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## Optimal Monetary Policy Responses to the Financial Crisis in the Context of a Macroeconomic Agent-Based Model with Dynamic Expectations

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**Optimal Monetary Policy Responses  
to the Financial Crisis  
in the Context of a Macroeconomic Agent-Based Model  
with Dynamic Expectations**

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**PRELIMINARY DRAFT WITH SHORT INTERPRETATION – NOT TO BE QUOTED**

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Agent-based economics, Mult-agent models, monetary policy, fiscal policy, expectation formation

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**Abstract**

Within the context of an agent-based macroeconomic model with dynamic bounded-rational expectations, the most important transmission links between the real sphere of the European economy and the US financial markets crises are simulated: (a) the devaluation of financial assets, (b) global interest rate changes, (c) the drop in US demand on the world markets, and (d) loss of confidence in banks, companies, and markets. Depending on the specification of the expectation formation process, optimal monetary policy reactions change significantly. We conclude, that expectations matter, even more for calculating optimal monetary policies than for simply simulating the model.

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## 1 Introduction

The global financial crisis, which has emerged from the US subprime crisis, has led to substantial economic difficulties in Europe and all over the world. The public discussion focuses on a loss of total economic wealth (which of course can only occur, if the real wealth is destroyed) due to failure of global financial market regulation. Nevertheless, the most important transmission links between the real sphere of the (European) economy and the (US) financial markets are (a) the sudden and severe devaluation of financial assets held by European banks and other economic subjects, (b) global interest rate changes, (c) the drop in US demand on the world markets affecting foreign trade, and (d) loss of confidence in banks, companies, and markets.

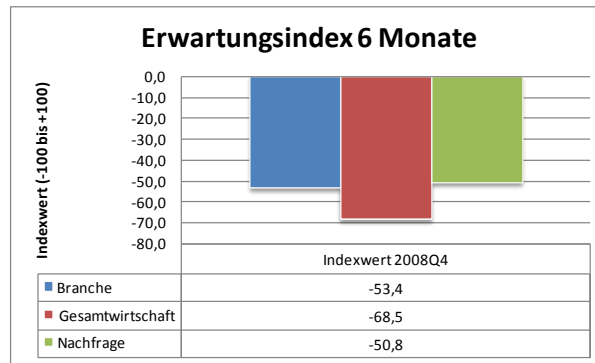
In this paper, all of these main aspects will be investigated within the context of an agent-based model for the Euro Zone (AS1 – vE2009b). The main goal is to calculate optimal policies within the context of the present financial crisis and given US monetary policies. As an additional aspect, macroeconomic effects for Austria, as an example for a small open economy facing an exogenous shock are investigated in more detail.

*Figure 1-1: ATX historical data (Vienna Stock Exchange index)*



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Figure 1-2: Expectations of companies concerning output and demand (Austria, December 2008)



Historical data from the Austrian stock market, as an example for world markets, clearly shows the financial bubble, which had been built-up and collapsed during the last years. Empirical evidence thus gives a clear indication on the importance of the early development of excessive growth expectations for the following hard landing of the economy.

As can be seen from economic forecasts (again for Austria, December 2008), there is an interesting inconsistency of output expectations for the whole economy and the (weighted) average expectations over all industries. Companies were much more pessimistic on the overall economic perspectives than on their own industries – which of course logically cannot hold on the aggregate level. Thus, we may conclude that there are no rational expectations involved in the process of the present slow-down of the economy. This is a clear indication for agent-based models with fine-grained rational expectations.

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## 2 Modeling Expectation Models inside the Model

One of the most prominent features of AS1, which is also very important for this exercise, is the explicit modeling of the information formation process by applying dynamically re-estimated models inside the economic multi-agent model. In order to achieve this, one or more separate economic research institute instances are set up for calculating forecasts of the economy. This is an extension to present work involved in multi-agent systems, because the traditional agent-based modeling approach focuses on the behavior of “smart” agents and the selection of individual strategies. This, of course, implicitly includes some adaptive or even forward-looking expectations, but the expectation formation process is generally not explicitly taken into account or modeled separately. An advantage of this encapsulation is the extensibility and explicit control over expectations. Apart from these important design features associated with such explicit expectation formation described earlier in the text, the implementation of a “model inside a model” should be considered in greater detail.

The present version of AS1 contains OLS regressions and simple VAR models. There is a class in AS1, which is called the `OLSMODEL` class, containing all the methods needed to calculate forecasts, based upon the “historical” information generated in the agent-based model. Based upon some of the concepts (and even some code) implemented in the `OLSMODEL` class, the `VARMODEL` class is capable of providing the statistical framework methods to estimate VARS and use them for forecasting.

Within the context of the agent-based model, model selection by the economic agents is introduced and investigated for monetary policy reactions upon a sub-prime

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financial shock. This is a good example of model modifications affecting the expectation and decision structures of the agents. To achieve this, the standard single economic research institute in the model is replaced by three alternative and competing research institutes that produce regular forecasts of the economy, which are published to all of the economic agents. The first research institute simply takes the previous value of a variable as a forecast of the future values for all future periods; the forecasts of the second research institute are based upon weighted backward-looking expectations over three periods (see specification below); the third economic research institute uses a simple VAR model.

$$E_{t+n}(x_t) = \frac{\sum_{i=1}^3 x_{t-i}}{3}, \text{ for all } n > 0$$

(Backward-looking expectations)

The setup with the VAR model can be seen as an “economic model within the agent-based model”, which uses time series input from the agent-based model in order to calculate dynamic forecasts by simulating the VAR model iteratively. For this application of AS1, expectations for price level (and inflation), output and private consumption are used. The VAR model contains the variables; real gross domestic product (GDPR), real private consumption (CPRIR), gross real private investment (INVPBR), real imports (IMPR), real exports (EXPR), and the price level (PRICE) as measured by the GDP deflator. Real government (public) consumption (CGOVR), gross real public investment (INVOBR), and net taxes are also included as exogenous variables to improve the goodness of fit. According to the methodology of a VAR model, even parameters not significant are kept in the estimation.

