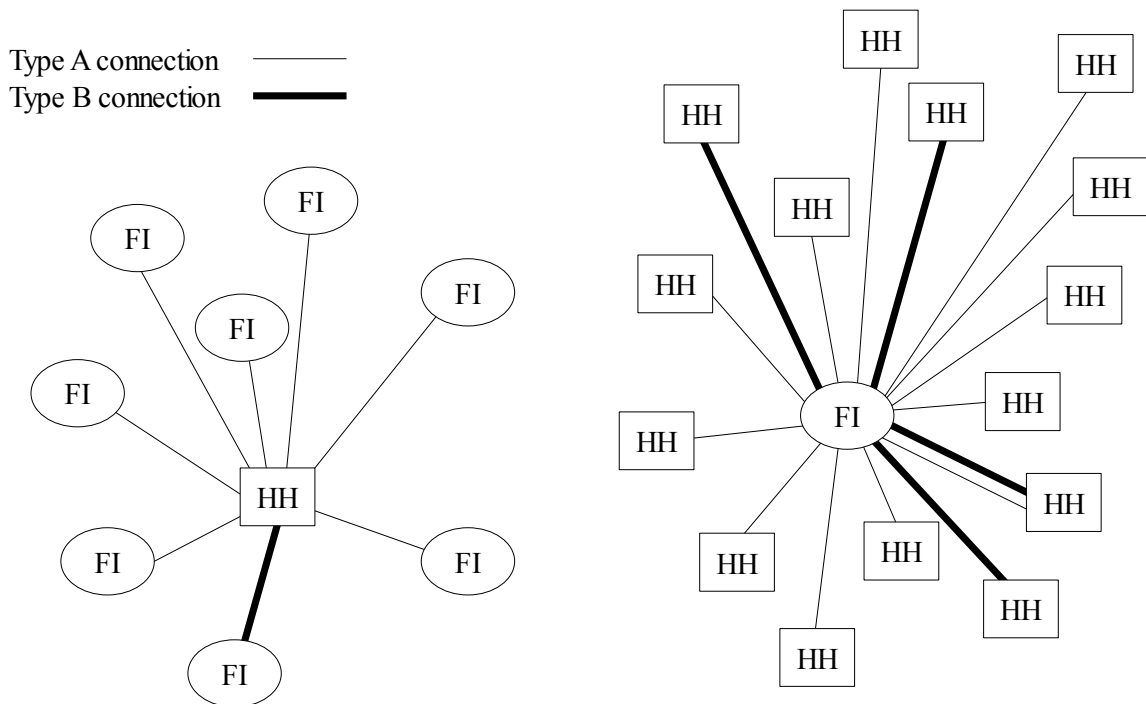


Figure 2: Example of the trading relation structure of a household (left) and firm (right).

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

²⁷The nodes of a bipartite network can be divided into two types. Each node is only connected to nodes of the opposite type.

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:

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

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

Setting k equal to $t - 1$, equation (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.

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

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 that he can only buy if he has previously gained enough income.

$$m_h \geq 0 \quad \iff \quad m_{h,initial} + \sum_{i=1}^{t-1} \text{income}_{t-i} \geq \sum_{i=1}^{t-1} \text{spendings}_{t-i} \quad (4)$$

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 . Following G2008 we assume that every household inelastically supplies one unit of labor. 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. Hence the law of one price does not necessarily apply. Firms do not know prices or wages of any competitor. Thus all knowledge is purely local.

2.2 Beginning of a Month

At the beginning of a month each firm has the decides 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 months. Following G2008, wage

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

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

The decision whether the number of employees or the price 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:

$$\bar{i}_f = \bar{\phi} \cdot d_f^{old} \quad (6)$$

$$\underline{i}_f = \underline{\phi} \cdot d_f^{old} \quad (7)$$

Where d_f^{old} is the demand for consumption goods of the most recent month and the parameters satisfy $0 < \underline{\phi} < \bar{\phi}$. 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 \bar{i}_f , a randomly chosen worker is fired, i.e. the corresponding type B connection is cut. 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 relation of inventories to sales. If recent sales are high compared to current inventories ($i_f < \underline{i}_f$) the firm considers to increase its price. In the opposite case of low sales ($i_f > \bar{i}_f$) 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 \bar{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.

$$\bar{p}_f = \bar{\varphi} \cdot mc_f \quad (8)$$

$$\underline{p}_f = \underline{\varphi} \cdot mc_f \quad (9)$$

Where the parameters satisfy $1 < \underline{\varphi} < \bar{\varphi}$. In analogy to the adjustment of w_f , prices are adjusted according to:²⁸

