New Economic Windows

Alessandro Caiani
Alberto Russo
Antonio Palestrini
Mauro Gallegati *Editors*

Economics with Heterogeneous Interacting Agents

A Practical Guide to Agent-Based Modeling

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Editors
Alessandro Caiani
Università Politecnica delle Marche
Ancona
Italy

Antonio Palestrini
Università Politecnica delle Marche
Ancona
Italy

Alberto Russo
Università Politecnica delle Marche
Ancona
Italy

Mauro Gallegati
Università Politecnica delle Marche
Ancona
Italy

Additional material to this book can be downloaded from http://extras.springer.com.

ISSN 2039-411X ISSN 2039-4128 (electronic)
New Economic Windows
ISBN 978-3-319-44056-9 ISBN 978-3-319-44058-3 (eBook)
DOI 10.1007/978-3-319-44058-3

Library of Congress Control Number: 2016947920

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

To Maurizio Mariotti

Foreword

This book emerges from a workshop activity of a research group on Agent Based Models at the Dipartimento di Scienze Economiche e Sociali at the Universitá Politecnica delle Marche, Ancona, which includes—in addition to the four editors—Leonardo Bargigli (Florence), Ermanno Catullo, Eugenio Caverzasi, Fabio Clementi (Macerata), Annarita Colasante, Corrado Di Guilmi (Sydney), Lisa Gianmoena, Federico Giri, Ruggero Grilli, Simone Landini (Tourin), Luca Riccetti (Rome), and Gabriele Tedeschi (Castillon). For many years, we have divided the very few honours and numerous research squabbles, exploring unknown research territories with many friends from different disciplines.

Financial and scientific contributions of the various European projects—in particular, SYMPHONY and FINMAP, DiSES and INET have allowed the survival of the youngest in years of financial famine that has deeply affected the Italian universities.

The book is intended for graduate and Ph.D. students, but also undergraduates with a minimal knowledge in computers and economics, and in general people curious in computational science and Agent Computational Economics, can enjoy it. Despite the fact that the reader will be guided step by step in the simulation, it is not an ACE guide for dummies and almost elementary computer skills are preferred—or at least to know how to switch on a PC. Hopefully the Groucho Marx dictum will be exaggerated: A 4-year-old child could understand this book. Run out and find me a 4-year-old child. I can't make head nor tail out of it.

We have had a lot of "laboratory mice", the students of advanced macro at UNIVPM and the participants in the Summer Schools on ABM, on September 2014 and September 2015.

Our gratitude goes also to Domenico Delli Gatti, Alan Kirman, Giulia Iori, Thomas Lux, Maria Cristina Recchioni and J. Barkley Rosser.

While this book was in its very final stage of compilation, our beloved friend and colleague Maurizio Mariotti passed away. We dedicate the book to him knowing that nothing will replace his kind generosity and are happy to have shared many days illuminated by his “buondì” and beaming smile

Ancona
May 2016

Alessandro Caiani
Alberto Russo
Antonio Palestrini
Mauro Gallegati

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Contributors

Leonardo Bargigli Dipartimento di Scienze per l'Economia e l'Impresa, Università di Firenze, Florence, Italy

Alessandro Caiani Dipartimento di Management, Università Politecnica delle Marche, Ancona, Italy

Ermanno Catullo Dipartimento di Scienze Economiche e Sociali, Università Politecnica delle Marche, Ancona, Italy

Fabio Clementi Dipartimento di Scienze politiche, della comunicazione e delle relazioni internazionali, Università di Macerata, Macerata, Italy

Ruggero Grilli Dipartimento di Scienze Economiche e Sociali, Università Politecnica delle Marche, Ancona, Italy

Antonio Palestrini Dipartimento di Scienze Economiche e Sociali, Università Politecnica delle Marche, Ancona, Italy

Luca Riccetti Facoltà di Economia, Dipartimento di Management, Sapienza Università di Roma, Roma, Italy

Alberto Russo Dipartimento di Management, Università Politecnica delle Marche, Ancona, Italy

Gabriele Tedeschi Departament d'Economia, Universitat Jaume I de Castellon, Castellón, Spain

