AGENT–BASED KEYNESIAN MACROECONOMICS

—

AN EVOLUTIONARY MODEL EMBEDDED IN AN AGENT–BASED COMPUTER SIMULATION

INAUGURAL DISSERTATION
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To Eva–Maria.

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List of Abbreviations

ACE:	Agent–based computational economics
AD:	Agent Dollar
ANOVA:	Analysis of variances
CAPM:	Capital Asset Pricing Model
c.p.:	Ceteris paribus
CPI:	Consumer price inflation
EBIT:	Earnings before interest and taxes
DoE:	Design of Experiments
CD:	Compact Disc
e.g.:	'Exempli gratia' (Latin) alias 'for example'
ERP:	Enterprise resource planing
EU:	European Union
EUR:	Euro (currency of the European Union/Eurozone)
GDP:	Gross domestic product
GE:	General Equilibrium
i.e.:	'Id est' (Latin) alias 'that is'
IMF:	International Monetary Fund
IT:	Information technology
MOA:	Medium of account
MOE:	Medium of exchange
NOLH:	Nearly Orthogonal Latin Hypercube
OECD:	Organisation for Economic Co–operation and Development
SCM:	Supply Chain Management
SeSAm:	Shell for Simulated Agent Systems
TFP:	Total factor productivity
U.K.:	United Kingdom
UOA:	Unit of account
U.S.:	United States of America
viz.:	'Videlicet' (Latin) alias 'namely'
vs.:	Versus

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Introduction

The foundation of macroeconomics, as a separate branch of economics, was laid down by John Maynard Keynes (1883 – 1946). Since the 1970s, probably encouraged by the 'Lucas Critique', many macroeconomists insist on a explicitly modeled 'microfoundation' of macroeconomics—as opposed to 'Keynesian' macroeconomics, where an explicit model is only existing on the aggregate level. This development resulted in the status quo of macroeconomic research: Since the early 1990s almost all important developments in the branch of macroeconomics were made by research based upon 'Walrasian microfoundation' (typically 'Dynamic Stochastic General Equilibrium' models)[1]. The central problem of this approach, as we see it, is the relation between micro and macro structure: In the overwhelming majority of applications, the 'microfoundation' of 'General Equilibrium' models is (according to simplification) built on the *aggregate* level. Obviously, this does not solve the essential problem of macroeconomics, namely how individual (i.e. microeconomic) behavior generates the dynamics on the aggregate (i.e. macroeconomic) level.

As an alternative approach, in recent years the agent–based simulation technique has emerged. This was enabled by a rapid improvement of computing power of IT systems and by the development of sophisticated programing languages. As a result of this development, the question arose, what is the main difference between the traditional 'General Equilibrium' framework in contrast to this new approach? We see the borderline between both approaches in the fact that agent–based macroeconomic models are built bottom–up, while 'orthodox' models are, as stated above, designed top–down on the macro level. Opposed to that, agent–based models are designed on the micro level. They contain about several thousand individual agents, and the researcher usually does *not*

[1] The 'General Equilibrium' framework was initially developed by Léon Walras. The modern, i.e. dynamic, interpretation of the 'General Equilibrium' approach is provided by a model developed jointly by Kenneth Arrow and Gerard Debreu. See the discussion in chapter 1, and especially footnote 17.

constrain the macro level through specifications, which are necessary to compute (or better to run) the model (or the simulation).[2] The modeler of an agent–based computer simulation only observes the generated macro dynamics of the simulation, while he designs the model solely on the basis of individual behaviors and interactions.[3] Basically, this approach is related to the theory of 'complex systems'. The named 'complex system' consists of interconnected parts; its properties, as a whole, are not necessarily represented by the properties of the individual parts. Interestingly, older neoclassics (foremost represented by Alfred Marshall) thought of economics as a representation of a 'complex system'—but they did not possess the mathematical tools to solve dynamic applications of such 'complex systems'. This situation has changed by the advent of agent–based computer simulations.

This description leads us to the phenomenon that the benefits of agent–based modeling, which stem from its flexibility, are sometimes challenged by economists: The often heard criticism is that a scientific theory must be based upon 'abstraction', and that the agent–based modeling opens a door for the (more or less detailed) 'replication' of reality. But such a 'replication' would overload an economic model. It would lead to complex interrelations which cannot build the solid groundwork for economic theory–building. This would oppose the idea of 'abstraction' as a basis of scientific research. The key criticism is therefore that scientific models should be far less complex than reality. We want to survey the relation between 'abstraction' and agent–based modeling in a different perspective. One can define 'abstraction' as the process (or result) of generalization by reducing the information content of a problem the researcher is interested in. It is crucial that this reduction takes place in order to *retain* only that information which is *relevant* for the particular purpose. Therefore, our central question should be, which information is of pivotal importance in the context of macroeconomics?

Macroeconomic research, as we see it, should retain the emergence of macro structure out of micro behaviors and interactions. This macroeconomic emergence and the according theory of 'complex

[2]Such a macro constraint is the general equilibrium. It is imposed to the aggregate level of a model, and it is necessary to solve it.

[3]In a further step he uses the observed macro outcomes in order to adjust the model. This is encompassed by the 'validation' of the model. See the discussion below.

systems' should be central issues in each complete macroeconomic investigation. Unfortunately, until now almost no research is carried out with respect to this research question in the field of dynamic monetary macroeconomics.[4] The present study aims to close this gap. Hence, we designed an agent–based macroeconomic model that is structured bottom–up, so that its aggregate dynamics develop out of both micro behaviors and micro interactions. As we will see, this leads to complex and non–linear micro–macro interactions. In this sense, our approach is related to Joshua M. Epstein's notion coined by the expression: "If you didn't grow it [author's note: the macro model], you didn't explain its emergence" (Epstein, 2006a, p. 9). Against this background, it is not legitimate to conclude that the complex micro–macro interrelations account for an unfavorable departure from 'abstraction'. The mentioned complexity is, in our view, the crucial feature of a macroeconomic system. It is therefore not legitimate to dispose these characteristics by 'abstraction', as usually done in 'orthodox' economics.

Objectives of the Study

The present study can be placed into the field of agent–based computational economics. As we will discuss in chapter 1, the agent–based technique enables a flexible way of designing, simulating and analyzing a particular model structure. In here, the structure of the model represents an intuitive analogy to reality. In addition, the benefit of flexibility induces the question, as to what extend the generated model is the 'right' one for a defined purpose? This is the subject of the model 'validation'. According to this, 'validation' is the key issue in agent–based research. Most importantly, our main purpose is therefore to develop a *reasonably validated* agent–based macroeconomic simulation model. Moreover, we have to outline the objectives the model is built for: The presented model needs to be a dynamic macro model. Its main innovation with respect to agent–based modeling is its 'monetary circuit' or 'monetary sphere'. As opposed to other agent–based research, the presented model belongs to the field of *monetary* macroeconomics. Equally important, the model has to contain 'Keynesian' and 'Wicksellian' elements. The former elements indicate several important 'Keynesian' properties, such as the importance of the demand side, the 'paradox of thrift', and so on. The latter elements impliy the role of the central bank and monetary policy. Accordingly, the

[4] In the state–of–the–art framework of 'New Keynesian' macroeconomics, the economy is modeled on the aggregate level by a 'representative agent'. See, for example, (Woodford, 2003), and the discussion in this study below.

presented model contains a central bank agent that conducts monetary policy through an interest rate instrument. Thereby, the basic framework is constituted by Knut Wicksell's idea of a monetary transmission mechanism.

The second aim of this study is closely connected to the first one. The objective to construct a first agent–based monetary macro model causes the problem that we cannot use any existing framework. Therefore, the second purpose of this study is to develop a guideline for future work in this field. Here, the focus lies (i) on *methodological* aspects. As we will see, agent–based computational economics constitutes an IT–based tool, which enables to simulate a certain model structure—it is not a methodological basis for the model structure. Consequently, we have to define a methodological framework for the modeling. According to the important role of the 'validation' task, we must, in addition, elaborate an appropriate 'validation' methodology. Those two methodological questions have to be answered. (ii) Secondly, our guideline focuses on the theoretical aspects of the model. Therefrom, it is our aim to refer to the theoretical roots of the presented model—especially in context of its 'monetary circuit'. On the other part, we do not want to discuss all technical aspects, which are needed to conduct an agent–based research in principle. (iii) Thirdly, we identify some pitfalls that one could experience in carrying out research such as the presented one. Therefore, we will give advice how to identify possible sources of problems.

Structure of the Study

The structure of this study is straightforward: Chapter 1 gives a propaedeutic survey of the main topics of agent–based research. One challenge is thereby is to discuss the methodological aspects, such as the basic methodologies of the modeling and 'validation' approaches. The subsequent chapter establishes the conceptual model. It gives an detailed overview of the theoretical roots and antecedents of the model, and it outlines the reasons for the chosen design. We will also address problems of model design in this context. The study finishes with a comprehensive model 'validation' in chapter 3. This is executed in several stages, which are built on each other. The methodology of this 'validation' procedure is prepared in chapter 1. The study ends with concluding remarks.

Chapter 1

A Road Map to an Agent–Based Computational Macro Model

An economy is an evolving, complex, adaptive, and dynamic system. Other scientific fields than economics made much progress in the study of similar systems, which feature the same basic elements, such as heterogenous and autonomous entities (agents) that are engaged in complex interaction profiles, while the macro behavior of the system as a whole emerges out of micro structures, micro behaviors and micro interactions. The aggregate behavior emerges bottom–up. Such approaches are found in the fields of medicine and brain research, logistics, ecology and biology. Within those fields, computer modeling and experimentation is widely accepted (without much question) as valuable tools. On the contrary, to this date agent–based analysis did not attract great attention in economics, and in macroeconomics in particular. This can be due to the fact that macroeconomists are averse to agent–based approaches (Leijonhufvud, 2006a). The reasons for this phenomenon are shrewdly characterized by Axel Leijonhufvud:

> "The apparent threat of cognitive loss is perhaps steeper in macro than in other areas. Each generation of scholars inherits a knowledge base of theory, of empirically confirmed 'facts' and of investigative techniques. Inherent in this base are directions for future work—which problems are interesting and which ones not, what facts are puzzling and which ones can be taken for granted, what methods of investigation are approved and not approved, and so forth. The macroeconomics of the last century, from Lucas through Presccot to Woodford, has been strongly wedded to stochastic general equilibrium theory.

> It is the well–developed knowledge base with which the last couple of generations of macroresearchers have been equipped. Acquiring it required a large investment. But then recruits to this research program are confident that their technical equipment is the best in the business." (Leijonhufvud, 2006a, p. 1627)

The objective of this chapter is to discuss an alternative framework based upon the agent–based simulation technique. Hence, this chapter illustrates the main aspects of the approach of agent–based computational economics (ACE) and its advantages compared to 'General Equilibrium' (GE) theory. In the last section, we will describe a suitable 'validation' framework for the development of an agent–based macroeconomic model. As we will see, 'validation' is the core issue within agent–based research. Moreover, this chapter defines the main concepts of agent–based models, which are in turn necessary to develop and validate the model throughout the remainder of this study.

1.1 What is Agent–Based Computational Macroeconomics?

Imagine the total number of economic processes, such as producing and trading, happening in any economy in reality. They are usually driven by the actions of hundreds of thousand individuals, social groupings or institutions. In many circumstances information technology systems (IT systems)[1] support the execution of such actions. The basic idea of an IT system is to map real actions, facts and circumstances into digital data. Especially firms utilize IT systems to improve the efficiency of business processes: Suppose a supplier in the automotive industry, where an 'enterprise resource planning system' (ERP system in brief) collects the data of production and logistic processes. This system provides suitably prepared and presentable data in order to allocate business resources (materials, employees), for example through the scheduling of new orders or the minimization of inventory costs. Inevitably, the operations of the ERP system requires the interconnection between the real business processes and the respective data inventory within the IT system. Hence, there have to be some exogenous actions affecting the ERP system. This means, for example, that the data inventory has to be updated on condition that the stock of inventory of the automotive supplier has changed. Such maintenance can be operated manually by the users of the IT system,

[1] IT defines the study, design, development, implementation, support or management of computer–based information systems, particularly software applications and computer hardware. IT deals with the use of electronic computers and computer software to convert, store, protect, process, transmit, and securely retrieve information.

as well as semi or fully automatically. In summary: The ERP system supplies information and data about business resources to the automotive supplier.