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

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

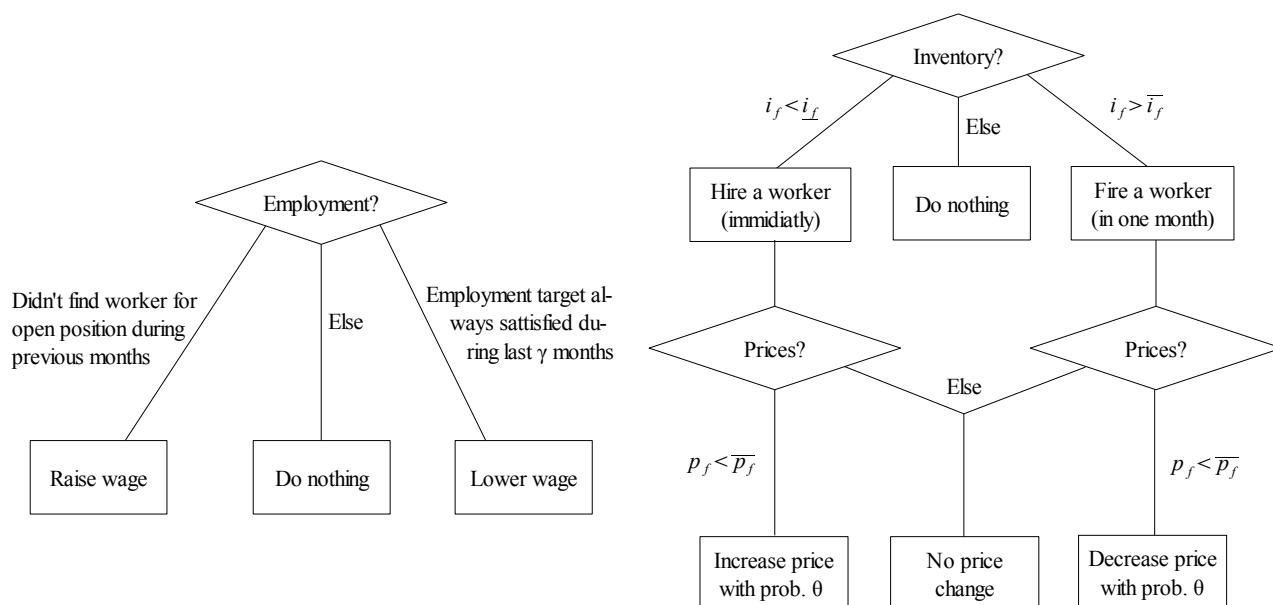


Figure 3: Flow chart of firms's decision procedure

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.

²⁸This rule is, like that for wage adjustment, also inspired by Gaffeo et al. (2008).

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 $\psi_{Quant} < 1$.

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 at least as high as the household's reservation wage ($w_f \geq \omega_h$), 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. 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 fundamental psychological law of Keynes (1936) we assume that real planned consumption expenditure increases with real liquidity but at a decaying rate.²⁹

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

Where P_h^I is the average goods price of all firms that household h has a type A connection with.

²⁹ A related approach is also used in Gaffeo et al. (2008).

And the parameter α satisfies $0 < \alpha < 1$. Since households receive income on a monthly basis, the decision of distributing it on consumptions and savings is also performed monthly. Accordingly c_h^r denotes planned real expenditures for the current month. If $\frac{m_h}{P_h^I} < 1$, equation (11) results in planned consumption expenditures that the household could not afford given the current amount of liquidity ($c_h^r > \frac{m_h}{P_h^I}$). To avoid such inconsistent planning behavior that violates the budget constraint, we change the equation to:

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

The planned real expenditure function is illustrated in fig. 4.