Introduction

One of the main problems that economics has faced—one could say right from the very beginning—is how billions of agents, with different tastes and abilities, coordinate with each other without any central control. The dominant economic theory has covered several paths, which model agents who interact indirectly. On the one hand, the approach in Walras's Elements Walras (1874)—and in the version of Arrow (1951), Debreu (1951), Arrow and Debreu (1954)—where a market auctioneer is provided with all the information—the single agents only know their own payoff and utility functions—and coordinates the market through the vector of prices. On the other, the equilibrium context without any coordinating figure, where information is distributed among the agents as in Dynamic Stochastic General Equilibrium (DSGE) approach. Both can be thought of as models for interacting agents, but only the second can aspire to become a paradigm for methodological individualism because, in the first it is crucial to model at the micro level in order to have an exact aggregation at the macro one (see the discussion in Chap. 1).

A model of such "interactions" among economic agents is nothing else but a "map" of the world. In microeconomic models, the agents meet in various markets and follow rules of behaviour, based on axioms or on empirical evidence (from which the modeller can obtain simple rules of the thumb). Agents and markets are the fundamental constituents also of every micro-founded macro model. If this is true, it seems to us that micro models are all agent-based and that their differentiation occurs at a following level, when considering information about the world for which the map is built. In traditional models it is assumed that one has a complete characterization of individual preferences. Or plainly speaking, one knows exactly what economic agents want. Payoff and utility function existence theorems were extracted from this hypothesis Debreu (1954), Debreu (1960), Diamond (1965), making it possible to represent the preference scheme of economic agents with scalar objective functions for which the maximum value exists.[1]

[1]Unfortunately, those same assumptions give rise to the Sonnenschein–Mantel–Debreu theorem Sonnenschein (1972), Debreu (1974), Mantel (1974) that demonstrates how many properties at the

From here follows the whole traditional approach to macroeconomics and micro-founded finance. An argument in Muth (1961) further elaborated by Lucas (1972), Lucas (1976) affirms, in fact, that if the economist assumes to be able to represent the preferences of individuals then, in the model, it must be assumed that the same individuals know their preferences and behave so as to get the best they can (optimization) given the information they have at their disposal about the world. In other words, in traditional models the fact that agents optimize is a mere consequence of the initial hypothesis, made by the scholar, of knowing the preference scheme of the agents who are the object of the analysis.

Agent-based literature, on the other hand, aims to study economic phenomena in their complexity; taking into account joint distributions of individual characteristics, the direct and not only indirect interactions and therefore the way in which economic networks are made and changed. Hence, it cannot assume to be able to perfectly represent the preferences and therefore to have an exact knowledge of the objective functions. The starting point of each agent-based analysis is a description of the rules of behaviour, that is, the map between the actions and the information set available to them in which a partial knowledge of the objective functions is included. These rules can be derived from empirical work, from economic experiments, from studies carried out in disciplines other than economics (psychology, sociology, etc.) or from a purely normative analysis. In other words, what would the aggregated relations be if the agents followed certain kinds of rules, which have had important results in auction models (Tesfatsion and Judd 2006).

From the beginning, the agent-based literature had to face the Lucas critique (Lucas 1976). When one wants to assess the effect of an economic policy one has to take into account that the latter will enter the information set of agents, changing their behaviour. This could result in a neutralization of the economic policy or its much lesser effect than expected ex ante. Agent-based models, to respond to the Lucas critique, have often resorted to the use of learning algorithms and switching mechanisms between different rules to take account of the effects of economic changes in the environment on the behaviour of agents. On the other hand the solution proposed by Lucas, based on the use of rational expectations, runs into a potentially worse problem than what had motivated it, since in order to work it has to assume that agents have perfect knowledge, perfect rationality, and almost infinite computing capabilities. "Satisfactory" adaptivity, bounded rationality and behaviour (instead of optimizing) are thus a typical feature of agent-based models: the agents can change their mind during the simulation and often change the rule. Given the only partial knowledge, ex ante, of the objective function there can only be an update, ex-post, on the basis of the results. A rule resists so long as it "works", that is produces good results. Otherwise it will be changed. Let's give a simple example. Suppose we want to divert a stream of ants marching straight towards our

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(Footnote 1 continued)
micro level disappears at the macro one, when aggregating. An important consequence is that many properties of an aggregate variable may be generated both by optimizing agents and non-optimizing agents.

house. The Lucas critique would tell us that we cannot simply put an obstacle in their path, or at least it might not be sufficient. The ants could go round it and continue undeterred towards our house. In an agent-based perspective we should study the ways ants bypass obstacles—and thus change the "local" rule of movement when they encounter an obstacle—depending on the size and shape of the latter: a macrofoundation of microeconomics.