However, some systems—such as complex 'Supply Chain Management' (SCM) systems—contain fully automated processes due to the use of robots. These robots react automatically to a change in the data. For example, provided that the stock of inventory of an intermediate product needed in the production process of an automotive supplier (such as the stock of inventory of unmachined engine hoods) falls short of a certain level (e.g. 1,000 engine hoods), the robotic agent starts a fully automatic digital procurement process via a network (presumably via the internet). This means that the software agent executes a routinized search for suitable offer(s) in one or more online trading platforms, where suppliers and buyers of certain intermediate products meet. Such processes can appear on several stages of a vertical value added chain in a more or less automatic sense. A SCM system therefore collects, maintains and delivers data—but it can also feature automated elements where, for example, robotic trading happens. As a consequence, real business processes are affected by the information system automatically through robots, causing true interaction between real processes and the IT system. It is important that such an active role of the IT system must be guided by a rule–based or routinized behavior of the software agents. This behavior can even represent some kind of 'artificial intelligence'.

In a next step, we can reveal the basic idea of agent–based simulation[2] technique by using these introductory explanations: Like ERP or SCM systems, an agent–based computer simulation collects first of all digital data. It is populated by many agents, and each of these agents features a certain data set. The point is that the data set is not a direct representation of facts or information about reality as is the case in an ERP or SCM system. Rather, the data inventory of agents represents an abstract model, which is in turn the simplified representation of certain relationships known from reality. Accordingly, agent–based computational economics build upon the construction of an

[2]A simulation is a certain type of modeling, whereas a model is a simplification of reality. Such a simplification implies a smaller, less detailed, or less complex representation of real processes or relationships. It thus builds on 'abstraction'. Similar to statistical models, simulation output is produced during a simulation run. This output depends on certain inputs (Gilbert and Troitzsch, 2005). We will investigate inputs and outputs of the presented model later on in this study. For a detailed discussion of simulation techniques in social sciences see Gilbert and Troitzsch, 2005.

artificial world, in which all actions are completely endogenous. This world covers special aspects of the real world we are interested in. The present study is interested in the behavior of a closed economy, i.e. the subject of the study is an an artificial world which represents an extremely simplified national economy encompassing the basic economic sectors. Within this artificial world, data are permanently generated, collected, and manipulated endogenously on the micro level. The key difference between the common (every–day) usage of information technology (e.g. as represented by an ERP system) and an agent–based computer simulation is that in the former at least some degree of interaction between reality and the information system is necessary, whereas in the latter all decisions, actions, and processes are fully automated—the agent world is autarchic.[3] This implies that an agent–based computer simulation contains agents, which are routinized robots, and which stand for the actors in the real processes we are interested in. This, in fact, represents basically the intuitive modeling approach of agent–based computer simulations. Moreover, such simulations are somewhat similar to complex SCM systems, in which robot agents are employed: If an agent simulation is started, each robot behaves exclusively according to the programed routines, so that no connection between the real world (e.g. the designer) and the simulation (run) prevails. To sum up, an agent–based computational simulation contains an autarchic artificial world containing robot agents represented by a set of data and rules (or routines). In the following paragraph we illustrate such an artificial world representing the subject of the present study.

Imagine the artificial world of Agent Island. Agent Island is a autarchic world populated by firm and household robot agents. If the computer simulation is started, the population arrives on Agent Island. Upon arrival each agent receives his personal data and instruction booklet: This booklet contains a set of rules and restrictions the agent has to follow as well as the initial data set. If the agent is trading any goods or services throughout the simulation, he has to register the movements in the data entries in his booklet. The agent–based simulation technique therefore supplies all possible data (individual, aggregate or otherwise manipulated data) to the researcher. The researcher can request the data entries in the booklets of those agents he is interested in. Data entries in the booklet of all agents are the basis for the routinized decisions and behaviors of the agents. That is,

[3]Indeed, it is imaginable that there may be also some kind of human action or interaction in an agent–based model. Throughout this study, we are not interested in such approaches.

an agent uses these data together with the routines in his booklet in order to operate decisions and actions. Routines define therefore the processes of the agent (e.g. production or trading processes). Thereby, routines need not be static, insofar as they can evolve over time—again according to simplified and routinized adaption behavior. In addition, we use a round–based simulation approach, and the agents employ data to their routines once a round. If all routinized decisions and actions are conducted, the economy on Agent Island enters the next round. At the end of each round we collect data on aggregate levels, because the business cycle dynamics of the Agent Island economy is the topic we are ultimately interested in.

As suggested by intuition, we have to design the individual sets of data and rules for all relevant aspects of the model—for each agent of the Agent Island population. To give an idea of such an design, the following subsections highlights some important aspects of ACE. The next subsection illustrates the main conceptual building blocks. Thereafter, we describe which research objectives can be pursued within such a model, and which ingredients are necessary. Finally, the introduction closes with the discussion of the methodological relevance of ACE.

1.1.1 Conceptual Building Blocks

Agent–based models can be characterized by several concepts. However, this subsection does not give an in–depth review of these theoretical concepts; the objective is rather to outline the relevant building blocks of an agent–based computational model and relate them to the framework of Agent Island. We will discuss in section 1.2 the virtues of agent–based computational economics by comparing the 'orthodox' framework of macroeconomics with the possibilities of ACE. Thereby, we will take up the conceptual building blocks again and deal with them in somewhat greater detail. The following overview therefore summarizes the main building blocks of ACE in brief:

Bottom–up perspective and macroeconomic emergence Traditional 'neoclassical' models follow a top–down perspective, where the aggregate level typically comprises a 'representative agent'. In contrast, agent–based models build on an environment, in which micro entities engage in repeated interactions. As in reality, the dynamic on the macro level emerges from the behavior of the basic entities on the micro level (Windrum and Moneta, 2007; Pyka and

Giorgio, 2005; Tesfatsion, 2003). It is thus intuitive that Agent Island is designed bottom–up. This corresponds to the assumption that the agents, upon arriving on Agent Island, receive a personal data and instruction booklet. The macro behavior of the economy of Agent Island emerges from repeated individual actions and interactions according to the instructions and data in the booklets. Such an approach allows us to investigate the relationship between micro and macro dynamics. This is done during the 'validation' process in chapter 3. The relationship between micro and macro properties is of particular importance, when one is interested in the analysis of 'fallacies of composition' in economics.[4]

Heterogeneity Agents might be heterogenous in almost all characteristics, i.e. with respect to data or behavior. The former might be defined through varying variables or initial values of some variables (Pyka and Giorgio, 2005). The latter is based upon varying behavioral rules or, at least, levels of behavioral parameters within one rule. According to that, the personal data and instruction booklets of the population of Agent Island reflect this heterogeneity. In here, we simplify by the assumption that agents of the same type (households, consumer goods firms, capital goods firms) receive the same rules, but the level of the parameters in the rules can vary.

Network direct interactions: Interactions among agents are direct and inherently non–linear. This means that the decisions of an agent depend to some extend on the past and present choices made by all other agents (Pyka and Giorgio, 2005). Moreover, in ACE the trading and procurement processes are usually modeled explicitly, which implies that the institution of the 'Walrasian auctioneer' is not mandatory (Tesfatsion, 2006). Consequently, it is possible to employ various forms of procurement processes within an agent–based model. In particular, ACE enables 'face–to–face' interactions within a procurement process. We will explain below that such a 'face–to–face' procurement process is adopted in the market for capital goods on the island. Then again, the consumer goods market is working simplified in institutional analogy to 'orthodox' economics (viz. by employing implicitly some kind of auctioneer).

[4] A 'fallacy of composition' could arise when one infers that something is true for the whole from the fact that it is true for some part of the whole. We will refer to this concept, and explain it with respect to a relevant application in chapter 2. See also Stützel, 1978, for an extensive discussions of such 'fallacies of composition' in economics (especially based upon flow–of–funds accounting).

Bounded rationality By its nature, the environment on Agent Island is too complex to apply hyper–rationality. This is for example apparent in the context of expectation formation, because agents on Agent Island are not able to derive rational expectation outcomes, as in 'orthodox' models. Rather, one has to apply routinized outcomes of myopic optimizations in combination with adaptive expectations. The latter is necessary, because agents face 'true uncertainty'[5] so that expectations cannot be rational as assumed by 'orthodox' economic theory. According to this, the agents on Agent Island face 'true uncertainty', so that they do not know (and cannot calculate) the future outcome of economic interactions on the island. This must affect the formation of expectations in such a way that expectations are adaptive.

Learning Behavior In many ACE models sophisticated learning algorithms are implemented (Tesfatsion, 2006; Windrum and Moneta, 2007).[6] Not so in the present study. In a first step of the development of the model, we have employed such a complex and sophisticated learning algorithm. As suggested by Tesfatsion, 2006, we have applied it to the supply decision of consumer goods firms. Unfortunately, this design produced undesired effects on the macro level, i.e. the assumed 'Phillips curve' relationship (viz. the positive correlation between output gaps and inflation rates) was upside down. Therefore we abandoned this approach and have adopted a more suitable approach for the supply decisions, as it will be described in subsection 2.2.2. In this approach, firms adopt their behavior to a change in the environment on Agent Island, but a complex learning algorithm is absent.

1.1.2 Objectives

The following description illustrates four main objectives of agent–based research. If necessary, we extend each description by a short link to the objectives of the present study:[7]

[5]Here, 'true uncertainty' means 'Knightian uncertainty' (Knight, 1921), i.e. situations which cannot be described with a certain probability of occurrence. This 'true uncertainty' is different from risk. The latter is usually employed in 'orthodox' economic models, where it is necessary to assign probabilities of occurrences in order to handle this kind of uncertainty (i.e. risk) in expected utility functions.

[6]For a discussion of several learning algorithms see Brenner, 2006.

[7]Tesfatsion, 2003, gives a review of the agent–based literature and relates the models to certain ACE topics. Insofar as none of these models fall into the field of monetary macroeconomics, we do not refer to them here explicitly. So far as we know, the only agent–based model that can be placed into the field of monetary economics is an older one, created by Bruun, 1995. Hence, we do not present an introductory literature review. Nevertheless, we will refer to specific ACE research throughout the representation of the model in chapter 2.

Empirical understanding In this case the researcher has to investigate the question, why certain empirical phenomena or regularities evolve. They seek for causal explanations for such phenomena through agent–based environments (Tesfatsion, 2006). Based upon empirical understanding an agent–based simulation can deliver predictions of future tendencies or events (Gilbert and Troitzsch, 2005).

Normative understanding An agent–based model can deliver normative insights as well (Tesfatsion, 2006). It is certainly possible to compare various policies (e.g. various central bank strategies) based upon a *valid*[8] agent–based model. The crucial point is the 'validation' of the ACE model. Even though we do not chase after any normative objectives, our analysis could to some extend be useful for further normative postulates. It delivers a correctly validated model, which is necessary to conduct a normative analysis.[9] Our objective is to deliver such a model: This could be a starting point for normative analyses in the future or, at least, a foundation for the further development of a valid monetary macro model that in turn could be used for a normative analysis.

Methodological advancement The question of interest is, how best to provide agent–based researchers with a suitable methodology needed to undertake a study of the economic system. Thereby, researches need to model structural, institutional and behavioral characteristics of the economic system; they ought to evaluate the logical validity of their model through computer experiments, and test their theories against real–world data (Tesfatsion, 2006). Due to the flexibility of agent–based models, those requirements can be fulfilled through a variety of ways. If the researcher is able to find a proper way for doing this, he develops further methodological insight with respect to the topic of interest. In the context of the present study, this is one aim. We strive for the development of a reasonable validated agent–based monetary

[8]See subsection 1.3 for the notion behind this term.

[9]Economists make a distinction between positive and normative that closely parallels Karl Popper's view of philosophy of science (Popper, 2005). See also Friedman, 1953 for a comprehensive discussion of this point. A positive statement is a statement about what is, and that contains no indication of approval or disapproval. Notice that a positive statement can be wrong. "The earth is made of chocolate" is incorrect, but it is a positive statement, because it is a statement about what exists. Then again, a normative statement expresses a judgment about whether a situation is desirable or undesirable: "The world would be a better place, if it were made of chocolate" is a normative statement, because it expresses a judgment about what ought to be. Notice that there is no way of disproving this statement. If you disagree with it, you have no sure way of convincing someone who believes in the statement that he is wrong. Along those lines of philosophy of science it is possible to divide the objectives of agent-based research into positive and normative groups.

macro model. This should become the basis for further analysis of monetary policy issues. In addition, we apply a 'validation' framework developed in the field of computer science (see section 1.3.3), which has never been applied to an economic issue until now. Accordingly, we wish to deliver a suitable framework for further research in monetary macroeconomics within the field of agent–based computational economics.