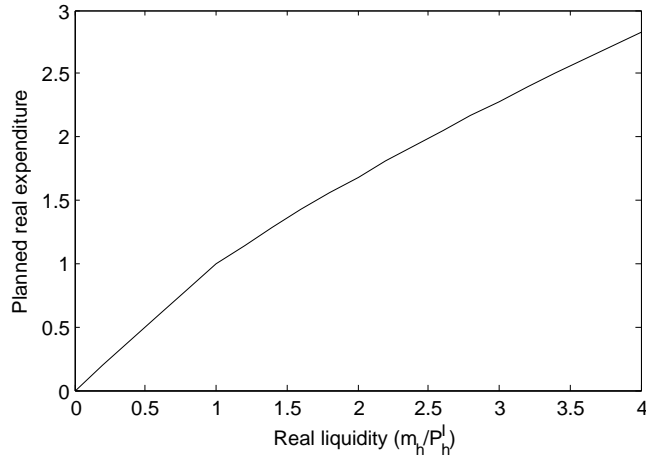


Figure 4: Planned real expenditure function ($\alpha = 0.75$)

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 $\frac{c_h^r}{21}$ and the household's liquidity is high enough to pay the goods ($m_h \geq p_f \frac{c_h^r}{21}$)

the transaction will be performed: The household's liquidity is reduced by the purchasing costs of $p_f \frac{c_h^r}{21}$, the firm's liquidity is raised by the same amount while its inventories are reduced by $\frac{c_h^r}{21}$.

If the household can not afford to buy the planned amount of goods ($m_h < p_f \frac{c_h^r}{21}$), his demand is reduced to the highest possible amount $\frac{m_h}{p_f}$. If the firm's inventories are lower than the household's 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% of the planned demand have been satisfied. Eventually remaining demand vanishes.

Next, each firm produces according to the production function:

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

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 firm's inventory is increased by the produced goods:

$$i_f^{new} = i_f^{old} + \lambda \cdot l_f \quad (14)$$

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. 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 . The 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. 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. For simplicity reasons, we do not introduce a third network structure for the allocation of profits.

In some cases the firm's labor costs might exceed the available liquidity. Consequently the firm can not afford to pay their workers. One would typically expect the firm to raise a credit or to

go bankrupt in such a case. However there are no banks in the model that can grant a credit. Furthermore the number of firms is constant since growth should not be considered. In order to deal with this problem of negative liquidity, money is simply transferred in the opposite direction. Instead of firms paying out profits to households, we let households pay the firms deficit. While this assumption seems unrealistic, it shall be emphasized that the occurrence of negative profits is a rare event that does never last very long. Most of the affected firms become profitable again after one or two months. Real world firms would also not be removed from the market immediately after operating unprofitable such a short period of time.

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. Instead, the household intensifies his search for a better paid job (section 2.2). If a household has been unemployed during the last month, his reservation wage is reduced by 10%. 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 can not be "solved". Instead, we will simply calibrate the parameters, set all properties to initial values, and let the agents interact in the predefined way. 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 on "the goods market" or "the labor market", it is performed at the micro level through the network of trade relationships. Each agent has a unique set of connections to agents of the opposite type. Since these connections evolve endogenously, markets – and hence their properties like existence and stability of equilibria – are themselves endogenous objects. Agents are heterogeneous with respect to their properties (internal states) and their positioning in the network.

3 Numerical Simulation

Now that the model is defined, we check whether it can match some of the stylized facts of aggregate dynamics. All simulations are performed using the calibration given in table 1.

Table 1: Calibration of the Model

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

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 check whether or not the artificial economy arrives at a general equilibrium state or not. Figure 5 displays a histogram of the the goods demand that households were not able to satisfy in relation to the planned demand. This relative unsatisfied demand is very small: In 95% of all periods it has been smaller than 0.65%. The course of aggregate employment for a subperiod of 50 years is illustrated in figure 6.³⁰ The number of employed households ranges between 958 and 1000. Since the total work force consists of 1000 individuals, this corresponds to an unemployment rate between 4.2% and 0%. We can thus conclude that the artificial economy arrives at a state close to a general equilibrium but with the presence of 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 involuntary unemployment of a realistic size. Real world economies show much higher unemployment rates but since we did not model voluntary and structural unemployment our model necessarily produces lower 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 interaction of agents who employ simple behavioral rules can lead to an almost fully efficient allocation on the aggregate level.

³⁰The rest of the simulated periods show similar patterns but have been excluded for visual convenience.