	GDPR	IMPR	EXPR	PRICE	CPRIR	INVPBR
GDPR(-1)	1.1982	1.0169	0.6012	0.0000	0.7919	1.0237
t value	1.1311	0.8278	0.4749	-0.1197	3.1050	1.2843
GDPR(-2)	-0.3480	-1.3656	-0.6390	0.0000	-0.5928	-0.2573
t value	-0.4859	-1.6444	-0.7466	0.6371	-3.4382	-0.4774
IMPR(-1)	-1.3443	0.9224	-0.4024	0.0000	-0.6096	-0.2627
t value	-2.0193	1.1948	-0.5058	-1.0907	-3.8031	-0.5243
IMPR(-2)	0.6638	-0.8604	-0.1207	0.0000	0.1005	0.6606
t value	0.4461	-0.4986	-0.0679	0.1555	0.2805	0.5899
EXPR(-1)	1.4367	-0.3760	0.9455	0.0000	0.2625	0.0285
t value	2.6628	-0.6009	1.4662	1.3466	2.0208	0.0701
EXPR(-2)	-1.3685	0.0999	-0.7557	0.0000	-0.5516	-0.8749
t value	-0.8606	0.0542	-0.3976	-0.0218	-1.4404	-0.7311
PRICE(-1)	-8592	-13117	-9167	0.4744	6004	-7199
t value	-0.6740	-0.8873	-0.6016	0.5674	1.9562	-0.7504
PRICE(-2)	10241	12970.7226	8608.9632	-0.0868	906.2263	5887.3330
t value	0.9802	1.0705	0.6894	-0.1267	0.3602	0.7488
CPRIR(-1)	-0.7147	-0.5753	-0.2324	0.0000	-0.7041	-0.5849
t value	-1.0669	-0.7406	-0.2902	0.7539	-4.3652	-1.1603
CPRIR(-2)	1.3269	2.2859	1.8982	0.0000	0.3795	0.9648
t value	1.8398	2.7333	2.2022	0.4678	2.1853	1.7778
INVPBR(-1)	0.2669	-0.4974	0.3687	0.0000	0.6152	-0.1230
t value	0.2151	-0.3456	0.2486	0.5569	2.0590	-0.1318
INVPBR(-2)	0.4209	1.9476	0.6634	-0.0001	0.9757	-0.0505
t value	0.3522	1.4051	0.4644	-1.2627	3.3903	-0.0562
Constant	-152456	-507120	-577502	-28.5684	33716.56	-469499
t value	-0.2404	-0.6894	-0.7618	-0.6868	0.2208	-0.9836
INVOBR	0.5546	-4.0704	-4.1473	-0.0001	1.3484	-0.0938
t value	0.2116	-1.3395	-1.3242	-0.7387	2.1371	-0.0475
CGOVR	-0.3097	1.4213	0.7079	0.0002	-1.1507	-0.4762
t value	-0.1021	0.4040	0.1952	0.9156	-1.5754	-0.2086
NTAXTR	-0.0643	-0.2533	-0.1002	0.0000	0.3699	0.0204
t value	-0.0854	-0.2899	-0.1113	-0.1087	2.0390	0.0361
R <sup>2</sup>	0.9992	0.9988	0.9987	0.9997	0.9999	0.9959
R <sup>2</sup> adj.	0.9964	0.9941	0.9939	0.9988	0.9994	0.9805
F statistic	350.1944	215.5016	206.3749	1030.7354	2089.8191	64.8510

Table 2-1: Estimation results of the VAR model (see Haber, 2002)

Obviously, the VAR model is not the “true” model of the artificial economy, but should be reasonably close. We would expect that the fit of the VAR model is better than the fit of the other simple models. Expectation errors may arise in both models and agents may chose to change their behavior based upon these forecasts. Moreover, agents might change their interpretation of the forecast data and decide upon using



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this data or not. Now, agents are free to choose one or the other model and may decide which model they prefer. Model selection is implemented by a genetic algorithm, and each agent uses a multivariate linear function to produce its individual forecasts for the main economic indicators of the economy as a linear combination of the alternative announcements. Thus, each agent has its own “private” model of the economy, based upon the three alternative forecasts for the economy.

For this purpose, a specialized GA class, the `GENETICFUNCTION` class, is introduced. This class implements a general form of a linear function with an arbitrary number of parameters. The function object includes a tunable number of parameter sets, encoded as DNA strings. For the purpose of this exercise, the default parameters are used with 10 genetic parameter sets and a selection rate of 70 percent. The remaining parameter sets are modified by a genetic cross-over operation, followed by a mutation operation with 2 percent mutation probability (on the bit level). The fitness of the forecast can be easily defined by the relative ex-post deviation of the forecast from the actual values. Note that in fact there is an internal calculation of fitness within the `GENETICFUNCTION` class, scaling the fitness values for improved efficiency, but the agent applying this class only has to supply the actual (or perceived) values of the previous period for calculating the values of the fitness function.

To implement different approaches for learning, the following alternative specifications are introduced as heuristic strategies:

- “Empirical value” (EV): If agent fitness increases, the weight of the research institute is also increased (delta: 0.1). This is basically some subjective individual reinforcement learning approach.

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- “Ex-post performance” (EPP): Agents increase the weight of a research institute, each time it performs better for the previous period than the other (delta: 0.1). This strategy could be regarded as objective individual reinforcement learning.
  - “Learn from the best” (LFTB): A proportion of the agents (50 percent) just copy the genetic information from the other 50 percent, which performed better in the last period in terms of income (which is taken as a fitness function), then mutation is applied.

Thus, we have three alternative expectation formation scenarios including all of the three forecasting models, where the agents follow alternative model selection rules (EV, EPP, LFTB).

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### 3 Modeling Monetary Policy in an Agent Based Model

Modeling economic interactions and mechanisms is one of the most prominent and important tasks in empirical work in economics. Alternative modeling strategies differ with respect to premises, objectives and typical difficulties. Several models used for empirical purposes follow very different methodologies and paradigms (for an idea of the range of different approaches see e.g. Fair, 1984, 1992 and 1994; McKibbin/Sachs, 1991; Sims, 1980 and 1996; Taylor, 1993). An explicit microfoundation for macroeconometric models has been treated, among others, in Malinvaud (1956). Traditional approaches to constructing partial or even total models of the economy on a macroeconomic level (econometric models, general equilibrium models, pure time-series models, stylized mathematical models, etc.) have always suffered from a lack of microfoundation and a low degree of detail with respect to questions related to distribution, substitution effects, growth, and expectation formation, for example.