Qualitative insight and theory generation Through research in agent–based models one can gather new insights about an economic issue of interest. An agent–based simulation can be used as a method of theory development, in order to improve the understanding of phenomena of the social world (Gilbert and Troitzsch, 2005). Consequently, a well–designed and suitable agent–based world can improve the understanding of the dynamic behavior of a complex economic system. Usually, this objective is based upon the systematic examination of simulation inputs[10] (initial values, behavioral and structural parameters, etc.) and their impact on simulation outputs of interest (Tesfatsion, 2006).

The last point expounds the idea that ACE has the potential to assist in the discovery and formalization of theories. Researchers can investigate theories in the artificial agent world they have built. In order to do this, the researchers have to take theories expressed in textual or conceptual form and formalize them into a specification which can be programed into the computer. According to this, the theory will be precise, coherent and complete. In this respect agent–based computer simulations could feature a similar role in social sciences, comparable to that of mathematics in the physical science (Gilbert and Troitzsch, 2005). On the contrary, mathematics have been widely used as a means of formalization in economics and econometrics. In fact, there are several reasons why agent–based simulations are more appropriate to social science than mathematics (Gilbert and Troitzsch, 2005). We will explain these main virtues of agent–based computational economics in section 1.2, and, in addition, compare them to 'orthodox' economic modeling (which is solely based on the mathematical framework of 'optimal control theory'). Inevitably, the presented model of Agent Island illustrates how the formalization of an agent–based monetary macro model can look like.

[10]See footnote 2 for an explanation of simulation input. We will explain the detailed role of inputs later on.

1.1.3 Ingredients

The following overview contains a broad set of ingredients, each agent–based computational model consists of (see Pyka and Giorgio, 2005):

Time As an agent–based model is by its nature a dynamic model, we have to define the time perspective of the model. As we will see, the model is round–based, i.e. it evolves in discrete time steps, which we define as periods. Next to this period time ($T = 1, 2, ...$), there exists an intra–period time. The sequence of decisions and actions within one period is based upon the concept of intra–period time. Hence, when one period ends, the intra–period sequence restarts.

Agents Each agent–based simulation is populated by a set of agents. The term 'agent' refers to bundled data and methods (or routines). It represents an entity constituting a part of a world constructed by computation. Agents can be (i) individuals (e.g. consumer, workers), (ii) social groupings (e.g. families, firms, government agencies), (iii) institutions (e.g. markets), (iv) biological entities (e.g. livestock, forest), and physical entities (e.g. weather, geographical regions) (Tesfatsion, 2006). In context of the present task, viz. the development of a monetary macro model, agents represent the actors within the opted framework, viz. households (i.e. consumers/workers), firms (i.e. consumer goods and capital goods firms) and the central bank. It should be noted that we assume a constant set of agents. The existing agents do not die (drop out), and no new agents are born during a simulation run. Thus, the once initialized population outlasts the whole simulation run. In general, agents are supposed to be (i) autonomous entities (i.e. the state of the agent and its actions are first of all independent from its environment or other agents), (ii) social entities (i.e. agents are able to interact with other agents), (iii) reacting entities (i.e. agents are able to perceive their environment, which usually leads to a reaction), (iv) active entities (i.e. agents are able to initiate actions themselves) (Pyka and Giorgio, 2005).

Micro variables Each agent is characterized by a vector of microeconomic (state) variables. Those variables are usually supposed to be modified endogenously throughout the simulation. In our model such microeconomic variables are, for example, the net financial wealth (or net debt) of a household agent, or the real capital stock of a firm agent, or the produced/supplied output of firms, and so on. During the 'validation' of the model it is one task to define reasonable initial values of several microeconomic variables (such as the initial capital stock of firms).

Micro parameters Next to the micro variables each agent is characterized by a vector of microeconomic parameters. Parameters are variables that cannot be endogenously adapted throughout a simulation run. Typically, such parameters describe the behavior of the agent (behavioral parameters) or certain restrictions (structural parameters). For example, the supply decision of a consumer goods firm is defined via a behavioral parameter. This parameter connects the produced/supplied output of the present period to the marginal profitability of one output unit in the last period. Moreover, this supply decision is restricted by a structural parameter characterizing the production function. To highlight the important micro parameters of the model we label them through lower case Greek letters.

Macro parameters The system as whole is characterized by a vector of macroeconomic parameters. Similar to micro parameters, macro parameters cannot be modified endogenously, i.e. once fixed to a certain level, these values remain unchanged. In the present model, the technological progress is represented through a 'random walk process' defined by two parameters, namely by a 'drift term' and the variance of the 'white noise' term. Such a technical progress is constituted on the global level (i.e. for the whole economy) and on individual firm levels. A combination of both figures constitutes the individual technical change of a firm. Besides this, on the global level the 'drift term' and the variance are defined by two macro parameters. We call such macro parameters also global parameters. To highlight the important macro parameters of the model we characterize them also through lower case Greek letters.

Macro (or aggregate) variables Finally, there exists a set of macroeconomic variables. Usually, such variables (such as the GDP) emerge through some kind of aggregation of micro variables. Other macro variables are by nature defined on the macro level (e.g. the credit interest rate). We call macro variables also global variables.

Interaction structure The interaction structure controls the flow of information between agents. Consider firm agents that are trading on the capital goods market. Provided that two specific agents close a contract for the sale of a capital good (i.e. a machine), the seller updates his order book, while the buyer books a purchase order. Simultaneously, the account is settled by the buyer. According to that, the cash reserve of the buyer decreases, while the cash reserve of the seller increases by the same amount. Besides this, there is a third party involved in this payment process, as we apply a banking system to the model. Thereby, subsequent actions of each of the parties (in the next period) can be affected by that trading. According to this rather simple example, on can imagine that relatively complex interaction structures emerge on Agent Island.

Micro decisions rules Each agent is endowed with a set of decision rules. Such rules are routines, which map observable figures (past micro variables and macro variables or parameters) into present micro variables. Such a mapping process is based upon the micro parameters (i.e. behavioral or structural parameters) of the individual agent. It can also contain stochastic elements, if necessary. The concept of decision rules is crucial to agent–based models. It mirrors the notion of routinized behavior, known from 'evolutionary' economics (see explanations below). As we will discuss later on, micro decision rules based upon micro parameters define the 'genes' of the agents.

Space In principle, it is possible that an agent–based computational model features a spatial dimension. For example, the real map of a landscape could serve as the environment, in which agents live, produce and trade. This enables a more specific perspective on trading and other interactions. However, for the sake of simplicity we do not integrate such a spatial dimension to Agent Island.

1.1.4 Methodology vs. IT–Based Tool

According to the descriptions mentioned so far, one could assume that agent—based computational economics constitutes a methodology—such as the 'Walrasian' GE approach defines the methodological framework of modern 'neoclassical' macroeconomics. This, however, is not true. Agent–based computer simulations are a tool, viz. an IT–based technique of simulating a certain model. In here, an agent–based model features a general structure as described in the last subsections. According to this notion, it is not surprising that an agent–based framework would in principle allow the analysis of a GE model.[11,12] In fact, this would lead to the degeneration of the virtues of an agent–based technique. Consequently, it is interesting to see whether an alternative methodological framework for ACE is existing: We prefer the framework of 'evolutionary' economics.[13] The following table 1.1 illustrates, why the assumptions or concepts of 'evolutionary' economics fit very well into the agent–based approach. As the reader can see, the agent–based simulation technique is an ideal tool for the analysis of 'evolutionary' economics. The table should in addition compare the assumptions of 'neoclassical' and 'evolutionary' methodology.

Assumptions	Neoclassical	Evolutionary
System behavior	Can be derived from micro level Time and place independent Need not be dynamic	Not deducible from micro level Time and place dependent Has to be dynamic
Individual behavior	Optimizing Mechanical	Satisficing[1] Rules–of–thumb & routines
Interactions	Perfect capabilities & information Actors are substitutable	Imperfect capabilities & information Actors are not substitutable Learning, path dependency, co–evolution
Actors	Hyper–rational agents No history Often homogenous	Boundedly rational robots History existing Typically heterogenous

Sources: See Alkemade, 2004; Arnold and Boekholt, 2002; Jaffe1 et al., 2002; Nelson and Winter, 1982. Note: 1) The term 'satisficing' is coined by Herbert Simon. The tendency to satisfice shows up in many cognitive tasks such as playing games, solving problems, and making decisions where people typically do not or cannot search for the optimal solutions (Simon, 1982).

Table 1.1: Comparison of methodologies – neoclassical vs. evolutionary economics

This review should render a better understanding of the elements of an 'evolutionary' model. The concrete meaning will become clear throughout the remainder of this study. However, the main differences and virtues of 'evolutionary' economics based upon an agent–based environment will be worked out through the next section. Within the following brief description of the basic concepts

[11]For an illustration of a 'Walrasian' agent–based computational model see Gintis, 2007.

[12]The main problem of such an approach would be the calculation of rational expectations in a forward–looking framework. However, when the model is completely developed within the boundaries of GE models (e.g. by the application of one 'representative agent'), one could handle this problem in the same way as 'orthodox' economics does, so that the 'representative agent' knows all structural equations of the mechanical system. As a result, he could calculate the rational expectations outcomes of the economy far into the future.

[13]In the context of macroeconomics the term 'evolutionary' economics goes back to the seminal work of Nelson and Winter, 1982. The framework of Nelson and Winter follows the 'Schumpeterian' view of capitalism as an engine of progressive change. This view is connected to the problem of economic agents concerning the future, viz: The key character of progressive change is that it seems impossible for agents to calculate the right thing to do. What is an appropriate action and what not, will be only revealed by future events (see also Knight, 1921).

of ‘evolutionary’ economics, we link them to the agent–based approach of the present study (see Nelson and Winter, 1982):

Routines The set of routines of an agent describes the way the agent is doing things and the ways he determines what he has to do. Hence, the concept of routines covers the more ‘orthodox’ notions of capabilities (budget constraints) and choice (maximization). Behavior defined through routines does neither mean that agents behave irrational nor that their behavior is unchanging. Moreover, the concept of routines links the present behavior of the agent to the actions the agent (or its environment) is taking or has recently undertaken. Even though the basic flexibility of routinized behavior is limited, we can extend the framework so that a changing environment can force agents to modify their routines (see the next point). The concept of routines is basically one of the most important concepts used throughout the development of the model in this study. Each agent decides and behaves according to routines. Usually, a routine links past data (macro or micro data) to present decisions and actions. For example, each period the supply decisions of capital goods firms is delivered through a routine. Capital goods firm calculate their individual offer price through a ‘mark–up’ calculation, i.e. via a given percentage ‘mark–up’ over given marginal costs. This routine delivers the supply price of capital goods firms. Importantly, routines are the genes of an ‘evolutionary’ theory.

Search This concept contains all activities which are associated with the evaluation and potential modification of routines. The point is that such activities are themselves routinized and predictable. Then again, they can also have a stochastic character. To use the example of the supply decisions of capital goods firms above, the firm modifies its supply decision each period through the adjustment of price ‘mark–ups’. This is in turn a routinized activity, as one can see within the next point.

Selection environment The ‘selection environment’ is the ensemble of conditions outside or inside the agent, which affects its well–being or success. Such conditions can be delivered on the micro level (of the respective agent for example) or on an aggregate level (for example on the industry level). For instance, the above discussed supply decision of capital goods firms is determined via ‘mark–up’ pricing. As stated, this as well as the adaption of ‘mark–ups’ is routinized. Importantly, the adaption of ‘mark–ups’ (i.e. the ‘search process’ for a better ‘mark–up’)

> is defined via the 'selection environment' of the agent. This is given through past supply decisions, the resulting sales and profit figures and the conditions of the capital goods market. The 'selection environment' defined through these conditions gives the basis for the routinized adaption of present price 'mark–ups' in a rational way.

The term 'genes' within that description sheds light on the analogy between 'evolutionary' economics and biology.[14] According to this, there a is link between the genotypic level (i.e. behavioral patterns, technologies, policies etc.) and the entities (i.e. the agents) accommodating these genes (Dosi and Nelson, 1994). In fact, this notion mirrors exactly the notion of agent–based modeling. It is thus not surprising that several examples of agent–based models based upon the methodological framework of 'evolutionary' economics exist (for example Dosi et al., 2005; Dosi et al., 2006; Dosi et al., 2008).[15]

1.2 Virtues of Agent–Based Computational Macroeconomics

In this section we review the weakness of the orthodox approach to macroeconomics, and confront these weaknesses with the virtues of agent–based computational economics. In here, we subsume both the (neoclassical) 'Walrasian' GE approach and the 'New Keynesian' framework[16] of monetary theory under the term 'orthodox' economics. In fact, all modern models that belong to the group of 'orthodox' economics are rooted in the Walras or Arrow–Debreu framework.[17] This section reviews some assumptions and aspects of these models—namely those aspects which are subject to criticism. In order to illustrate the main positions of orthodox economics and compare them to the agent–based approach, we introduce a nearby island to Agent Island. The artificial economy of this neighbor

[14] Before the development of 'evolutionary' economics Alfred Marshall in fact states "that the Mecca of economics [lies] in economic biology rather than economic mechanism" (Marshall, 1948, p. xiv).