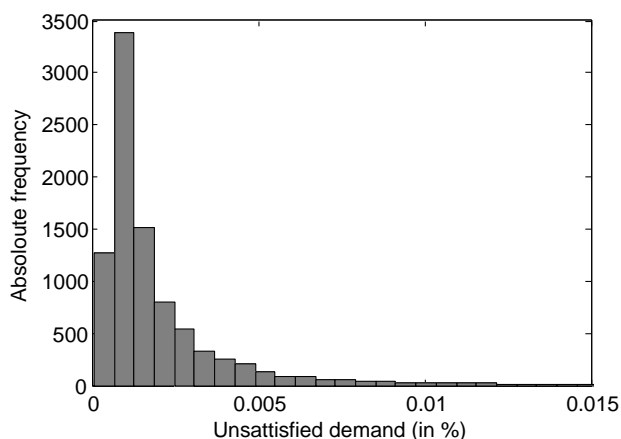


Figure 5: Excess Demand

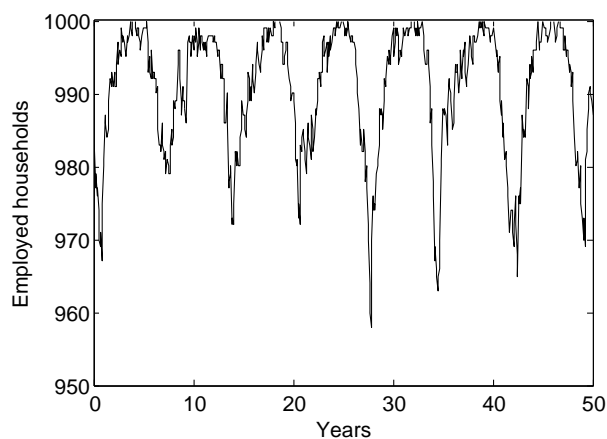


Figure 6: Employment

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.³¹ No individual possesses the information or the computational power to calculate it. The same is true for the ABC model. The efficient state is reached by cutting and rewiring connections in a network of agents. An operation, that can not be performed by individuals in isolation. Finding the equilibrium is therefore an emergent property of the aggregate.³² In contrast to DSGE models, we have explicitly modeled the working of the invisible hand and did not simply presume its existence.

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, ...) on the economy. In the ABC model, however, this feature is endogenously occurring (figure 6). 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.³³

Business cycles in standard macro are often understood as stochastic deviations around a trend. In the ABC 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

³¹ Hayek (1945), Al-Suwailem (2010)

³² See also Epstein (1999).

³³ 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).

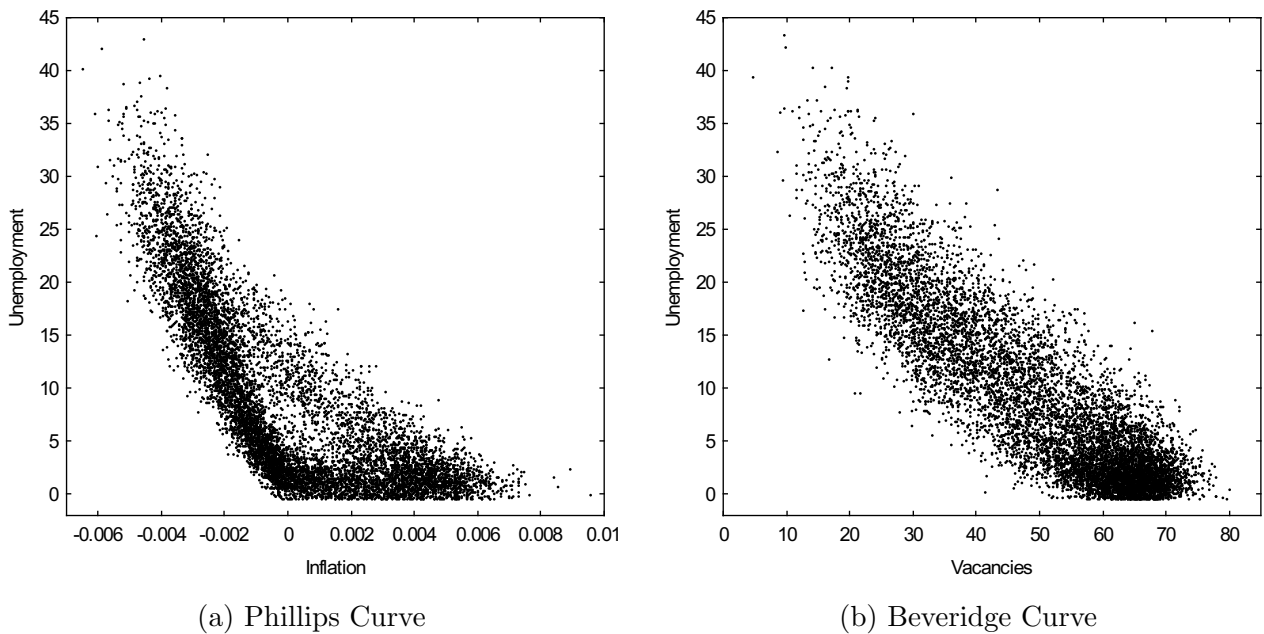


Figure 7: Empirical trade-offs between unemployment and inflation / vacancies

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 ABC model there are no stochastic peaks above potential output. Therefore it is generally possible to fill the troughs without shaving the peaks.³⁴ Stabilization policy might thus perform much better in ABC models than in DSGE ones.