Consequently, economic multi-agent systems have gained more and more attention over the last decade, also for the purpose of policy analysis (details on this kind of application are given e.g. in Akerlof, 2002) Russo et al., 2007, apply an agent-based model for fiscal policy analysis, and several papers have dealt with policy analysis on the micro level, an early contribution being Midgley et al., 1997, for the design of the coffee market). By modeling individual economic agents on the micro level and aggregating their behavior on the macro level, artificial economies can be constructed which are “richer” than the traditional macro models. The main difference in this paradigm compared to traditional modeling strategies is the absence of structural behavioral equations on the aggregate level and the ability to take different

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strategies into account regarding information processing and the action patterns of the agents. The advantages of economic agent-based models are primarily (but not limited to):

- the possibility to model dynamic or evolutionary processes,
- room for heterogeneity of the agents,
- the application of dynamically evolving expectation models embedded within the agents,
- the scalable degree of detail in certain parts of the model, and
- support for highly non-linear and/or probabilistic models.

On the other hand, most agent-based models do not provide a comprehensive picture of the economy as they are not fully-specified total models of the economy (one of the few other examples, EURACE, is described in e.g. Deissenberg et al., 2008/ van der Hoog et al., 2008). For many applications, including analyses of institutional setups or partial micro markets, this is no problem, but for general monetary and/or fiscal policy analyses, this might influence the results. Moreover, calibrating such models is generally difficult because the large number of potentially heterogeneous agents leads in turn to a huge number of parameters in the model. This may result in a perfect ex post fit, but may also lead to very low predictive power. As a consequence, agent-based economic models have rarely been applied to high-level macroeconomic policy analysis (one of the very few papers is Russo et al., 2007, analyzing the effects of the tax rate on aggregate output), but rather to problems with a strong microeconomic focus on a certain industry or market, or

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general analyses of processes of evolution and growth, where the strengths of this paradigm can be fully exploited.

There are several features of agent-based models useful for macro-economic policy analysis: For monetary analysis, the model has to include all the main markets in the economy, and especially the monetary sphere of the economy. Moreover, the public sector itself has to be present in sufficient detail for fiscal analysis. Standard macroeconomic policy analysis traditionally tends to oversimplify the policy instruments and often avoids an operational definition of which instrument is altered to which extent.

A traditional analysis of monetary policy suffers from simplifying the monetary instrument(s) and target(s). Two approaches have been widely used in the literature for modeling a “general” monetary instrument: either “money supply” is seen as an instrument or “the interest rate” (examples are e.g. Taylor, 1993; Fair, 1994; Bundesbank, 1996; Haber, 2002). Both stylized pictures are, of course, empirically doubtful as we know that the monetary aggregates, such as M1 or M3, cannot be successfully controlled by a central bank and that the (various heterogeneous!) market interest rates cannot be set directly by the central bank, as they also depend crucially on endogenous money demand (see Haber, 2002). Neglecting the macroeconomic interactions between money supply and the economic feedback on money demand tends to overestimate the power of the monetary instrument and underestimate the distortion produced by the intervention. As a consequence, when calculating optimal economic policies with econometric models, frequent and too intense variations in the monetary instrument have to be ruled out, e.g. by including the monetary instrument in the objective function (see e.g. Feichtinger/Hartl, 1986).

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For macroeconomic policy analysis with an agent-based model, a rather detailed approach has to be used because we need to capture at least most of the relevant macroeconomic markets in sufficient detail. The AS1 model used here (Haber, 2008) is one such comprehensive model for economic policy analysis applications. Specifically, the monetary sector of the economy is modeled in great detail, and both the central bank and the public sector are set up as separate agents with their own expectations and optimization efforts. Expectation formation plays a central role in the model.

DRAFT

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## 4 Overview of the Model: the Agent-Based Model AS1

Multi-agent models provide the opportunity to design economic models bottom-up in an agent-based manner. Here, the agent-based model AS1 (Haber, 2008) is used, introducing an important feature for the analysis of economic policy: The model is closed on the macro level, i.e. it is fully specified as a total model of the macroeconomic system, rather than focusing on only some specific micro markets. Of course some complex methodological difficulties are involved in this approach, especially with respect to calibrating and validating the model (see, e.g., Gilli/Winker, 2003, Fagiolo et al., 2007, and Winker et al., 2007). An iterative approach has been selected to overcome these calibration issues, which provides a stable model with a good dynamic fit. In particular, data on the Austrian economy has been used to calibrate the current version of the model to empirically fit the period 2000 to 2006. In this paper, a single-country version of the model is used.

### 4.1 MODEL STRUCTURE AND CONTROL FLOW

The model is basically a 2D landscape multi-agent model implemented in C#. Agents are stationary in the landscape but it also includes geographic features, which are called the “infrastructure layer” of the model. The infrastructure layer can be used to implement a geographical structure which goes beyond the simple rectangular layout but it will not be used for the simulations presented here. The initial geographical distribution of the agents is chosen randomly (following a uniform random distribution with no gravity spots), with the central bank and the government located in the center of the landscape.

All of the agents in AS1 are able to perform self-motivated smart actions which are triggered by the “world”, a kind of super-agent containing all of the “regular” agents in the model. The basic idea in agent-based models, calling one agent after another to perform their actions, is not sufficient for such a complex system in which information has to be gathered, expectations have to be formed, actions have to be prepared (bids and asks on markets), actions have to be actually performed, and behavioral parameters have to be updated. Instead of a single call to each of the agents, four stages are defined within the action cycle (default stage, pre-stage, main stage, post-stage). As suggested by the terminology, the most important actions (e.g. transactions on the goods markets) take place in the main stage while, for example, observing the liquidity constraints in the banking sector is done in the post-phase.

Figure 4-1 shows the most important types of agents in the model.