[15] For more information on the link between 'evolutionary' economics and agent–based computational economics see, among others, Dosi and Winter, 2002; Tesfatsion, 1997; Dosi and Nelson, 1994.

[16] See Woodford, 2003, for an introduction to the 'New Keynesian' framework. It is derived as the so–called 'New Neoclassical Synthesis' from the 'New Keynesian' paradigm (see e.g. Mankiw and Romer, 1991) and 'Real Business Cycle' models (see e.g. King and Rebelo, 1999). Woodford calls his approach also 'Neo–Wicksellian', because it builds on the distinction between the natural rate of interest and the money or credit interest rate (Woodford, 2003). We will explain both concepts in the following chapter.

[17] The 'Arrow–Debreu' framework is the modern successor of the original Walras model (see the original paper of Arrow and Debreu, 1954). It is the groundwork for all 'Dynamic Stochastic General Equilibrium' (DSGE) models, which were mentioned in the last subsection. The key is that it extends the static framework of Walras by introducing so–called 'Arrow-Debreu securities'. The notion of such securities draws on the concept of risk, i.e. that future states of the world could be defined through probabilities. If a certain state occurs, only that specific 'Arrow–Debreu security' assigned to this specific state pays out. All other 'Arrow–Debreu' securities pay zero return.

island is built upon a different structure compared to Agent Island. The following paragraphs illustrate that.

Population

The economy of the neighbor island of Agent Island is constituted by a 'representative agent'.[18] Now, what is, or rather what does the 'representative agent' in the artificial island economy? Gun, 2004, characterizes the idea of the the 'representative agent' unequivocally:

> "However, the representative agent of new macroeconomics is not 'representative' in this way [note of the author: here, 'this way' means representing a lot of different people]: He is identical with the people he 'represents'—because only identical persons are considered. Why are only identical persons considered? Because aggregation of non–identical agents creates problems. But, if people are identical, they have no reason for trading (exchange results from differences, in tastes, endowments, technologies): the situation is exactly the same if there is one or 'many identical' persons. 'Representative agent' is, thus, another name for Robinson Crusoe: new macroeconomics is 'Crusoe microeconomics' and, therefore, devoid of usefulness—it is even a regression in comparison with the 'old' (IS–LM) macroeconomics. Moreover, it is nonsense. New macroeconomists probably feel this, as they practically *never* try to justify the representative agent assumption. In the alphabetical index, at the end of their books or textbooks, they often 'forget' to mention him (as also happens with the 'auctioneer', in the index of microeconomic textbooks)." (Gun, 2004, p. 120)

Thereby the crucial point of the assumption that such an economy is populated by many identical households is not the word 'many'—rather, the key word is 'identical' (Gun, 2004). This notion implies that the many agents can be represented by one single agent. For this reason, we call this island subsequently Robinson Crusoe Island. The need for the modeling of the 'representative

[18] The 'representative agent' framework, as applied in almost every modern application of the 'orthodox' framework, goes back to Ramsey, 1928, and Cass, 1965. It should be noted that these seminal papers were normative studies, i.e. they search for economy's best path. Accordingly, it would be ideal, if aggregate savings behaved according to the constrained optimization of an aggregate utility function. However, in many modern applications (within the 'orthodox' branch of economics) the idea of the original normative 'representative agent' model is applied to positive models (Gun, 2004). This is a substantial chance, because the notion of the 'representative agent' approach could be seen as an ideal (efficient) outcome of barter. But it could be hardly seen as a good positive representation of reality.

agent', which is indeed a pretty strong simplification, lies in its simplicity: It reduces the complexity of the orthodox framework in order to get stable and unique equilibria (Fagiolo and Roventini, 2008). Another study describes the failure of modern 'representative agent' macroeconomics in the following way:

> "[...] it seems worthwhile to review why Walrasian microfoundations should be considered as the wrong answer to what is probably the most stimulating research question ever raised in economics, that is to explain how a completely decentralized economy composed of millions of (mainly) self–interested people coordinate actions." (Gaffeo et al., 2007, p. 91)

Hence, the 'representative agent' living on Robinson Crusoe Island represents not a component, simpler than the system of which he is part (Leijonhufvud, 2006a). This would be an intuitive assumption of an economy and its parts. The idea that the whole system is more complex than the part it is made up of, is one core assumption of 'complex system theory'. In addition, such a system consists of interrelated components. Not so the economy of Robinson Crusoe Island. Its economy is reduced to a unique single agent. But this contradicts the very essence of microeconomics, because without diversity of agents, there cannot be any exchange (Gun, 2004).

A good critical review of the 'representative agent' approach is delivered by Kirman, 1992. He finds at least five major aspects of criticism to the 'representative agent', which summarize the core problem of this approach: (i) Individual rationality does not imply aggregate rationality. This means that one cannot provide any formal justification for the assumption that the maximizing individual behavior could be applied to the aggregate level. (ii) The reaction of the 'representative agent' to shocks cannot coincide with the aggregate micro reactions of individuals. (iii) Even if the above mentioned problems are solved, other cases are existing where out of two given situations x and y, the 'representative agent' would prefer x, while all the individual agents would prefer y. (iv) There appears an additional problem at the empirical level. If one tests a theory delivered by a 'representative agent' model, one is also jointly testing the 'representative agent' hypothesis. (v) Finally, in case of heterogenous agents, it is implied that basic properties of linear dynamic micro properties are not preserved by aggregation. For example, the aggregation of *static* micro–equations could produce *dynamic* macro equations (Froni and Lippi, 1997).

We want to finish the discussion of the 'representative agent' living on Robinson Crusoe Island by a pointed picture delivered by Gun, 2004:

> "But, at the same time, they present representative models as positive models, and try to fit the model with existing data (through 'calibration' and other techniques): observed GDP, employment, consumption, investment of a country during, say, 10 years, are thus compared with what a representative agent's intertemporal choice would be–taking into account observed 'shocks'. This is total nonsense: How can any reasonable person admit that, for example, the evolution of the US aggregates' results from decisions made by a single individual who owns all factories and who decides how much to produce, how much labor to use, how production will be distributed between consumption and investment, and so on? It is quite incredible that the majority of a profession (which pretend to be 'scientific') readily indulges in this kind of absurdity, teaches it, and does a lot of 'research' on it—with maths, statistics, and computers—attempting to specify the representative agents 'parameter' (that is, coefficients in his utility and production functions) which allow good fits with observed data." (Gun, 2004, p. 121)

In contrast to this view, agent–based computational economics enables maximum flexibility in the design of heterogeneity. The artificial economy of Agent Island is populated by many agents, and these agents might be heterogenous in many dimensions (such as endowments, technology, tastes, behavior, etc.). We have already explained this issue. It is the difficult task of the model design and its 'validation' process to find a reasonable specifications for the heterogeneity. However, the role of heterogeneity is not as trivial as one might expect. It is not a mere extension of the homogenous agent framework: If heterogeneous agents (e.g. heterogenous with respect to behavior) adjust continually to the overall situation they create together, then they adapt within an environment they created together. And in so adapting, they change that environment (which could also be termed 'ecology'). According to this, 'evolution' (in the sense of 'evolutionary' economics) is used in the broadest sense of the word, which can be interpreted as elements adapting their state to the situation they together create (Arthur, 2006). We see that in this sense our adopted framework of 'evolutionary' economics emerges naturally from the very construction of the modeling in the agent–based framework. It need not be added as an adjunct.

Against the background of those explanations, it should be clear that the artificial economy of Agent Island emerges bottom–up; it is not constructed top–down as the Robinson Crusoe economy. We start from individual choices, whereas the latter takes as its starting point observed relations between aggregates. In general, agent–based computational are characterized in the following way:

> "There is no central, or 'top down', control over individual behavior in agent–based models. Of course, there will generally be feedback between macrostructures and microstructures, as where newborn agents are conditioned by social norms or institutions that have taken shape endogenously through earlier agent interactions. In this sense, micro and macro will, in general, co–evolve. But as a matter of model specification, no central controllers (e.g., Walrasian auctioneers) or higher authorities are posited ab initio." (Epstein, 2006b, p. 1588)

Consequently, the present analysis is able to investigate the true relationship between micro behavior and macro dynamics, which is not possible in 'representative agent' models. This will ultimately enable the discussion concerning 'fallacies of composition'.

Behavior

Next to the problematic aspect that Robinson Crusoe Island is populated by just one single representative inhabitant, the behavior of this Robinson Crusoe agent is furthermore quite unrealistic: Its basic structure is defined through a fundamental abstraction. It covers intertemporal choice, according to which an intertemporal expected utility (in case of uncertainty) is maximized subject to the budget constraint(s). This is a typical dynamic programing problem, known from 'control theory'—an interdisciplinary branch of engineering and mathematics.[19] It is, for example, similar to the program that an engineer has to solve in order to determine the best path for the flight of a rocket (e.g. with minimum use of fuel), given its target (Gun, 2004):

[19] Such models belong to the field of 'dynamic stochastic optimal control theory' (Colander, 2006).

> "It is a problem for an engineer, *not* for an economist. And, it can be very complicated to solve (as always with non–linear programs). Indeed, generally, it is not possible to find the exact optimal path, but only successive approximations of it (using computer and so on). So, the door is open to a lot of of 'work', and 'papers', about maths and econometric techniques that to get an 'as good as possible' approximation for the optimal path, with different kinds of utility and production functions, and 'shocks'. As unkowns (paths) are sequences of functions (and not numbers, as in common micro problems), Hamiltonians replace Lagrangians, and first order condictions take the form of differential equations; as there is an unlimited horizon, 'transversality' conditions exclude infinite solutions, and so on. These are very complicated problems; but they are Robinson Crusoe's problems—not ours!" (Gun, 2004, p. 122)

In addition, there are further problems concerning the behavior of the 'representative agent': For example, one can state that he is in fact 'schizophrenic', because he is at the same time a firm and a household: He employs himself and sells (buys) to himself. He pays himself (and earns) a wage equal to the marginal productivity of labor, and pays (again to himself) an interest rate equal to marginal productivity of capital (Gun, 2004). Finally, such models rest usually on the inconsistency that all firm and household agents are price takers. Firms and household treat prices as given in their optimization problem (in case of perfect competitive markets). But if prices are given for everyone, who sets those prices? See the following statement of Hal Varian:

> "The biggest problem is one that is the most fundamental, namely the paradoxical relationship between the idea of competition and price adjustment: if all economic agents take market prices as given and outside their control, how can prices move? Who is left to adjust prices?" (Varian, 1992, p. 397)

Within 'orthodox' theory this puzzle is solved by the concept of the 'Walrasian auctioneer', who searches for prices that solve the mutual optimization problem of all agents in the economy (see the 'formal view' of the GE framework below). Hence, he matches demand and supply schedules in all relevant markets of the economy of Robinson Crusoe Island. We will discuss below the implications of this abstraction, and its impact on interaction of agents and the role of information. However, we know that Agent Island is populated by a plurality of agents that employ rule–based or routinized behavior. This is a strong deviation from the 'orthodox' framework: It enables a maximum flexibility to the design of agent behavior. This leads to a more realistic modeling of interaction, information processing, uncertainty, and so on. The researcher is not caught in the narrow 'prison' of 'Walrasian' economics; however, if necessary, he can 'borrow' some aspects form 'orthodox' economics. The point is that the modeling features the flexibility to move as near as necessary to the relevant behavior of agents. Nevertheless, agent–based models possess a likewise high level of 'abstraction'. In contrast to some critics of agent–based research we can state that 'abstraction' in ACE prevails as the core concept of scientific research. Agent–based modeling, however, opens the possibility to adjust the degree of abstraction perfectly to the needs of the research field or the investigated topic as opposed to 'orthodox' economics, where the degree of abstraction is unchangeably defined by the strict assumptions of the GE framework.