G2008 and Gatti et al. (2008) have suggested to judge an ABC macro model by its ability to reproduce aggregate empirical "laws" like the Phillips curve or the Beveridge curve. As shown in figure 7 the model is able to reproduce both of these empirical laws.³⁵ Another stable empirical finding mentioned by the authors is that the distribution of firm size is right skewed. Again the ABC model can mimic this fact quite well (figure 8; sample skewness is about 1.72). Nakamura & Steinsson (2008) have found that the frequency of price changes follows a right skewed distribution with median between 9% to 12% per month. The ABC 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 0.35) with a median of 11%.

³⁴This idea is not new for behaviorally oriented economists. See for example Yellen (2007).

³⁵Since 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 figure 7.

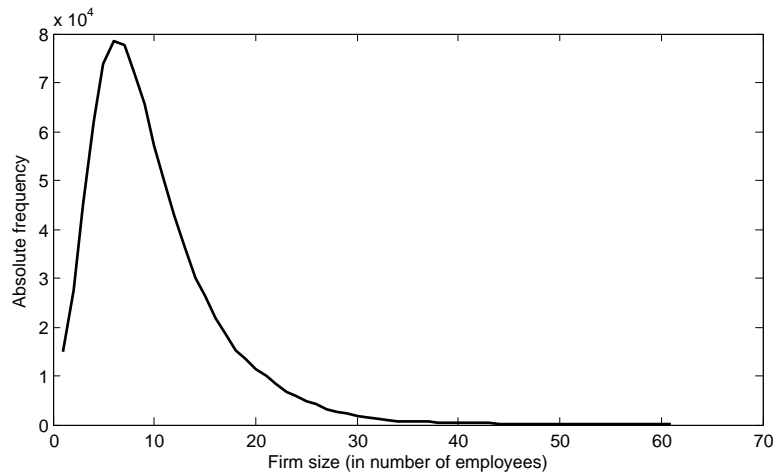


Figure 8: Firm Size Distribution

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 (2003) inflation tends to be below trend when GDP is above trend and increases in GDP tend to be followed by increases in prices. Figure 9 displays the correlation structure of output with lagged price index. The solid line displays results of simulated time series while broken lines represent US data including and excluding the recent financial crisis.³⁶ The basic ABC 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. The quantitative values of correlation for simulated time series are higher than for empirical ones. This may indicate that the model produces aggregate cycles that are "too regular" (see also figure 6). Future research should be directed to improve this point.

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.³⁷ The ABC model suggests a very different implication. The simulation run has not been subject to any shock. Therefore the correlation structure might be a generic property of market economies and not the result of any kind of exogenous shock.

It has been mentioned above that the model contains no goods or labor markets in the traditional sense. Likewise there is also no market for money, where supply and demand of money are balanced

³⁶ Empirical time series have been detrended using an HP-filter.

³⁷ Kydland & Prescott (1990), Judd & Trehan (1995), Ball & Mankiw (1994)

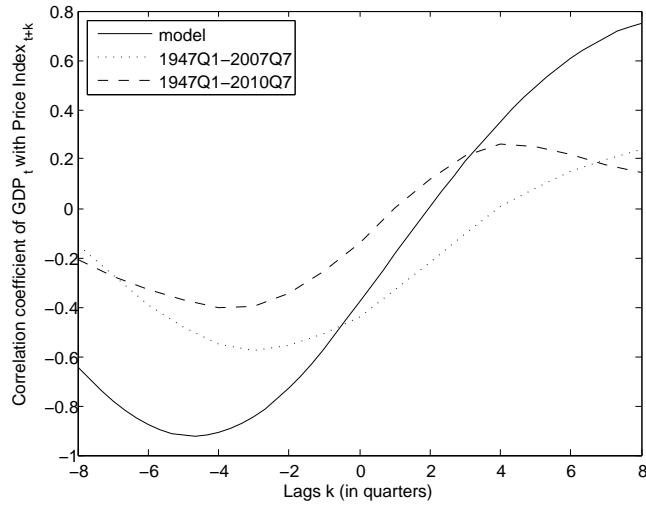


Figure 9: Correlation of GDP with lagged price index

by the interest rate. Because the model should be a baseline one, no additional network for trading money and no banks are included. Therefore it remains to clarify which role is assigned to money.