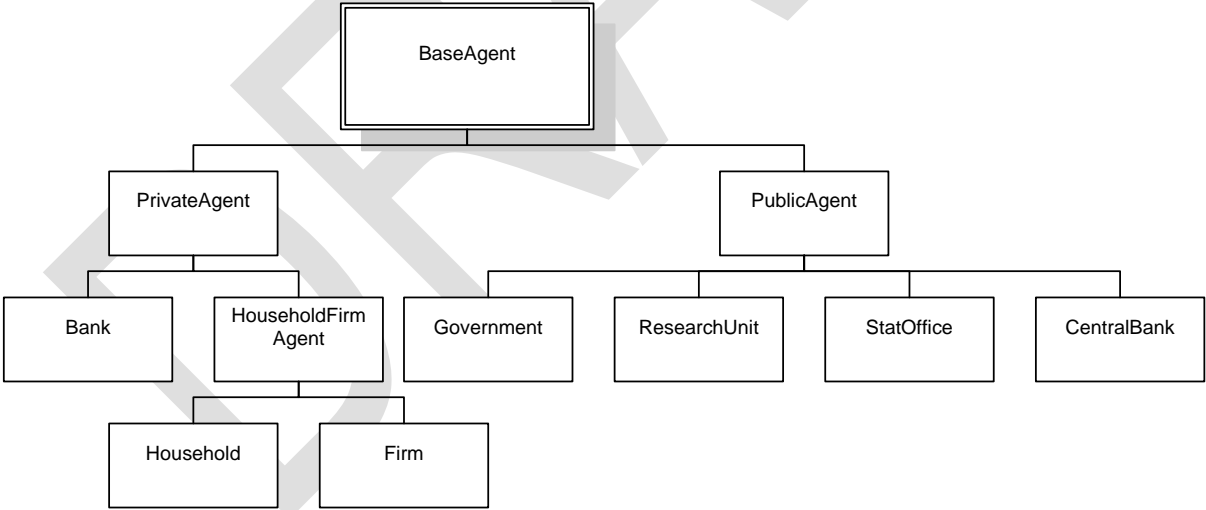


Figure 4-1: General agent hierarchy in AS1

There are no stylized types of traditional “auctions” in the market: The agents negotiate transactions on the goods markets directly – based upon their respective



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cost and utility functions, but also influenced by geographical vicinity and other factors which are not perfectly rational but which account for real-world observations with respect to customer decisions.

## 4.2 PRODUCTION AND CONSUMPTION

There are two types of resources: final goods and inputs. Goods are produced using human manpower and inputs. There are some interesting features in the goods markets. First of all, there is the concept of innovation in the model because the number and types of resources, both intermediate inputs and final goods, are not fixed. The model keeps track of all available resources, and in each round, new resources might be “invented” randomly. When new resources are invented, the production and utility functions of the firms and households are dynamically adjusted to include the new resources as well.

The CES production function is given by

$$(1) Y(x_1, x_2, \dots, x_n) = \left[ \sum_{i=1}^n a_i^{\frac{1}{s}} x_i^{\frac{s-1}{s}} \right]^{\frac{s}{s-1}} .$$

The output quantity  $Y$  is a function of the quantities of the factors of production ( $x_i$ ), where  $a_i$  are the parameters associated with each factor of production and  $s$  is the elasticity of substitution. By default, all the parameters are set randomly when the production function is set up; thus alternative production technologies might exist at the same time. The random values for the parameter  $s$  are limited by default to the interval  $[0.1; 10]$ , the  $a_i$  parameters are limited to  $[0; 100]$ . These values are selected arbitrarily and can be overridden in the simulations.

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The simple standard form of the utility function in AS1 which is applied for the simulations below is

$$(2) u_i = \frac{1}{a_{i1}} \ln(a_{i2}x_i + 1)$$

Partial total utility  $u$  by consumption of good  $i$  is given as a function of the two parameters  $a_{i1}$  and  $a_{i2}$ , taking into account the quantity consumed ( $x_i$ ). Total utility is computed as the sum of all  $u_i$ . Consumption is driven by the following schedule:

- In each period, agents look for available products in their geographical vicinity by asking sellers to quote the prices and available quantities of their goods.
- The agents buy a bundle of goods, subject to their liquidity constraints, by maximizing total utility and maintaining an initial proportion of  $l=0.2$  of their average income during the last  $p_s=3$  periods (“savings”).

Production and utility functions (and the marginal propensity to save) evolve in each simulation period due to the application of an evolutionary algorithm with genetic operators. In the simulations presented here, the  $a_{i1}$  and  $a_{i2}$  parameters of the utility function are altered in each period by mutation ( $p=0.01$ ) and cross-over ( $p=0.2$  for each parameter, with a weight of  $w=0.8$  for the current value and  $[1-w]$  for the weighted average of  $n=5$  agents of the same type in the vicinity). There is no fitness function for the utility function (no selection) as it simply reflects a change in preferences over time induced by individual changes and social mechanisms. For the production function, the objective variable is cost per unit produced.

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### 4.3 PRIVATE AND PUBLIC AGENTS

Private agents in the model consist of households, firms, and (private) banks. The hierarchy of these agents is as follows: There is an abstract “PrivateAgent”, which is the ancestor of all private agents in the model. Banks are directly derived from this basic agent, while households and firms are derived from an intermediate “HouseholdFirmAgent”, including e.g. all basic financial transaction capabilities.

All public agents are derived from a single prototype and comprise: the government, the central bank, economic research institutes, and a statistics provider.

In contrast to the simple assumption of a single interest rate level and the illusion of possible direct control of monetary aggregates (as explicitly formulated in most traditional economic models), the institutional design of the monetary sphere is included in the model. European institutions have been chosen as a template for the model. Agents in the model keep track of all the financial positions relative to each other and a rich set of financial contracts is available to the agents. There is a budget (or more specifically: liquidity) constraint for all agents; if this constraint is violated, the agents have to borrow money from a commercial bank.

The labor market is based on explicit labor contracts individually negotiated by the households and firms. There are a number of communication mechanisms between households and firms for such purposes. Due to some kind of “regional stickiness” in supply and demand, regional effects could also be investigated. In traditional macroeconomic models, a reduction in employment leads to an overall reduction in purchasing power, decreasing private consumption and thus lower demand on the aggregate level. In the agent-based model, firms firing their employees also suffer from the local and regional effects of their action because the drop in purchasing

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power might affect them more than firms located far away. Of course, these effects also depend on the preferences of the households, which determine whether the product sold by a specific firm is in demand locally or not.

One of the most important parts of the model is the expectation formation process. On the agent level, there are dynamic strategies, driven by genetic algorithms, which involve the agents learning, based upon genetic reinforcement on the individual level. Adaptive learning by genetic algorithms and possible applications in agent-based models have been described in detail e.g. in Dawid (1999), Arifovic (1994) and Arifovic (2000). These individual expectations are driven by “general expectations” available to all of the agents in the model. A special “economic research institute” agent is introduced as an institutional framework for the collective formation of expectations. This approach also allows for several competing forecasters applying different “models within the model” to calculate their forecasts. Thanks to this approach, a major design innovation can be implemented, namely heuristic dynamic model selection of the smart agents within the model. Due to the specification of the expectations of the agents as dynamically changing linear combinations of the forecasts calculated by embedded forecast models, a new design concept for rational expectations in economic models has been developed (Haber, 2008) where agents try to find and optimize the fit of a “true” model of the economy by inventing, selecting, and validating their own forecast models.