Another important issue of agent behavior is the role of uncertainty. We know that Robinson Crusoe (of 'orthodox' economics) follows the notion of far forward–looking rational expectations[20]. To understand this idea, we have to make some preliminary considerations: In this context the differentiation between 'risk' and 'true uncertainty' is important. This topic is introduced by Knight, 1921, whereby 'risk' refers to situations where an agent can assign mathematical probabilities to the randomness which he is facing. On the contrary, in case of 'true uncertainty', the existing randomness can *not* be expressed in terms of probabilities. This phenomenon lies in the mere complexity to *assign* probabilities to events. Because of the complexity of an economy as a whole and because of the interacting behaviors, it seems to be impossible for any economic agent to calculate probabilities for relevant states. This point was already emphasized by John Maynard Keynes in his 'response' to his critics in 1937 where he states:

> "By 'uncertain' knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty; nor is the prospect of a Victory bond being drawn. Or, again,

[20]The term 'rational expectations' is coined by Muth, 1961. It implies that agents' expectations are *correct on average*. To put it differently, although the future is not fully predictable, agents' expectations are assumed not to be systematically biased. The agents use all relevant information in forming expectations of economic variables. The notion behind that is the 'best guess' of the future or 'the optimal forecast' of future outcomes.

> the expectation of life is only slightly uncertain. Even the weather is only moderately uncertain. The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence, or the obsolescence of a new invention, or the position of private wealth owners in the social system in 1970. About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know." (Keynes, 1973, p. 113-114)

In addition, Keynes added:

> "[...] the hypothesis of a calculable future leads to a wrong interpretation of the principles of behavior." (Keynes, 1973, p. 122)

The concept of rational expectations applied to the optimization problem on Robinson Crusoe Island is therefore questionable. It should thus not surprise that Agent Island is subject to 'true uncertainty': The islanders cannot calculate any rational expectations outcomes for the future values of economic variables. They simply do not know the true 'meta model' of the economy. The researcher does not know this model neither. He rather endows the agents with data and routinized behavior, but he has no 'meta model' of how the interaction of many thousands of such routines operates. If he had, he would not need to conduct agent–based computer simulations. Lastly, it is important to examine the behavior of agents under 'true uncertainty'. According to Keynes two 'factors' influence the expectation formation of an agent (Keynes, 1936): (i) current facts, and (ii) the expectations of other agents. Keynes argues that expectations formed under 'true uncertainty' tend to be to a considerable degree backward–looking as they project past or current situational 'factors' into the future instead of being exclusively forward–looking, as suggested by the rational expectations hypothesis. According to this notion, it is apparent that the inhabitants of Agent Island form backward–looking expectations, because they are not able to forecast the true future outcomes of the model.

In brief, the Robinson Crusoe agent is endowed with a sort of hyper–rationality or 'olympic' rationality (Fagiolo and Roventini, 2008). Its rationality knows no bounds (Leijonhufvud, 2006a).

In contrast, the artificial economy of Agent Island is built upon simplified rule–based or routinized behavior; agents are thus subject to the concept of 'bounded rationality'. This 'bounded rationality' has two components (Epstein, 2006b): Agents have neither global information nor infinite computational power.

Economic Interactions

One important source of interaction is rooted in the role of uncertainty. According to Pesaran, 1987, decision making under uncertainty can be described by a process in which an agent is not perfectly aware of the consequences of his action. When one examines the role of uncertainty in economics, two different sources of uncertainty can be identified (Pesaran, 1987): (i) 'exogenous uncertainty', and (ii) 'endogenous uncertainty'. 'Exogenous uncertainty' covers uncertainty due to exogenous 'factors' (in the context of macro dynamics this is for example described by the role of exogenous disturbances like wars or other political events). In contrast, 'endogenous uncertainty' can be attributed to the impact of economic actions chosen by some other agents. Therefore, 'endogenous uncertainty' is also characterized as 'behavioral uncertainty', because it arises endogenously from the behavior of other market participants. Following 'endogenous' or 'behavioral uncertainty' the occurrence of a certain state is not an invariant result of the agent's own behavior. The existence and prevalence of 'behavioral uncertainty' is rather due to the capacity of individuals to adapt and react to another in a non–negligible manner (Pesaran, 1987). Consequently, the degree of 'behavioral uncertainty' is related to the extent to which individuals are be able to influence the actions of others by their own actions, or conversely, to what extent they are themselves influenced by the actions of other agents. Therefore, Pesaran, 1987, concludes that in reality all decentralized systems of economic decision making are subject to 'behavioral uncertainty'.

This point highlights the weakness of the 'microfoundation' in the case of Robinson Crusoe: In this approach 'endogenous' or 'behavioral uncertainty' is not comprised. Agents do not react explicitly to the behavior of other agents. They rather do constraint optimizations in order to obtain their individual demand or supply schedules. All 'interactions' are considered via the 'Walrasian auctioneer':

> "The most salient structural characteristic of Walrasian equilibrium is its strong dependence on the Walrasian Auctioneer pricing mechanism, a coordination device that eliminates the possibility of strategic behavior. All agent interactions are passively mediated through payment systems; 'face–to–face' interactions are not permitted. [...] The equilibrium values for the linking price [...] variables are determined by market clearing conditions imposed through the Walrasian Auctioneer pricing mechanism; they are not determined by the actions of consumers, firms, or any other agency supposed to actually reside in the economy. Walrasian equilibrium is an elegant affirmative answer to a logically posed issue: can efficient allocations be supported through decentralized market prices? It does not address, and was not meant to address, how production, pricing, and trade actually take place in real–world economies through various forms of procurement processes. [...] What happens in a standard Walrasian equilibrium if the Walrasian Auctioneer pricing mechanism is removed and if prices and quantities are instead required to be set entirely through the actions of firms and consumers themselves? Not surprisingly, this 'small' perturbation of the Walrasian model turns out to be anything but small. [...] As elaborated by numerous commentators, the modeler must now come to grips with challenging issues such as asymmetric information, strategic interaction, expectation formation on the basis of limited information, mutual learning, social norms, transaction costs, externalities, market power, predation, collusion, and the possibility of coordination failure." (Tesfatsion, 2006, p. 833–835)

Against the background of the stated notion of behavioral uncertainty it becomes obvious, that the economy of Crusoe Island does not feature such behavioral uncertainty or any forms of interactions beyond the price mechanism governed by the 'Walrasian auctioneer'. In addition, according to the application of the 'representative agent' in the household and firm sectors, the logic of 'behavioral uncertainty' within these sectors is totally factored out. In contrast, trading on Agent Island is governed by procurement processes. Evidence from real world implies that:

> "[...] customers and suppliers must identify what goods and services they wish to buy and sell, in what volume, and at what prices. Potential traders must be identified, offers to buy and sell must be prepared and transmitted, and received offers must be

> compared and evaluated. Specific trade partners must be selected, possibly with further negotiation to determine contract provisions, and transactions and payment processing must be carried out." (Tesfatsion, 2006, p. 834)

This observation is the basis for the design of interaction through 'face–to–face trading' and procurement processes on Agent Island.[21] In case of removing the 'Walrasian auctioneer' and turning to more realistic procurement processes, we have to apply a minimal requirement: This implies that individual agents on Agent Island have to be endowed with rules, which satisfy that (i) terms of trades (prices and production levels) are defined, (ii) a seller–buyer–matching is described (defined through search routines), (iii) actual trade is conducted, (iv) settlement is fulfilled, and (v) a rationing mechanism is defined in case of excess demand (Tesfatsion, 2006). Furthermore, generating and processing information takes up an important role with respect to the interaction of agents. The following paragraphs discuss that point.

Information

By now it should become clear that the access to information and the possibility to process the available information is crucial to the structure of the economy. The economy of Robinson Crusoe Island is based upon some strict and special assumptions concerning the treatment of information. In principle, there are two alternative views concerning the role of information in the 'Walrasian' framework:

Informal view According to the 'informal view' the process of price determination is not defined clearly. It is the vague notion stated above, namely that all agents are price takers, and prices are set by an unknown process. According to Kirman, 2006, this characterization of the 'Walrasian' system characterizes an uncontrolled system, where equilibrium prices are found through a undefined bargaining process. The crucial point is that according to the 'informal view', the Robinson Crusoe agent possesses a great deal of information (effectively all information existing in the whole economy). Moreover, the agent must exhibit all calculation capabilities to process the information. Consequently, the 'informal view' represents the idea of hyper–rationality or 'olympic' rationality—as stated above. The key problem of the 'informal

[21] This is especially true for the capital goods market, which features 'monopolistic competition'.

view' is that in reality agents are endowed with limited computing power and they have access to limited information only (Colander, 2006). Thus, one can assume that no real–world agent can do such complex calculations into the far future, for which economist have to use complex computer–based approximation algorithms. Note that the GE framework is, however, far less complex than reality. Hence, in reality, agents would need much more computational power to solve 'Walrasian' optimization problems.

Formal view In contrast to the 'informal view', there exists the more abstract and precise view, which is near the original view of Léon Walras or Kenneth Arrow and Gerard Debreu. The 'formal view' assumes that the amount of information that individuals have to know and process is negligible (Kirman, 2006). All the agents need is the current vector of prices and their opportunity set. Given those facts, 'Walrasian' agents have to calculate and announce their excess demand to a central institution. But agents have to know nothing about the generation of equilibrium prices. The mechanism behind the generation of prices is the 'Walrasian auctioneer'. Assuming this, little information is needed by individual agents, because the relevant information is processed for them. The key problem to this central price setting mechanism is the fact that the application of this central auctioneer to reality is impossible. Such a central institution would need an infinite amount of information in order to bring the system into equilibrium (Kirman, 2006).

In both views the treatment of information is crucial. Both views represent pretty unrealistic assumptions on generating and processing information. In contrast, on Agent Island, agents do not posses perfect information, nor is there a central planer that is needed to calculate equilibrium prices for the markets.[22] Accordingly, some individual data (i.e. information) are designated as publicly accessible to all other agents, some are designated as private and therefore not accessible by any other agents, and some are designated as protected from access by all but a specified subset of other agents (Tesfatsion, 2006). Figure 1.1 illustrates the role of information within economic interactions on Agent Island.

[22]As already noted, the consumer goods market on Agent Island is cleared by a central institution that collects individual supply and demand schedules. This is for the sake of simplicity. But this is not the case in the capital goods market.

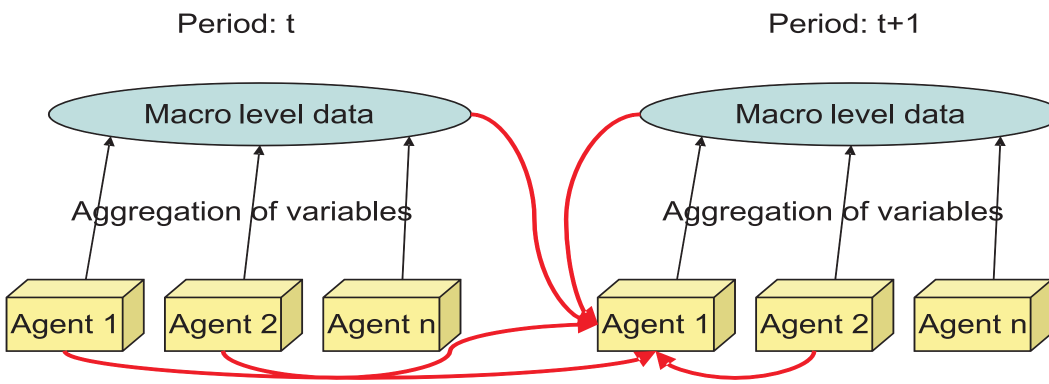

Figure 1.1: Interaction profile represented by the information flow

Figure 1.1 depicts the fact that aggregate information emerges bottom up by aggregating individual information (e.g. by aggregating individual incomes to GDP). This aggregate information set is used in the following period by agents, which is illustrated through agent 1 in the figure: He receives information from the last–period aggregate level (e.g. the last–period's consumer goods price) and from the present aggregate level (e.g. the present credit interest rates). In addition, he receives information from other agents (e.g. the individual supply prices for goods he demands), generated in the present or in the previous period. Finally, agent 1 receives own information generated in the last period, such as the last–period's disposable income. Hence, there are many sources of information. In sum, this enables complex interaction effects within the model. One can state, as Leight Tesfatsion does, that "everything seems to depend on everything else" (Tesfatsion, 2006, p. 861). This is obviously a major difference between Robinson Crusoe Island and Agent Island.