Every agent has the *liquidity* property 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 are exchanged between two agents, liquidity (or money) is exchanged in the opposite direction. Instead of introducing money on top of a working model that is defined in real terms, the ABC model is stated as an exchange economy and therefore assigns an explicit and natural role to money from the outset.³⁸ Note however, that we did not explain how money originally entered the model. We simply assumed that a fixed amount is present. Augmented future versions of the model should introduce a banking sector and a central bank to endogenize the money amount.

This role of money as the medium of exchange is visualized in figure 10. 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 to zero while that of households rises sharply. The

³⁸ Consult for example Woodford (2006), Goodhart (2007) or Arestis (2009) on the role of money in contemporary New Keynesian DSGE world.

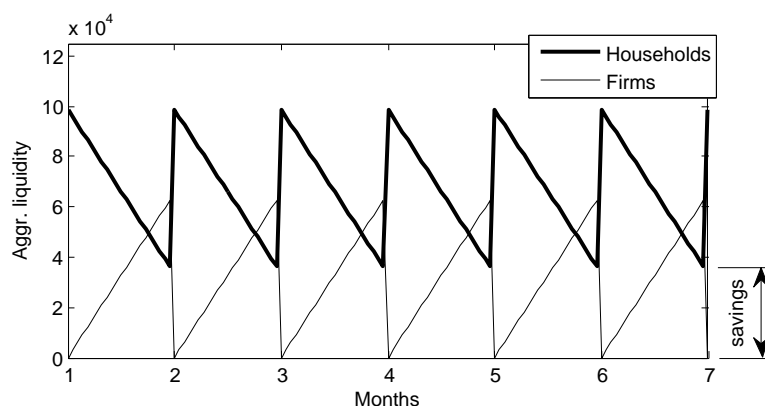


Figure 10: Aggregate liquidity of households and firms

next month begins and the pattern repeats. Now that the role of money has been clarified, we can turn to the analysis of monetary policy.

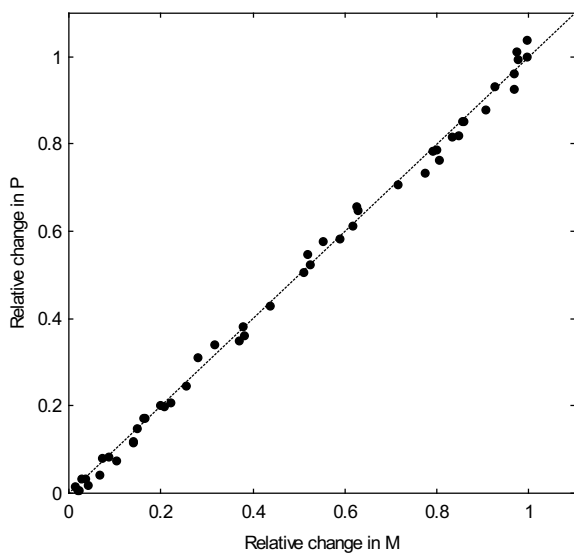
4 Monetary Policy

The effect of monetary policy in the long run crucially differs from that in the short run. It is widely accepted today that a relative growth in money supply in the long run creates only inflation and has no influence on the level of production.³⁹ To check whether this property holds in the ABC model, we run another 50 simulations. In each simulation the money amount is raised randomly by an amount between 0% and 100%. Practically this is done by multiplying the liquidity value of all agents by a factor between 1 and 2.