The following sections briefly describe some of the most important features in the context of monetary policy analysis: the model structure with respect to financial markets. Further details can be found in Haber (2008).

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## 5 Modeling Monetary Policy in AS1

### 5.1 THE MONETARY SYSTEM: MODELING THE CENTRAL BANK

There are several different systems of central banking all over the world with respect to the objectives and instruments of central banks. Most of the systems include at least three groups of monetary instruments: (a) open market operations, (b) discount operations, and (c) minimum reserve requirements (e.g. Fed, 2005; ECB, 2004; ECB, 2006).

The European Central Bank (ECB) is one of the most important central banks in the world and one of the most recently designed so the approach taken by the ECB is a key foundation for modeling central banks in AS1. The monetary policy operations of the central bank can also be seen as the refinancing tools for commercial banks and have been described in detail in the literature (see e.g. Scheller, 2004). As for banks in real life, some of the most important refinancing sources of commercial banks are the “main refinancing” operations of the central bank. The refinancing operations are announced by the central bank, in the next step the commercial banks submit their interest rate offers, and finally central bank money is allocated to the banks with the highest interest rate offers until funds are exhausted. As in the Euro system, all banks have to pay a uniform interest rate, the marginal lending rate.

The second key element for central banks in the model is the “standing facilities” instrument (marginal lending facility and deposit facility), whereby banks may borrow or lend money overnight (or rather “over-one-period” in the model). These two instruments are of great importance for the development of interbank interest rates because they represent natural upper and lower limits. Implementing standing

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facilities also prevents the financial markets in the model from exhibiting explosive behavior due to persistent money market disequilibria and ensures that the liquidity of the banking system is guaranteed.

The central bank follows an inflation rate targeting rule by default with an inflation rate target of 2 percent, which is similar to the real strategy of the ECB. In each period, the central bank calculates a weighted average of the previous inflation rate and the expected inflation rate as calculated by one of the research institute agents. Then this indicator is used to raise or lower the minimum bid rate of the main refinancing operations and/or the amount of money provided by this tender operation. In a similar fashion to the ECB, the interest rates of the standing facilities are adjusted accordingly (with parallel moves around +/- 1 percentage point with respect to the minimum bid rate). The parameters in the decision rule of the central bank are determined by a genetic algorithm whereby the fitness function is given by the reciprocal of the quadratic deviation of the actual inflation rates from the target values.

## 5.2 HOW TO MODEL FINANCIAL TRANSACTIONS

A model suitable for macroeconomic monetary policy analysis relies heavily on the careful modeling of financial transactions among the agents. The most important elements in this context are: accounts, books (objects containing all the financial relations on the agent level), and a standardized way of communicating financial information (i.e. about financial quotes, “bids” and “asks”). For transactions between central banks and commercial banks, there are some specialized objects for requesting central bank money via tender procedures or the standing facilities and keeping track of all these tender transactions.

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Inspired by traditional bookkeeping, all of the agents' accounts contain double entries. When financial assets or liabilities are created, each agent involved creates an account with the other agent in the transaction. This account stores all of the information associated with the financial position, including nominal value, maturity, nominal interest rate, fixed or variable interest rate agreements, and information as to whether the interest payments will actually be transferred or just added to the principal. By modeling so many details of the transaction, the monetary sphere in the agent-based model becomes very rich and fine-grained – which is a necessary condition for all kinds of monetary analyses.

Of course, some financial transactions have to be prepared in advance before being decided on by the agents. While wage payments in the model are “simply received” by the household as determined by the relevant labor contract, for example, loans have to be negotiated prior to agreeing on a specific quote. Generally, a request is set up by an agent interested in doing some financial transaction, and then the receiver of the request is asked to submit a valid quote – which the receiver, of course, may also reject, or modify as necessary (e.g. reduce the amount that could be granted). In the next step, the sender of the request decides whether to accept this offer.

There is virtually no other agent-based model available so far with such a detailed implementation of the banking sector and the relation of banks with commercial firms, households, the government and the central bank. The only model with a detailed focus on the central bank and a monetary instrument is applied in Raberto et al. (2008) but there are still no detailed interactions between the central bank and the commercial banks. When banks want to take part in the main refinancing operations

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of the central bank, they have to submit bids for the tender procedures. The central bank is capable of performing the actual tender operations by sorting the bids and assigning the correct volumes and interest rates to each of the bids. By default, the central bank applies European-style tender operations.

### 5.3 COMMERCIAL BANKS AS THE LINKS OF MONETARY TRANSMISSION

Commercial banks are the backbone of the financial system, both in the real world and in the artificial agent-based model world. Banks in the model accept deposits and grant loans to all other (financial) agents in the model.

But even more importantly, there is also an interbank market included in the model, i.e. commercial banks may borrow money from other commercial banks at a rate to be negotiated. Generally, the behavior of banks is determined by a genetic algorithm defining a mark-up on money market interest rates, differentiated for households, firms, the public sector, and other commercial banks. This approach includes some learning by the commercial banks and goes beyond the more technical approach implemented by Raberto et al. (2008), where the commercial banking system is more closely linked to the central bank. Moreover, commercial banks perform some basic controlling, calculating the average interest rates on both sides of their balance sheets. A simple approach to setting interest rate quotes would be to calculate the average interest rate achieved on the opposite side of the balance sheet and to use a mark-up for risk and profit. This method is also known as the “pool method”, the interest rate for a loan being based upon the average interest rates of the deposits, for example. Unfortunately, pooling the whole right-hand side of the bank balance sheet (the deposits taken by the bank) results in severe methodological problems related to matching the term-structure of the asset positions with the liabilities. The



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modern approach of banks to calculating interest rate quotes for their transactions is therefore based upon opportunity cost principles, involving a multiple-step calculation of interest rates and profit components.

The “market rate method” described e.g. by Schierenbeck (2003) and Hartmann-Wendels et al. (2004) can be used to separate the asset and liability parts of a transaction. The main idea behind this approach is to start with the interest rate of overnight money, which represents the short-term anchor of the term-structure of interest rates (see Figure 5-1). The difference between the overnight rate and another interbank rate with a maturity similar to the evaluated transaction can be interpreted as the part of marginal revenues associated with the term-structure. For example, a 2-year loan would call for a long-term money-market rate as a means of comparison. Next, this longer-term interbank interest rate is compared with the actual interest charged to the customer of the bank. This difference denotes the profit mark-up of the bank (including a component to cover fixed costs and a risk premium). Note that “money market” in a banking context is not the same concept as usually defined in economics: the “money market” in this sense is the market for short-term financial transactions up to twelve months on the interbank market.