Role of Money

Both artificial island economies are designed to perform monetary policy analysis[23]—but on Robinson Crusoe Island money is not decisive. This means that the economy is based upon the real exchange of goods and services: All economic transactions are rooted in their real parts. If at all, money is *added* rather than *integrated* into the model. In addition, the islanders of Robinson Cursoe Island have perfect calculation capacities, so that the main functions of money (such as the reduction of transaction cost through fewer relative prices) are obsolete:

[23]In this case Robinson Crusoe Island represents the 'New Keynesian framework' as outlined by Woodford, 2003.

> "However the structure of the dominant macro– and microeconomic theories of our time, which are built upon the modern version of Walrasian general equilibrium theory, ignores the financial dimensions of capitalist economies. [...] The postulate of general equilibrium theory which ensures that money and finance are excluded from the core of the theory is that variables in preferences systems are goods and services." (Minsky, 1995, p. 197 and 207)

On the contrary, the economy of Agent Island is endowed with a central bank that issues means of payment. Money is decisive on Agent Island, and it is integrated in each economic process. Accordingly, there exists a 'unit of account', a 'medium of account', and a 'medium of exchange' on Agent Island.[24] This enables, for example, the storage of wealth through financial assets. Finally, the model of Agent Island features a stock–flow consistent framework of an economy. There exists a double–entry book keeping system, so that, for example, 'flow–of–funds accounting' is possible. It is therefore possible to analyze systematically the 'monetary circuit' of Agent Island. In each computational step of the simulation run the researcher has access to any accounting data, such as flow–of–funds data of each individual agent, or on each level or aggregation. This is obviously an advantage over 'orthodox' economics.

Macroeconomic Dynamics

The artificial economy of Robinson Crusoe Island moves even beyond perfect information by adding stochastic risk (defined through probability distributions) to the general equilibrium optimization problem over time. Accordingly, the behavior of Crusoe becomes a gigantic 'dynamic stochastic optimal control problem' (Colander, 2006). One key difference of Agent Island and Robinson Crusoe Island lies therefore in the notion of equilibrium:

> "One key departure of ACE modeling from more standard approaches is that events are driven solely by agent interactions once initial conditions have been specified. Thus, rather than focusing on the equilibrium states of a system, the idea is to watch and see if some form of equilibrium develops over time." (Tesfatsion, 2006, p. 843)

[24]This terms are defined at the end of chapter 2.

On Robinson Crusoe Island the equilibrium is exogenously imposed on the economy, i.e. the researcher searches for simultaneous equilibrium prices in all relevant markets. This searching is conducted by the 'Walrasian auctioneer'.[25] In contrast, no exogenous equilibrium concept is *imposed* on the Agent Island economy. The aggregate behavior and dynamic of the economy evolves bottom–up out of individual actions and interactions. It is one topic of the 'validation' procedure to find an appropriate equilibrium concept, which can be applied to our simulation model.

Lastly, the artificial economy on Robinson Crusoe Island does not contain an explicit theory of business cycle dynamics, because the economy rests in the steady state unless it is hit by some *exogenous* stochastic shocks. It does therefore not explain the movements of the business cycle endogenously. It rather generates its dynamics with a sort of 'deus–ex–machina mechanism' (Fagiolo and Roventini, 2008). 'Walrasian' researches ask the question, how can deviations from the equilibrium take place? They search for shocks that account for such fluctuations. In addition, they usually add 'imperfections' (such as nominal price rigidities) to the system, which account for the fact that shocks are not perfectly dampened (Colander, 2006). For example, on 'Woodford Island' (the island of the 'New Keynesian' macroeconomics, the state–of–the–art in modern monetary theory) real effects of monetary policy are exclusively based upon the existence of price rigidities. If they were absent, the model would immediately fall back into a new flexible–price equilibrium state, after the occurrence of an exogenous shock. In this equilibrium state the real interest rate is the outcome (i.e. the equilibrium price) of the market for savings and investment. In contrast to that view, the artificial economy of Agent Island has a tendency to chaotic behavior, which is kept under control by institutions. The important question is therefore, why is there as much stability in an economy as there is? Thus, one difference between the perspective of Crusoe Island and that of Agent Island lies in the instability of the system. For Agent Island, "what is unusual about the macroeconomy is not that it exhibits instability; it is that it is not in total chaos" (Colander, 2006, p. 10).

Drawbacks of Agent–Based Computer Simulations

According to Tesfatsion, 2006, one can identify (of course) some drawbacks of the agent–based computer simulation approach: (i) An agent–based model requires a dynamically *complete* modeling.

[25] This is the logic of the above described 'formal view' of the 'Walrasian' GE.

This implies that starting from the setting of the model, the model must permit and fully support the playing out of agent interaction *without* further intervention from the researcher. Due to complex interactions and feedback loops, this initial adjustment of the model is a really difficult task. (ii) According to this requirement of *complete* modeling, the researcher has to consider all possible cases (outcomes or states); otherwise the model could stop, provided that a state occurs which is not considered in advance (such as the capital stock of a firm is falling to zero). (iii) In the next place, it is not clear how well agent–based models will be able to scale up to provide empirically and practically useful models of large–scale systems with many thousand agents. (iv) Lastly, the major problem is the 'validation' of the agent–based model, i.e. the adjustment of the model settings against empirical data. This last point is the central issue of the following section.

1.3 Validation Framework

It is the main purpose of the present study to deliver a reasonable validated macroeconomic model. 'Validity' is thereby the key property of an agent–based simulation model (Klügl, 2008b). It means that the 'right' model is used with respect to the intention of the researcher (Balci, 1994). Hence, validity of an agent–based model is necessary for any normative analysis: A valid model produces reliable results, and only a valid model is able to answer questions directed at the original system. Therefore, 'validation' can be defined as "the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study" (Law, 2005, p. 24). In general, there exists a variety of 'validation' types. For example 'validation' can be empirical, or statistical; 'validation' can cover the theory, the conceptional model, or the program code, and so on.[26] In this study we follow the 'validation' approach suggested by Klügl (Klügl, 2008a; Klügl, 2008b), which is developed in the field of computer science. Figure 1.2 illustrates the framework of this approach.

Before we describe the single steps depicted in figure 1.2 during the following subsections, we want to illustrate some problems regarding the 'validation' process. ACE is an interesting framework due to the intuitive structure of the models based on the analogy between agents and the active

[26]See for example Sargent, 2007, for a review of the various 'validation' types.

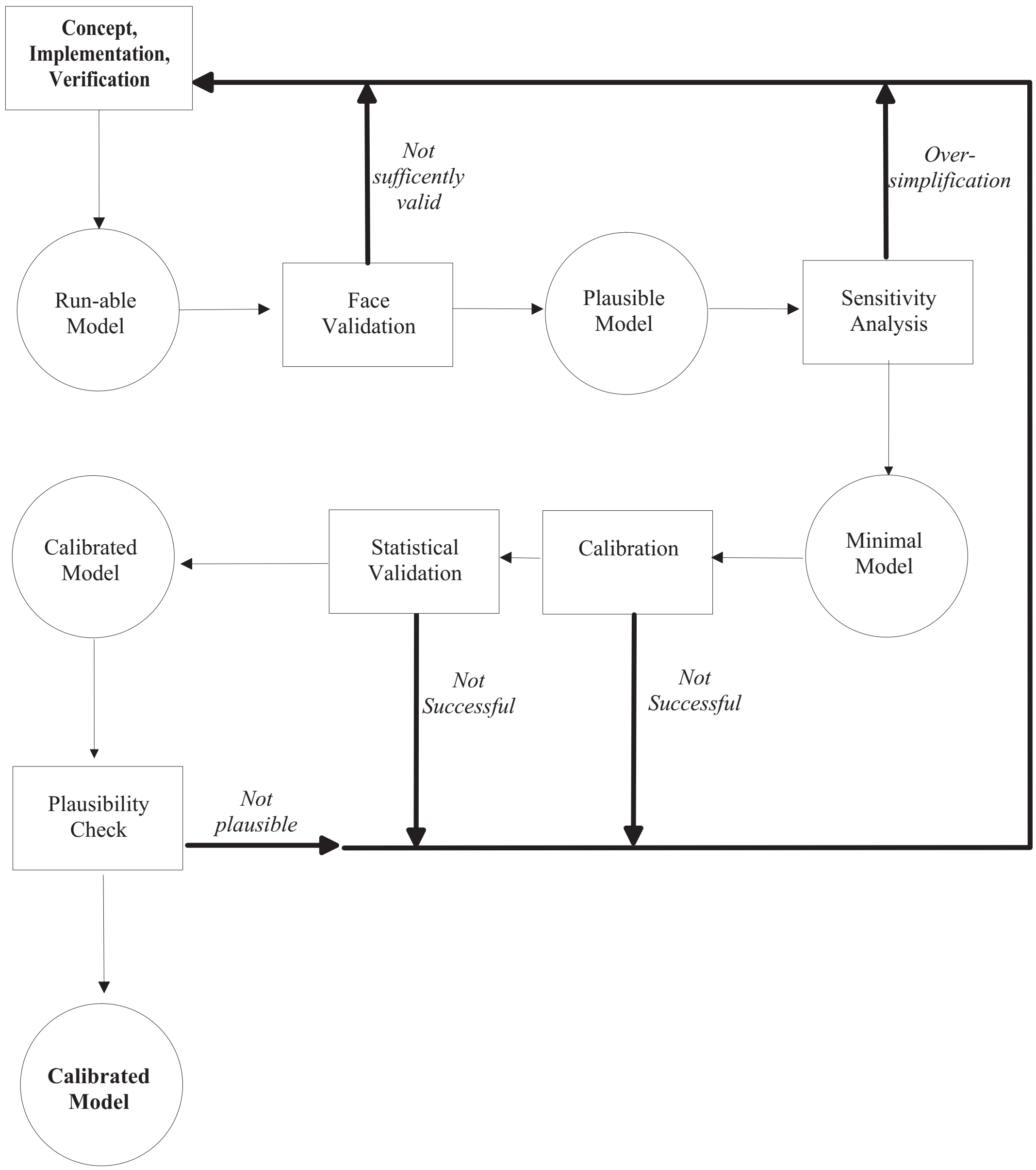

Figure 1.2: Validation framework; Source: Klügl, 2008

elements in the 'original system'. The 'validation' of such an ACE model is an essential task, which features several problems (see Klügl, 2008b): For example, empirical and statistical 'validation' is only possible, if characteristic figures can be defined that describe the system in a correct way. The topic of the present analysis treats time series data on the aggregate level. In this circumstance, it will be necessary to compress the time series data to some individual figures, e.g. expected value and standard deviation. Moreover, agent–based simulations are adequate for studying transient dynamics. It is therefore of interest whether the dynamics of a system can or cannot lead to a steady state. In addition, the 'validation' task is further complicated through complex interaction effects, feedback loops and non–linear effects of parameter changes on simulation outputs.

Furthermore, it is problematic that the 'validation' process is optimally conducted on multiple levels. In effect, this means that input–output relations have to be investigated on the aggregate level, but also on some disaggregate levels—down to the individual agent level (Klügl, 2008b). In the context of the 'validation' of the present model, we forgo such a 'validation' on multiple levels of the model. According to our framework, we validate the model exclusively to phenomena perceived on the macro level: Thereby the parameters on micro level have to be adjusted in such a way that the macro output matches that of the 'original system'. We call this 'original system' also the 'reference system'. The approach of validating a model only on the macro level is along the lines of the concept of 'generative sufficiency', which is explained in the subsequent paragraph. Besides this, 'validation' on the individual level would be a difficult (if not impossible) task. This is at least due to lacking individual micro data. We will see later on that most empirical studies are conducted on the aggregate level (such as the estimations of aggregate savings' rates, or aggregate production functions, and so on). Empirical studies based on micro data are quite rare. Finally, there exists the problem of over–parametrization: Suppose that the model contains to many 'degrees of freedom'. In this case an automatic optimizing calibration tool will be always able to fit the model to the data.