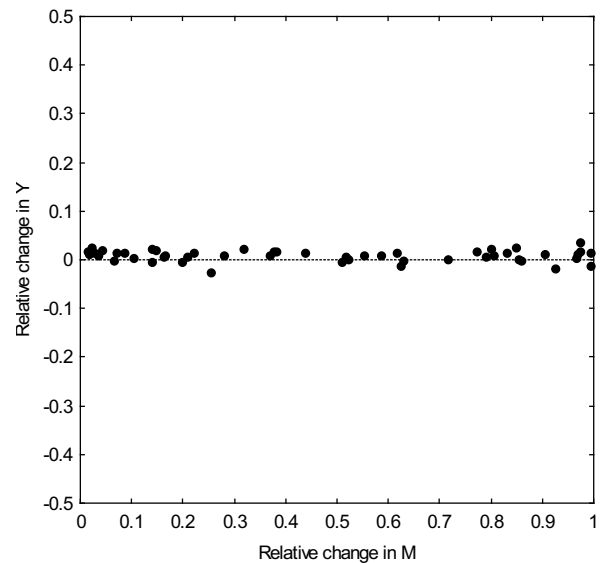
Figure 11 (left panel) shows a scatter plot of the relative change of the money amount against the induced relative change in the price level after 100 years. The induced relative difference in production after 100 years is given in the right panel. Since all points in the left panel closely follow a 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 in the ABC model. Inflation is – at least in the long run – a monetary phenomenon. The effect of monetary policy in the short run is somewhat more controversial in the literature. It is however accepted that it is not neutral with respect to real variables. To analyze the short run effects of monetary policy, we perform the following experiment:

1. Generate the model dynamics for one simulation run.

³⁹For an introduction into monetary policy (in the long and short run) consult Walsh (2003).



(a) Effect on Price Index



(b) Effect on Production

Figure 11: Long run effects of an increase in the money amount

2. Generate the same dynamics with identical realizations of the pseudo random numbers, but with an increase of the money amount by 5% in one 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 2,500 times.

Figure 12 illustrates the mean differences in price index and production that are resulting from the monetary shock in the short run. The price index rises until it reaches its peak after $4\frac{1}{4}$ years. The GDP on contrast increases sharply in the first year. Both time series decrease afterwards and follow a cyclical path with decreasing amplitude around their long run average (horizontal line) until they finally disappear after some decades. The short run non-neutrality of an expansionary monetary shock has thus also been reproduced by the ABC model. In the next section we are going to turn our attention to a very different kind of shock that does not hit the overall economy at the aggregate level.

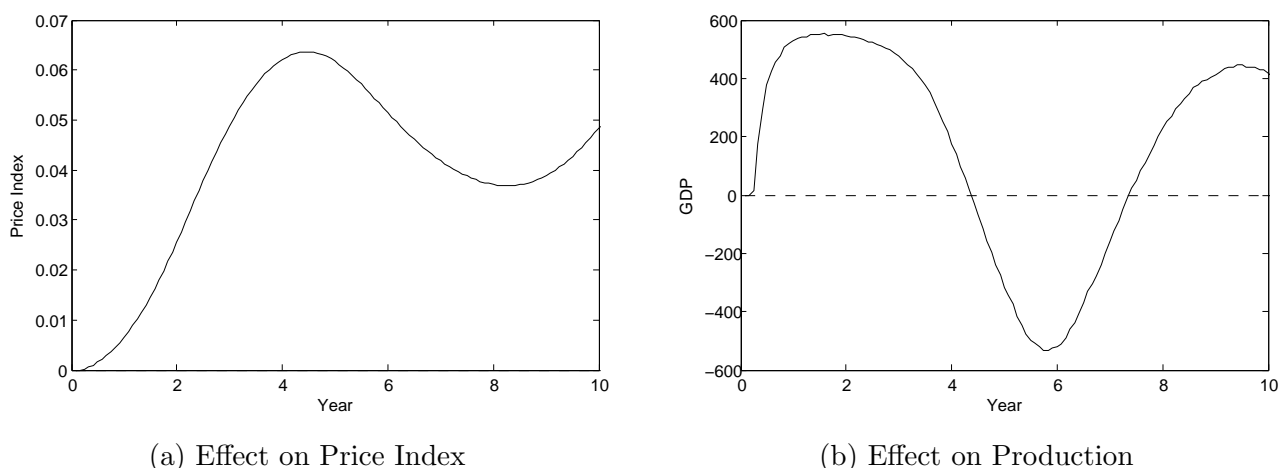


Figure 12: Short run effects of an increasing the money amount

5 A Pinch of Chaos

Can a single person spending €5 more or less at one particular day change the business cycle significantly? Yes! 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 on the aggregate level, we perform a very "small" one on the micro level. At one day in the middle of a month we reduce the demand of one household by 5%.

Figure 13 illustrates the mean impact of this shock as the mean difference between the trajectories including the shock minus those excluding it (thin line). The mean impact is practically zero for all periods following the shock. Therefore the small shock does not make a significant difference to the aggregate dynamics on average. The bold lines illustrate the mean of the same differences in absolute value. Since it is significantly 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 100 years after the shock.