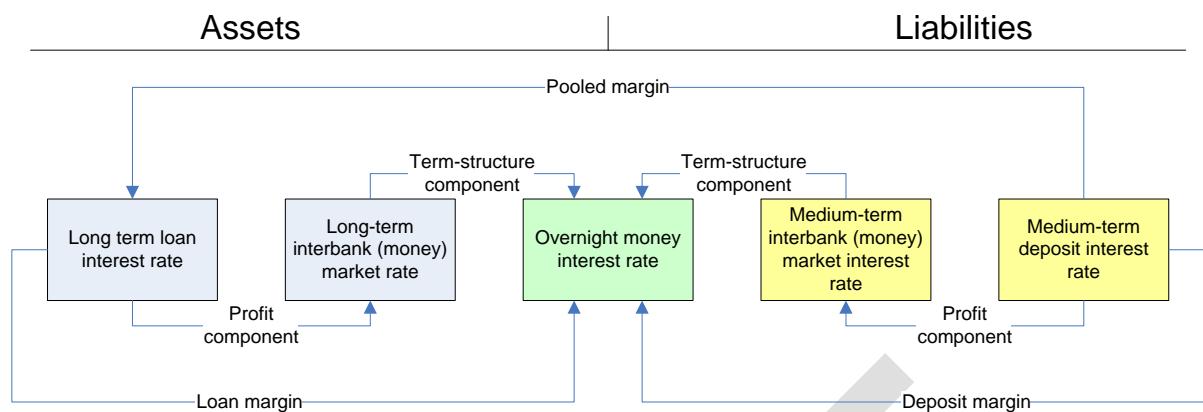


Figure 5-1: Schematic bank calculation

Thus, in the model banks use this opportunity cost approach and calculate a mark-up on the opportunity cost, based upon interbank market interest rates with maturities as close as possible to the planned financial market transaction. In the present default implementation, the profit mark-up has to be positive for a transaction to take place. Default risk is not explicitly taken into account by the bank on an individual level, but the bank adds its historic (moving average) risk cost mark-up to the profit mark-up.

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## 6 Simulation Experiments

### 6.1 CREATING A BASELINE SIMULATION

The first step in macroeconomic policy analyses is to carefully construct a baseline simulation which is stable on the macroeconomic level and provides “reasonable” time-paths for the most important economic indicators. This section should also illustrate the general approach to doing macroeconomic policy-related analyses within an agent-based context, thus the procedure for obtaining the baseline simulation and its properties are shown here in detail.

Like all other agent-based models, AS1 produces lots of output: basically, disaggregated information on each individual agent is available. This is, of course, not very useful for extracting some stylized key facts, and thus the model software includes features to produce reports on aggregate figures. By assigning all the agents an “agent type” it is easy, for example, to set up different household types but to aggregate their state information to a single key indicator.

For the simulation experiments in this section, a specially calibrated version of the standard model has been used. Remember that there are many features, especially relating to geographic phenomena, infrastructure, and innovation by the introduction of new products etc., which will not be explicitly treated in the text. The version of the model used here is calibrated by an iterative calibration and validation method in order to produce reasonable time-paths with non-explosive behavior.

Calibration is done by using a data set obtained from a dynamic base-line simulation of the econometric model AMOD1 (Haber, 2002). In the first step, some of the behavioral parameters of the agents are restricted a priori, while the parameters of

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the utility functions and the production functions of the households and firms and the mark-up of the banks are randomly changed. Next, 30 simulation runs of the model are calculated (out-of-sample) for each parameter-set giving average time-paths for each set. Then the model calibration with the best fit with respect to real GDP, unemployment, nominal private consumption, and inflation rate is chosen. The best fit is measured by the total sum of squares of the deviations. This procedure is rather simple yet computationally feasible, and still produces a reasonable baseline of the model for the policy experiments. In future work, this approach will have to be critically revised, especially by also taking into account variances.

The number of resources is set to 10 different goods and 5 different kinds of input factors. In all of the simulations, 50 households, 20 firms, and 3 banks are located randomly in the landscape (size: 1,000 by 1,000), and there is no movement of the agents around the landscape. Although multi-country simulations are a challenging model feature, in the experiments described here, only a single country with a closed economy is simulated. The main agents (households, firms, banks, research institutes, the statistics office, the central bank, and the government) are set up according to the parameters obtained during the calibration. In the last step of the calibration, a population of these agents is set up, and the parameters obtained after 30 periods are set as the initial state of the simulation runs. This approach is useful for cutting off a “stabilization phase” at the beginning of each simulation run. This occurs when uncalibrated agents are used because the genetic algorithms and expectation formation patterns generally take some time to stabilize.

The first thing to do with a new model for applying scenario analyses is to perform a baseline run as a benchmark for the model which can be used as a comparison with

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the other scenarios. In this sense, policy analysis with an agent-based model does not differ from approaches involving traditional models. Thus, the development of some selected model variables will be described as observed in the initial run, but for the main simulation experiments only a few aspects will be presented in the form of deviations from the model baseline. The model being highly non-linear, the actual baseline chosen might have an impact on the simulated policy outcome. By repeating the same experiments based on different baselines, a sensitivity analysis of the effects with respect to variations in the baseline might be conducted. This will be a separate task to be accomplished in future work.

The time horizon of the baseline simulation presented here is 30 periods, which are defined as months. Note that none of the values in the simulation (e.g. wages) corresponds to a real currency and the levels are arbitrary. It would be possible to fit the model to resemble e.g. Euro values, but this has not been done, as we are mainly interested in the deviations from the baseline and in the direction of the effects. Especially for the baseline run, a high number of repeated runs of the model are necessary in order to achieve a rather stable benchmark. Due to the dynamic and random nature of the framework, no two single simulations of the model will give similar results. On the other hand, increasing the number of “rounds” to simulate (this term is used to describe the “outer” loops of the repetitions in contrast to the “periods” within a simulation) might extinguish cycles in the model which could be of interest. Thus empirical experiments with the model have shown that 30 rounds seem to be an appropriate choice for most of the exercises. This is also in line with the rough statistical rule of thumb demanding 30 or more observations so as to be able to assume that the quality of a statistical sample is sufficient. Of course, the choice of

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30 periods is rather ad hoc, so in future work a more sophisticated procedure could be applied, e.g. calculating the statistical moments of selected key variables (such as GDP and inflation) in a rolling iterative procedure and aborting when changes are below a critical value from one iteration to the next. Thus the criterion for determining the optimal number of simulations could be

$$(3) \left| \frac{\frac{\sum_n(m)}{n}}{\frac{\sum_{n-1}(m)}{n-1}} - 1 \right| < \varepsilon.$$

where  $n$  is the number of the current iteration,  $m$  is the selected statistical moment, and  $\varepsilon$  is a threshold value.