As a consequence of multiple problems concerning 'validation', the concept of 'generative sufficiency' was introduced by Epstein, 2006a:

> "Agent-based models provide computational demonstrations that a given microspecification is in fact *sufficient to generate* a macrostructure of interest. Agent–based modelers may use statistics to gauge the generative sufficiency of a given microspecification—to test the agreement between real-world and generated macro structures. [...] A good fit demonstrates that the target macrostructure—the *explanandum*—be it a wealth distribution, segregation pattern, price equilibrium, norm, or some other macrostructure, is effectively attainable under repeated application of agent-interaction rules: It is *effectively computable by agent society.* [...] Indeed, *this demonstration is taken as a necessary condition for explanation itself.* [...] Thus, the motto of *generative social science*, if you will, is: If you didn't grow it, you didn't explain its emergence. [...] In summary, if the microspecification m does not generate the macrostructure x, then m is not a candidate explanation. If m does generate x, it is a candidate. If there is more than one candidate, further work is required at the micro–level to determine which m is the most tenable explanation empirically" (Epstein, 2006a, p. 8 and p. 9)

According to 'generative sufficiency', the focus of our model development lies in the ability to reproduce observed aggregate phenomena based upon individual agents and their interactions. We apply this notion and integrate it into the 'validation' framework of Klügl, 2008b: As explained above, the intention of 'validation' is to verify that the 'right' model is used for the purpose of interest. The point is, what the word 'right' implies? In the present context we use the concept of 'generative sufficiency' to concretize the notion behind the term 'right model'. Accordingly, our model is the 'right' one, if it is able to reproduce (bottom up) the macro behavior of the 'reference system'. Because it is our aim to develop a micro structure that generates the macro phenomena we are interested in, the present model belongs to the group of 'generative social sciences'—and the 'validation' approach of figure 1.2 guarantees that the model is able to fit to the macro phenomena. Conversely, we exclude the formal testing of any 'micro validity'. The following subsections explain briefly the 'validation' steps indicated by figure 1.2.

1.3.1 Conceptual Model

The basic building block of an agent–based simulation is the 'conceptual model'. Constructing an ACE model gives the researcher a sense of playing God in his own artificial world. As explained throughout section 1.1, the researcher has to define a number of agents with characteristic variables, a set of decision rules or routines, and an environment in which interaction takes place. Those definitions are constituted in the 'conceptual model'. In case of the presented model, the programing took place in the SeSAm programing environment.[27]

For the initial construction of the model we followed a three–step approach (see Bruun, 1995). In the first step, we have to find macro–bindings, which are relevant to our macro system. We thus define that the model of Agent Island has to feature the following aspects on the aggregate level:

1. The Agent Island economy is a closed economy without a government sector (i.e. government expenditures do not take place). The aggregate national income equation for the Agent Island economy is $Y = C + I$.

2. We design a 'perfect competitive' consumer goods market and a capital goods market featuring 'monopolistic competition'. In addition, a labor market must be integrated, in which a central bargaining between a labor union and an employer association takes place at the beginning of each period.

3. Agent Island has a closed 'monetary circuit' without cash money, i.e. there is a perfect bookkeeping system for monetary flows and stocks.

4. Economic policy on Agent Island is executed through interest rate policy of a central bank. This implies the existence of monetary 'transmission channel(s)'. In here, we use a 'Wicksellian' framework.

The identification of macro–bindings does not imply that we should model those macro–bindings first, but they assist us in the subsequent steps. In the second step, we consider the micro analysis:

[27]SeSAm stands for 'Shell for Simulated Agent Systems'. The reader can find the SeSAm software, tutorials, as well as additional material on http://www.simsesam.de/. The installer for the presented simulation model is located on the CD in appendix C.

This covers the design of individual behavior of agents, i.e. how they act and react. As mentioned, we have to bear in mind the above mentioned macro restrictions when modeling behavior on the micro level. Accordingly, the Agent Island economy encompasses markets for consumption goods and capital goods. The latter is necessary because of the intertemporal characteristics of the model, i.e. according to to the central bank interest rate policy. Moreover, the central bank policy must affect some decisions of the agents, so that there is at least one 'transmission channel' of monetary theory. The financial settlement of transactions is conducted through a book keeping system. Finally, we assume 'perfect competition' in the consumer goods market, 'monopolistic competition' in the capital goods market, and central bargaining in the labor market. We will explain these assumptions during chapter 2. However, the design of the markets affects the individual routines of all agents. We have to keep these points in mind throughout the design of any transaction. The third and final step of the basic model design is the simulation. It combines macro and micro perspectives. This implies the interaction of micro behaviors and the macro bindings within the programed computer simulation.

1.3.2 Face Validation

The 'validation' process described in figure 1.2 starts with a run–able model. This implies that simulation output can be generated through simulation runs. It is important to note that this does not mean that 'validation' is irrelevant in earlier phases of the model development. In fact, the opposite is true: If not, at first, the conceptual 'validation' is considered, the subsequent steps considered in the 'validation' framework do not make sense (Klügl, 2008b). We define 'face validation' in accordance to (Klügl, 2008b, p. 3): "All tests based on reviews, audits, involving presentation and justification of assumptions and model structure are used for reaching this form of plausibility". Importantly, 'face validation' takes place on several aggregation levels, i.e. it can be applied on the macro or individual level (Klügl, 2008b). Usually we are interested in aggregate model outputs given through absolute values, relations between different values, and the dynamics of certain variables. In here, the researcher (i.e. a human expert) has to evaluate whether the simulation behaves like the 'original system'. In context of the model of Agent Island, the process of 'face validating' the model has taken up several months. In our view, it is maybe the most helpful (or effective) device within the whole ‘validation’ process. Without intensive ‘face validation’, we could have never developed and validated the model in a reasonable way.

1.3.3 Sensitivity Analysis

Within the present framework depicted in figure 1.2 the results of the sensitivity analysis delivers a minimal model to be investigated in the further ‘validation’ process. This implies that parameters without significant impact on model output drop out from further investigations. Equally important, the sensitivity analysis is used to verify the assumed relationships between micro parameters and macro output. Accordingly, we use the sensitivity analysis to develop a basic understanding of our simulation model (Kleijnen et al., 2003). In this context the present subsection should give some basic methodological guidelines for a sensitivity analysis and computer experiments. The latter is necessary, because the data used in the sensitivity analysis are generated through computer experiments. Hence, we need to discuss some basics in ‘experimental design’ (usually termed ‘Design of Experiments’, or DoE in brief) as well. Before we turn to these specific topics, we have to define some terminology (see Fang et al., 2006):

Experiment, ‘Design of Experiments’ An experiment is the methodical configuration of a systematic scientific inquiry.[28] Such an experimental inquiry can be conducted physically or as a computer experiment. Within an experiment there is at least one experimental ‘factor’ (see the next point) which is varied, in order to investigate the systematic effect on the ‘response(s)’ of the experiment (see again below). The configuration of the variation of ‘factors’ is subject to the ‘Design of Experiment’. Thus, DoE indicates how to vary the settings of the ‘factors’ to see whether and how they affect the ‘responses’.

Factor A ‘factor’ is a controllable parameter (such as structural or behavioral parameter, but also initial values of endogenous variables) that is of interest in the experiment. In general, a ‘factor’ may be quantitative or qualitative. Except for one case we treat only quantitative ‘factors’. The only qualitative ‘factor’ leads to a distinction of cases within our analysis. In a computer experiment (as in the present study), a ‘factor’ is often called ‘input variable’ as

[28] In general, an experiment is a method of investigating less known fields, solving practical problems, and proving theoretical assumptions.

well. Henceforward, we will use both terms (i.e. ‘factor’ and ‘input variable’) as synonyms.

Experimental domain, level, and scenario The experimental domain is the space where the ‘factors’ or the input variables take values. Within computer experiments this is also called ‘input variable space’. A ‘factor’ may be chosen to have few or many specific values, at which the ‘factor’ is tested. We call these selected values the levels of the ‘factor’. In addition, a level combination defines an investigated scenario, i.e. it defines a certain point in the ‘input variable space’ or the ‘experimental domain’. Sometimes it is also called ‘experimental point’.

Run A run defines the implementation of a scenario (or level combination) in a computer experiment. Multiple runs within the same scenario (i.e. replications or reruns) reproduce the same results, when the model is deterministic; or they produce various results, when the model exhibits stochastic elements. The latter is the case within the model of the present study.

Response The ‘response’ defines the results (outputs, or outcomes) of a simulation run based on the purposes of the experiment. Usually, the ‘response’ is a quantitative measure, but it can be also qualitative or categorial. We concentrate on quantitative ‘responses’ throughout this study.

Factorial design A ‘factorial design’ is a set of level combinations with the main objective of estimating the effects of the ‘factors’ on the ‘response(s)’. It is the topic of DoE to find an appropriate ‘factorial design’. In some cases, it is possible and appropriate to investigate the total experimental domain in an experiment. Such a design is called ‘full factorial design’. On the other hand, in a ‘fractional factorial design’ only a subset of all level combinations (i.e. the entire input variable space) is investigated.

In the next step we explain, at first, the opted ‘experimental design’. This gives the basis of the experimental investigations in section 3.3. Thereafter, we give a short illustration of the statistical methodology applied in the sensitivity analysis of section 3.3. As explained above, the sensitivity analysis is based upon data generated through computer experiments.

Design of Experiments: Nearly Orthogonal Latin Hypercube

Considering the model of this study, it will be necessary to design the experiments in an appropriate way, because we have to investigate many 'factors', and the underlying processes are assumed to be complex and non–linear. The following statement should illustrate the rationale for designing experiments and what happens if this is not done:

> "Instead of using even a simple experimental design, many analysts end up making runs to measure performance for only a single system specification, or they choose to vary a handful of the many potential 'factors' one–at–a–time. Their efforts are focused on building, rather than analyzing, the simulation model. DoE benefits can be cast in terms of achieving gains (e.g., improving average performance by using DoE instead of a trial–and–error approach to finding a good solution) or avoiding losses (e.g., obtaining an optimal result with respect to one specific environmental setting may lead to disastrous results when implemented)." (Kleijnen et al., 2003, p. 2)

As explained above, DoE covers the variation of the experimental 'factors', i.e. it treats the factorial design. Suppose a sensitivity analysis with n 'factors'. We can therefore define a 'design matrix' F_X for experiment X:

$$F_X = \begin{pmatrix} f_{1,1} & f_{1,2} & \dots & f_{1,n} \\ f_{2,1} & & & \\ \dots & & & \\ f_{m,1} & & & f_{m,n} \end{pmatrix}$$

In general, the columns of the 'design matrix' correspond to 'factors', and the entries within a column represent settings (or levels) for the corresponding 'factors'. The rows represent a particular level combination, scenario, or design point. The levels may be coded (e.g. '+' for the high level, '0' for the medium level, and '-' for the low level in a three–level design). Considering the present study, we do not use coded levels, i.e. we use the 'natural levels' of the 'factors'. The matrix above is arranged in the following way: $f_{1,2}$ delivers the level of 'factor' 2 (second column) in the first of m scenarios (first row). In general, the 'design matrix' is spanned over a set of n 'factors', and m scenarios. This gives a $m \times n$ 'design matrix'. Besides this, we assume r replications of the m

scenarios. Accordingly, we need to conduct $r \times m$ total runs in the experiment. Next to the 'factor matrix' F_X, the 'responses' of experiment X are captured in a 'response matrix' R_X (including l 'responses'):

$$R_X = \begin{pmatrix} r_{1,1} & r_{1,2} & \dots & r_{1,l} \\ r_{2,1} & & & \\ \dots & & & \\ r_{m,1} & & & r_{m,l} \end{pmatrix}$$

This matrix is arranged in analogy to the 'design matrix' above. Again, as we apply r replications, we obtain r replications of this 'response matrix'. The description so far will give us a rough idea of 'experimental design'. However, there is an obvious problem: When the number of 'factors' becomes large, the data requirement grows exponentially. For example, if we investigate only two 'factors' with two levels, we have to conduct $2^2 = 4$ runs. If we expand the levels from 2 to 10, this number rises to $10^2 = 100$ scenarios. If we investigate 10 'factors' with just 2 levels, $2^{10} = 1,024$ runs must be conducted and investigated. Finally, if we are interested in 10 'factors' each of them comprising 10 levels, this amounts to 10 billion simulation runs! Thereby, no replications are assumed. In anticipation of the description of the conceptual model and the according parameters, we must state that we are interested in more than 10 'factors', each of them spanned over a broad domain.

As a consequence, we have to apply a smart DoE method in order to conduct the sensitivity analysis (see Sanchez, 2006): We apply the design of a 'Nearly Orthogonal Latin Hypercube' (NOLH).[29] This design provides a flexible way of constructing an efficient design for computer experiments with many 'factors'. In particular, a NOLH features good 'space filling' properties. See the scatterplots in figure 1.3 for a comparison of a 'full 5^4 factorial design'[30] and its NOLH counterpart for 4 'factors'. In the 'full factorial matrix' each of the $5^4 = 625$ 'design points' have to be investigated. Unlike the 'full factorial design', the NOLH design employs only few design points: In case of the 4 'factor' design (see figure 1.3), we just need 17 'design points'. Thereby, the design is called 'Latin Hypercube', because it requires that there is only one 'design point' in each row and one in each column. This

[29] This design goes back to Cioppa, 2002.
[30] 5^4 means 4 'factors' each of them comprising 5 levels.

gives a 'Latin Hypercube'. Moreover, this notion is extended by the the concept of 'orthogonality', which implies that the entire 'input variable space' is sampled evenly. As a consequence of the NOLH design, we require 65 'design points' for the investigation of an experiment comprising 16 'factors'.[31] As we will see in section 3.3, we are interested exactly in 16 'factors'.