The shock is extremely small in relation to the aggregate.⁴⁰ But since the decisions of all individuals are interrelated it can propagate through the network structure and make huge changes to

⁴⁰Only one of 1000 households reduces the demand at only one of 21 days by only 5%.

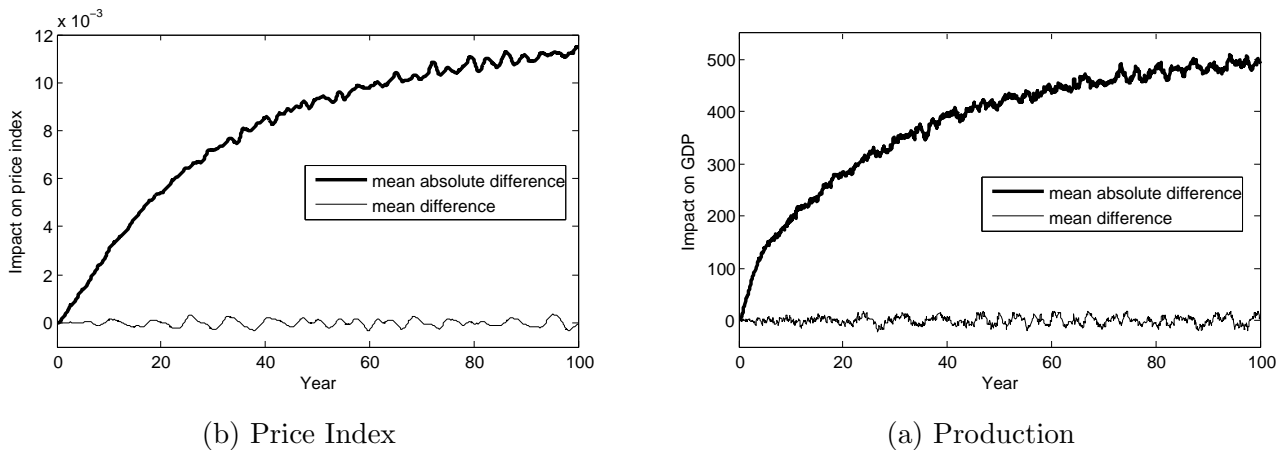


Figure 13: Effect of a tiny change in demand of one household

the aggregate developments some decades later. The mean absolute difference after 100 years equals the mean absolute difference of production in the 500 years simulation of section 3 and therefore it equals the mean absolute difference between all possible values of production weighted with their probability of occurrence. This proves, that a tiny change somewhere on the individual level can change the business cycle after some years significantly (e.g.: turn a peak into a trough) and the provocative statement at the beginning of this section is true. Such effects are common for complex systems and known as butterfly effects.⁴¹ This result *a posteriori* justifies the use of simple adaptive rules of behavior, because individuals can not expect the future rationally if all tiny changes that occur somewhere on the individual level can change the aggregate in such a tremendous way.

6 Conclusion

We have developed a baseline ABC macroeconomic model. The only economic agents it consists 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 that emerge endogenously from interaction, reasonable levels of involuntary unemployment, empirical laws like the Phillips or Beveridge curve, right skewed firm size distribution, a median value of price change frequency between 9% and 12%, dynamic correlation structure between output and inflation, long run neutrality and short run non-neutrality of the money amount.

⁴¹ 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 macroeconomy in our model.

At the same time, the criticism often raised recently among macroeconomists does not apply to the presented model. First, the passage from micro to macro takes individual decisions and interactions into account. Behavioral and experimental economics provide us with ever more insights into the decisions of real human beings. ABC macro is a method for bringing these empirically observed individual behavior to the aggregate level in a 100% consistent way.⁴² Hence, the ABC method (in contrast to DSGE) deserves the attribute *microfounded*. Second, the model does not rest on the assumption of equilibrium. Instead, equilibrium is shown to be an endogenously emerging result of the market. Consequently disequilibrium and coordination failure is not ruled out by assumption. A property that makes ABC 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 using them. Nonetheless we were able to show that these agents managed to organize themselves closely to a general equilibrium.

The recent global economic collapse has brought a critical discussion about the methodological foundations of macroeconomics on the agenda. It has been shown in this paper, that ABC modeling is a promising new tool to counter 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. The aggregate economy has its own patterns and properties that can not be deduced directly to utility optimization calculus. Thus it allows for a re-emancipation of macro from micro dominance without neglecting microfoundations.

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⁴² Consult Duffy (2006) on the relation of human subject experiment and ABC modeling.

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