In the original baseline simulation, the economic research institute produces forecasts for key economic indicators with a backward-looking algorithm, whereby the average of the previous three periods is taken as a simple forecast for the next periods. The forecasts for all future periods are consequently identical. The expectation formation function is defined as:

$$(4) E_{t+n}(x_t) = \frac{\sum_{i=1}^3 x_{t-i}}{3}, \text{ for all } n > 0.$$

In this specification,  $E_{t+n}(x_t)$  denotes the expectation of variable  $x$  for the period  $t+n$ , based upon the information in period  $x$ . Of course, this backward-looking expectation formation process is rather simple, but it is chosen deliberately for the baseline simulation to keep things simple. Note that any other specification could be used as well and there is no theoretical reasoning behind choosing three periods

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This section shows the most important results obtained from the baseline simulation run. Remember that no two runs will ever produce exactly identical results because all of the processes also contain strong stochastic elements due to the self-motivated actions of the smart agents. However, if the number of rounds selected is appropriately high (which is not always possible due to computing power constraints), the statistical moments of the cross-section data converge to a limiting distribution.

The average total assets of a firm are built up mainly by the amount of money it has, the market value of the input factors and products in stock, and the assets on bank accounts minus the liabilities with banks and other agents. Retained earnings increase these assets. Moderately increasing asset positions are observed and can be seen as a good sign for the development of the business sector. The range of employment figures at company level is very inhomogeneous, ranging from nearly zero to up to nine employees per firm. The production volume is in fact the net revenues of the firm, including any subsidies and excluding sales taxes. There is some growth in the model, even in the version without dynamic product innovation, because the production function is changed by a genetic algorithm, improving the efficiency of the transformation of input factors to output (which, of course, can be seen as not having reached a final equilibrium state under perfect competition – longer stabilization periods for the GA might remove this property). Profits are low, but positive, which can be interpreted as an indication for still rather highly competitive markets.

Due to inflation processes, increases in efficiency/productivity, and frequent wage negotiations on the labor market, wage expenses increase slightly over time in the baseline.

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Private consumption is one of the driving forces in traditional econometric models. This is also true for AS1, not on an abstract aggregate level, but with respect to the physical flows of goods in the model. Due to the liquidity constraints of the households, private consumption behaves rather in a Keynesian manner in the sense that it is closely related to household income in the short run, although the model is mainly driven by dynamic expectations in the long run. Real private consumption increases slightly over time in the baseline.

In AS1, unemployment may not only result from problems of the households finding jobs, but also from failed negotiations and other frictional unemployment. Households consist of only one worker.

The range of household income reflects the disparities which can be observed empirically. The maximum rises more dynamically than the average, and the minimum remains rather constant. In other words, income disparity increases slightly over time. Households use their current income and their savings to buy goods and services, based upon the utility function, some random behavior biased towards sellers in the vicinity of the household, and subject to genetic change.

Very similar dynamics can also be observed for the development of household wealth, which consists of all the savings of a household due to retained income, either from labor or from the profits obtained from firms. For simplicity's sake, in this baseline we assume that company profits are partly transferred to the households proportionally to their labor income. Of course, this is a very crude assumption, but as there is no stock market where households can hold equity in the present version of the model, it can be used to close the economic cycle.



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Nominal GDP rises constantly, but inspection of the simulation data provides a strong indication for the GDP time-series being a trend-stationary process (both the ADF and the PP tests reject the unit root hypothesis on the 99 percent level). There is significant movement in the real GDP time series, reflecting some business cycles, which sometimes last for several periods and sometimes seem to vanish in the next period. Growth rates in the range of nearly  $-6$  percent to more than  $+10$  percent show that the behavior of the artificial economy is subject to significant variation, even if no exogenous shocks are included.

There is some volatility in the inflation rate, which has to be attributed to the lack of power of the central bank to control the monetary aggregates completely, and to the well known lag structure of monetary policy. Moreover, the actions of the central bank are always based upon expectations of inflation, which need not be correct. In this simulation the central bank uses a simple model containing previous inflation and previous GDP along with the expected values for these variables, which are included in a "genetic function". Basically, such a genetic function in the model is a general multivariate linear function in which the parameters are dynamically changed by a genetic algorithm implementing individual reinforcement learning. To achieve this, a pool of possible parameter sets is contained in the function object and genetically modified as needed. In spite of the relative simplicity of the forecast model and the problems inherent in efficient monetary control, the central bank is rather successful in its objective of setting the inflation rate at 2 percent. Deviations from the target value are generally less than 1 percentage point.

In view of the tight monetary control, it follows that the variance in the price level in the different simulation rounds is very low and the price level time-series exhibits

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constant growth. Average unemployment rates lie between 1 and 4 percent and are subject to major changes from period to period. Note that the figures suggest that there is some serial correlation in the cyclical behavior and that this should follow directly from the institutional design of the labor market. In some of the periods and for some of the simulation runs, even full employment can be observed (in 6 out of 90 cases).

The behavior and economic policy of the central bank are closely related to developments in the inflation rate and price levels. Reacting to the rising output in the economy, the central bank has to increase money supply as measured e.g. by the monetary aggregate M1 in the model over time. Due to the fully modeled banking system, short-term deposits are automatically increased in times of high growth, leading to higher money balances without any significant intervention. For short-term interventions, the central bank sets the minimum bid rate for the main refinancing operations and the interest rates of the standing facilities as required to form the interest rate corridor. Money market interest rates adjust rather quickly to the new conditions. Inspection of the various interest rates shows that the variation in the central bank interest rates and the market interest rates is within reasonable bounds.

The commercial banks indirectly increase M1 and the other monetary aggregates in the model by increasing the volume of loans (and deposits, at least to a certain extent, at the same time). Consequently the assets of the banking system increase.