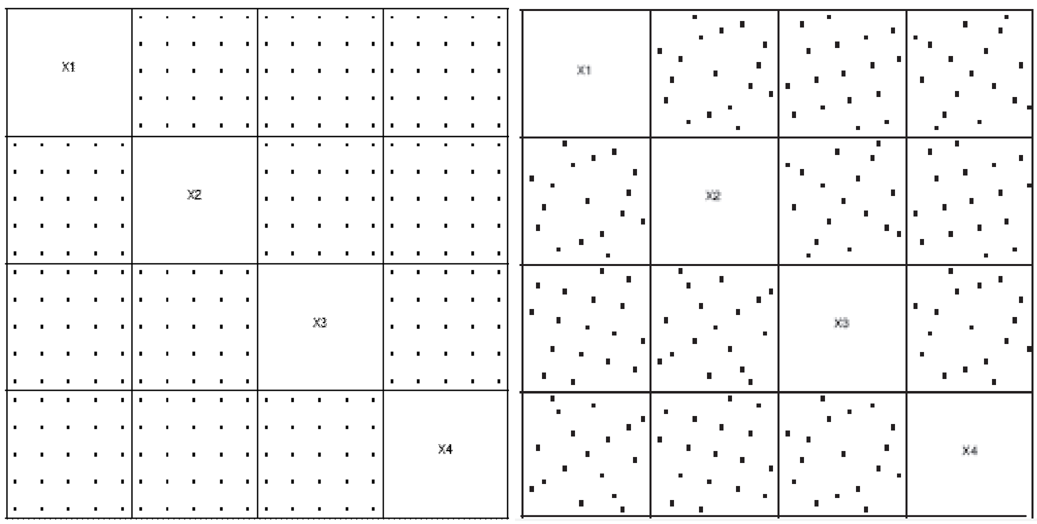

Figure 1.3: Scatterplot matrices of (i) a full 5^4 factorial design (left panel) vs. (ii) an Orthogonal Latin Hypercube design with 4 continuous factors (right panel)

Gaussian Kriging

The sensitivity analysis in section 3.3 is based upon the estimation of a 'meta model'. Suppose that $x_i, i = 1, \ldots s$ are design points over an s–dimensional experimental domain, and suppose a response y. In addition, we assume that there exists a true 'meta model' (of the economy of Agent Island) that describes the connection between inputs and the response (see, for example, Fang et al., 2006). This 'meta model' is represented by a real–valued function:

$$y = f(x_1, \ldots x_s) = f(x),\ x = (x_1, \ldots x_s)' \in T.$$

[31]The Excel spreadsheet is available on http://diana.cs.nps.navy.mil/seedlab/software.html. It delivers the specification of the 65 scenarios. In general, the spreadsheet supplies 'nearly orthogonal designs' up to 29 'factors'. The obtained outputs constitute a 'Nearly Orthogonal Latin Hypercube' design in the units of the problem.

In here, T defines the entire input variable space. The scenarios investigated in the sensitivity experiments deliver the data required to estimate an approximation $\hat{y} = g(x)$ of this (true) 'meta model' $y = f(x)$. In this context we use a 'Gaussian Kriging'[32] model, which belongs to the family of linear least squares estimation algorithms. The goal of the 'Gaussian Kriging' model is to estimate the value of the unknown true function, f, at a point x^*, given the values of the function at some other points $x_1, \ldots x_s$. The crucial point is that the 'Kriging' method is usually applied, if one is interested in a large number of inputs, and if one is able to investigate a rather small subset of the entire input variable space (as suggested above by the NOLH design): Therefore, 'Kringing' provides a sophisticated method to *interpolate* the value of a random field at an *unobserved* location from observations of its value at *nearby* locations.

The 'Gaussian Kriging' model is defined by Fang et al., 2006, as

$$\hat{y} = g(x) = \sum_{j=0}^{L} \beta_j B_j(x) + z(x),$$

whereby $B_j(x), j \in [0, \ldots, L]$ is a set of 'basis functions' defined on the investigated subset of the input variable space. The figure z constitutes the random error. In case of the 'ordinary Kriging', this equation (i.e. the 'basis functions') is simplified to

$$\hat{y} = g(x) = \mu + z(x),$$

As opposed to the usually applied IID assumption, i.e. that the random error is independent and identically distributed, the 'Kriging' method rather assumes that $z(x)$ is a 'Gaussian process'.[33] This rather assumes that the realization of y (i.e. the 'response') is normally distributed with mean μ and variance σ^2. The variance–covariance matrix is represented by $\sigma^2 R$, and the R matrix is composed of elements r_{ij}. The used JMP statistical software package applies a product exponential correlation function with a power of 2 as the estimated model:

[32] The word 'Kriging' is synonymous with 'optimal prediction'. The method was originally proposed by the geologist D.G. Krige. See Krige, 1951.

[33] A 'Gaussian process' is a stochastic process which generates samples $\{X_t\}_{t \in T}$ in any set T such that no matter which finite linear combination of the X_t one takes, these linear combination will be normally distributed. Two 'Gaussian processes' that deliver equal functions for the expected value and the covariance are distributed equally.

$$r(\theta; i, j) = Corr(z(i), z(j)) = exp\{-\sum_{k=1}^{s} \theta_k (x_{ik} - x_{jk})^2\},$$

The parameters μ, σ and θ_k are all fitted in the JMP software via 'maximum likelihood'. It reports the figure ($-2 \times log$Likelihood), that is minus 2 times the natural log of the likelihood function evaluated at the best–fit parameter estimates. As a consequence, smaller values produce better fits. See also the explanations below in section 3.3.

1.3.4 Calibration

Agent–based simulation can be a valuable tool for studying real world economies. Thereby, calibration can be a useful device: Within the calibration procedure selected parameters of the model are varied in such a way that the model output resembles in sufficient detail the output of the original system. Hence, calibration is a computer experiment, in which an optimization is applied (Klügl, 2008b). One important topic within the calibration of the model is therefore the selection of the parameters as well as a quantitative measure of goodness, i.e. an 'objective function' that indicates how good or bad the simulation model matches the original system. We will explain in section 3.4, which measure characterizes the behavior of the original system in a satisfactory and appropriate manner. Equally important, it is necessary to identify significant parameters within the previous sensitivity analysis, i.e. parameters which influence the model outputs of interest. Conversely, insignificant parameters drop out from further analysis and from the calibration procedure. The remaining parameters constitute the 'minimal model' to be adjusted within the calibration procedure (see the description in figure 1.2).

We develop the simulation within the SeSAm programming environment. SeSAm also enables the development of computer experiments based upon the programed model. Besides this, there are several 'plug–ins' available for SeSAm, among others, a calibration 'plug–in'. This employs an optimization method that minimizes (or maximizes) a quantitative 'objective function'.[34] Importantly, the calibration tool searches for a parameter combination (a scenario) that minimizes the 'objective function' by employing the 'simulated annealing' optimization method. In the following

[34]For a detailed description of the used calibration tool see Fehler, 2008, or Fehler et al., 2005; Fehler et al., 2004.

we want to give a short description of this optimization method: 'Simulated annealing' is a heuristic optimization method that searches for a global maximum or global minimum of an 'objective function'. The method is usually applied, if the relationship between the 'objective function' and parameters is complex, and if a basic trial and error process cannot be applied because of too many possible parameter combinations. Consequently, 'simulated annealing' constitutes a method for the *approximation* of a global minimum (or maximum). Other heuristic optimization methods can get stuck in a local minimum (or maximum)—not so the 'simulated annealing' method: It usually finds a way out of a local minimum (or maximum).

The basic idea of this method is derived from the annealing method in metallurgy.[35] Accordingly, it is a technique where controlled heating and cooling of a piece of metal is used to increase the size of its crystals and reduce their defects: When the metal is heated, its atoms can move freely. When the temperature of the metal is slowly reduced, atoms can move in order to adopt a more stable orientation. Finally, when the metal is cooled slowly enough, the atoms are able to relax in the most stable orientation. In analogy to this physical process, in each step of the 'simulated annealing' algorithm, the current 'temperature' of the optimization method is gradually reduced. The implication of this cooling will become clear immediately (Kirkpatrick et al., 1983; Fang et al., 2006): Suppose an 'objective function' $O(\vec{x})$ which should be minimized by varying the parameters described by the vector $\vec{x}$. The process starts with an initial 'temperature' T (in case of the calibration in the present study $T = 500$) and an initial level combination, which defines the initial vector $\vec{x}_0$. Now a small random variation $\Delta\vec{x}$ (in the investigated parameters) is initiated. If the resulting value of the function $O(\vec{x} + \Delta\vec{x})$ is smaller than $O(\vec{x})$, the new position $(\vec{x} + \Delta\vec{x})$ is chosen. However, this algorithm can become stuck in a local minima, because the values of the function $O(\vec{x})$ would be non–increasing. That is, the algorithm searches for smaller values of $O(\vec{x})$, while temporarily rising $O(\vec{x})$ is ruled out. In order to circumvent such a lock–in effect in a local minimum, 'simulated annealing' must contain a further instruction. Here, the 'temperature' T comes into play: 'Simulated annealing' allows to jump to higher values of the function (which should be minimized) conditional to the 'temperature' of the simulation (which is exogenously annealing). Such an 'uphill' movement depends on the probability p, given through $p = exp\frac{O(\vec{x})-O(\vec{x}+\Delta\vec{x})}{T}$. Obviously, the

[35]See Kirkpatrick et al., 1983, for the original illustration of this method and its analogy to metallurgy.

probability p depends on the 'temperature' T in such a way that a very high 'temperature' allows (c.p.) 'uphill' moves in the value of the 'objective function' $O(\vec{x})$ with a higher probability. But, the longer the simulation runs, the lower the 'temperature' gets. Accordingly, the probability that 'uphill' moves are allowed decreases (c.p., i.e. for given $\Delta O(\vec{x})$). In brief, 'simulated annealing' requires four ingredients (Kirkpatrick et al., 1983):

1. A description of the parameters of the system;
2. A random generator for moves in the parameters of the system;
3. A quantitative 'objective function';
4. An exogenous annealing scheduling of the 'temperature', and the simulation length.

Within the calibration 'plug–in' we fix the maximum (i.e. the start) 'temperature' to 500, and the minimum 'temperature' to 50. Moreover, there is a fixed process of annealing the 'temperature', which is based on the simulation length. We fix the latter to a maximum of 1,000 simulation runs. Usually, the calibration procedure is finished after 400 to 700 single runs. This method is used to generate a calibrated model (see figure 1.2). In the last step, one has to verify the calibrated model through statistical 'validation'.

1.3.5 Statistical Validation

In the last building block of the 'validation' framework, the statistical 'validation' has to be conducted. This is necessary to verify the results of the calibration procedure. If one would not apply statistical 'validation', the model could be merely tuned through calibration to reproduce given facts. Hence, we employ several statistical analyses, i.e. we compare some descriptive statistics of the simulation output with statistics of the original system. Thereby, we use different data than in the calibration process (Klügl, 2008b). Again, we investigate only outputs on the aggregate level.[36] After the successful statistical 'validation', we add 'plausibility' checks of aggregate model outputs (delivered by several 'face validation' runs). Accordingly, we review the obtained data *qualitatively*

[36] In contrast to this, during 'face validation' we also investigate data of individual agents. This is necessary to work out some regularities of the model. But we do not apply systematic 'validation' methods on the level of individual agents.

against the background of our model and the intended relationships. If, after all of these 'validation' steps, the model produces reasonable results on the aggregate level, we conclude that it is validated by the macro dynamics of the 'original system'. 'Validation' is then finished.

1.4 Conclusion

This section explains several basic aspects of agent–based computational economics. It should become clear:

1. What elements an agent–based model must contain;
2. For what reasons a researcher may prefer agent–based computational simulation technique over the orthodox framework;
3. How a reasonable validated agent–based macroeconomic model can be obtained.

According to that, we have a starting point for the following chapters. There, the conceptual model will be illustrated in detail, and the 'validation' procedure of the model will be discussed.

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