The average asset interest rates of the banks (interest rates for loans) are always higher than the interest rates paid for deposits. The resulting interest rate margin is usually between 3 and 5 percent, but larger deviations can also be observed. High margins in combination with growing assets lead to significant increases in the profits

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of the banking system, which seem rather high but can still be regarded as being empirically intuitive.

Although the public sector starts from a rather low debt level, nearly always positive deficit figures lead to a constant increase in public debt (with a rather stable range of variation in the experiments). This can be attributed to the behavior of the government agent, who increases transfer payments with rising average income in this simulation (in order to adjust for some kind of change in minimum social standards and inflation), keeps the tax rates constant, and suffers from expenditure climbing more quickly than the tax payments. Of course, this behavior reflects the modeling approach with a rather passive public sector in the default model, but this is suitable for a neutral benchmark because we could then introduce more active discretionary economic policy or even policy rules and compare the results with the simple rules assumed in the baseline.

This detailed description of the most important figures, especially for the monetary sphere of the economy, shows the richness of the results obtained from the agent-based approach. Thus, economic interactions can be modeled that would not be available from analyses with traditional economic models. While this may lead to a whole number of innovative results, both for monetary and fiscal policies, the following sections confine themselves to just showing that (a) agent-based models are capable of providing all of the macroeconomic results which are usually obtained from the traditional approaches and (b) the expectation formation process might crucially influence the power and effects of macroeconomic policies.

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## 6.2 MONETARY POLICY SIMULATIONS FOR A FINANCIAL CRISIS

Modeling the sub-prime shock in this paper is rather simple and straight-forward. As mentioned above, four main stylized links for European economic policy are identified:

- a. the sudden and severe devaluation of financial assets held by European banks and other economic subjects,
- b. global interest rate changes,
- c. the drop in US demand on the world markets affecting foreign trade, and
- d. loss of confidence in banks, companies, and markets.

Thus, the following shocks are imposed on the model, aiming at capturing the most important links:

- a. financial assets of the households and firms are reduced gradually to a level of 40 percent over twelve months,
- b. a risk mark-up of 2 percentage points is gradually introduced for all bank quotes over twelve months.

As with the baseline simulation, 30 repetitions of each scenario are calculated for 30 periods each. All the figures are arithmetic means of the respective variables. All the “deviations” are the differences of these means from the baseline (mean) values. Due to the fact that the simulations presented here are very stylized, only some figures are given here to provide an overview of the core results. Thus, only average values over the time-horizon (for all 30 periods and all 30 rounds) and selected variables are given in the tables (EV = empirical value, EPP = ex post performance, LFTB = learn from the best).

	GDP growth (real)	Inflation	Price Level	Unemployment	Public Debt	Public Deficit
	percentage points	percentage points	percent	percentage points	percent / GDP	percent / GDP
EV	-2.45	-1.56	-1.23	+4.86	+1.12	+1.59
EPP	-2.12	-1.41	-1.12	+3.91	+1.17	+1.36
LFTB	-2.31	-1.52	-1.16	+4.39	+1.15	+1.45

*Table 6-1: Selected Benchmark Results for the Sub-Prime Shock*

Table 6-1 and Table 6-2 show the most important macroeconomic figures and indicators for the monetary sphere of the economy for all of the three expectation formation scenarios.

	Private Consumption	Profits	ECB Minimum Bid Rate	ECB Marginal Rate	Avg. Retail Interest Rate	EUR Exchange Rate
	percent / GDP	percent	percentage points	percentage points	percentage points	percent
EV	-1.98	-7.91	-2.12	-2.15	-0.92	-5.14
EPP	-1.76	-6.78	-2.39	-2.49	-0.78	-7.23
LFTB	-1.87	-7.17	-2.21	-2.25	-0.85	-6.15

*Table 6-2: Selected Benchmark Results for the Sub-Prime Shock*

### 6.3 OPTIMAL ECONOMIC POLICY WITH RESPECT TO EXPECTATIONS

Next, a numerical approach is used to calculate optimal monetary policies for the different expectation scenarios. The following variables are included in a standard

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quadratic welfare loss function: GDP, private consumption, inflation, and the unemployment rate.

To assess the welfare effects of different policy actions, a single measure of economic performance is needed. Such a measure can be the intertemporal welfare losses. To calculate these welfare losses, an objective function has to be specified. For computational ease, an additively separable quadratic welfare loss function has been chosen. The welfare losses  $\Omega_t$  in each period  $t$  are equal to the sums of the weighted ( $\lambda_i$ ) quadratic differences between the actual values  $\tau_i$  and the optimal values  $\tau_i^*$  for each of the  $i$  target variables:

$$\Omega = \sum_{t=1}^T (1+r)^{-t} \Omega_t, \quad \Omega_t = \sum_i \lambda_i (\tau_i - \tau_i^*)^2$$

In order to take into account the dynamic structure of the overall welfare losses, the welfare losses in each period have to be discounted to their present values (using the rate of time preference  $r$ , which is assumed to be 10 percent) and to be summed up over the time horizon  $T$  to get the total welfare loss.

In the following simulations, the reaction patterns of the ECB (the parameter setting the inflation rate target value, which is normally 2) are stochastically changed, and the scenario with the lowest welfare losses is chosen. This is no full optimization solution, but a simplified “multiple shooting” approach, as the full optimization approach would be computationally too expensive for the present version of the model.

Table 6-3 shows the results of the modified simulations as deviations from the benchmark simulations.

	GDP growth (real)	Inflation	Private Consumption	Avg. Retail Interest Rate	Public Deficit	Unemployment
	percentage points	percentage points	percent / GDP	percentage points	percent / GDP	percentage points
EV	+0.49	+0.13	+0.21	-0.22	-0.23	-0.59
EPP	+0.67	+0.36	+0.40	-0.46	-0.36	-0.80
LFTB	+0.56	+0.21	+0.32	-0.33	-0.28	-0.72

*Table 6-3: Selected Results for Optimal Monetary Policy*

The results show, that the optimal monetary policy scenarios generally tend to produce more inflationary policies, and that there are significant differences for the alternative expectation formation settings.

## **7 Conclusions**

Expectation formation mechanisms tend to alter not only model behavior in pure simulation experiments, but also significantly influence optimal monetary policies. In the context of a financial markets crisis, this confirms the importance of the “animal spirits” of the economic agents and the level of information processing capabilities. Moreover, agent-based macroeconomic models may be more appropriate for investigating periods of high importance of expectations on the overall economic situation.

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