This book guides the reader in the world of such agent-based models (ABM) and of the technicalities that need to be solved to evaluate the effect of different rules and their switching. One thing must immediately be made clear. The current agent-based literature is vast and is not just about economics. Our review of the techniques will inevitably be biased towards the work and the problems that our research group has had to face and resolve in more than 20 years of analysis, producing numerous scientific publications. When we refer to agent-based models, the reader must always keep in mind this explanatory bias.

That said an ABM, then, is a computational model, populated by many heterogeneous agents interacting with each other from the bottom—bottom up—that is, without a central coordinator. These interactions produce emergent results in which the aggregate result is different from what it would be if each agent were isolated from the others, that is, without feedback or externalities (see the review on aggregation made in Chap. 1). In ABM economic results can be aggregated, and in particular added together to calculate the GDP, consumption and investment, and in general also the distributions (see the analysis of distributions made in Chap. 4) and economic networks can be studied. These economic statistics are difficult to obtain using traditional approaches and analysis of economic networks is virtually absent.

For a macroeconomist that the GDP is the sum of individual activities is something perfectly familiar: as shown in Chap. 1, even though the approaches are different, a DSGE model could give similar results to an ABM in terms of aggregate dynamics. After all, even a DSGE model is populated by many agents who interact and the results of these interactions produce economic results, and if we add up these results we obtain the GDP and so on. Our argument is that by giving up the assumption of perfect knowledge of the objective function (except for exogenous disturbances), one can describe a much richer set of phenomena than with the DSGE models. Obviously there are important differences between ABM and DSGE, even in the pre-analytical vision. It is however possible, in principle, to pass from an ABM to a DSGE through successive simplifications that identify, unless there are stochastic disturbances, the objective functions. One only has to impose the demand–supply equilibrium, that there are one or more representative agents (or that the distribution of individuals in the period $t + 1$ can be computed), that the agents maximize an objective function bound to some balance sheet, that from an agent-based model it is possible to theoretically obtain a DSGE. In other words, an important difference between the two approaches is the information and computational capabilities of the agents.

If the information is incomplete the future becomes uncertain while asymmetry leads to interaction. This, however, is not harmless, since economic agents are strategic agents and with their actions change the structure (and the laws: not by chance does one speak of empirical regularities). Moreover, with heterogeneity one interacts locally and the "system" becomes endogenous.

In an ABM, the interactions are governed by rules of behaviour that the modeller codifies directly in the individuals who populate the environment. In an ABM, the behaviour is the point in which a modeller begins to make hypothesis. The DSGE modellers make assumptions about what an optimizing agent wants, compatibly with budget and resource constraints, and represent these wishes with concave real-valued functions defined over convex sets. Based on the combination of objectives and constraints, the behaviour is derived by solving the first-order conditions and when necessary also the second-order conditions. The reason why economists set their theories in this way—making assumptions about the goals and then drawing conclusions about the behaviour—is that they assume that the allocations, decisions and choices are guided by individual interests. Decisions and actions are carried out with the aim of reaching a max-min goal. For consumers, this usually regards utility maximization; a purely subjective assessment of well-being. For businesses, the goal is typically to maximize profits. This is exactly where rationality, for DSGE, is manifested in economics. In a nutshell, in DSGE models the modeller sets the objective function and the consequent maximization generates the rules. In the ABM the modeller sets directly the behavioral rules given empirical evidence and experiments that should control the degrees of freedom. The introduction of information problems in the Walrasian model is only apparently harmless for the externalities and non-convexity deriving from it. The issue of asymmetric information assumes that the agents are different from each other (Greenwald and Stiglitz 1993). According to Leijonhufvud (1981) this distinction is a condition sufficient to generate failures in coordination. In particular, whether information is complete or not, if it is evenly distributed, banks and businesses would become a single aggregate where every debt–credit ratio is cancelled and money has no role to play. The game theory has also shown that rational behaviour can generate multiple equilibria. Along the same lines, it can be argued that if there is asymmetric information the problems of adverse selection prevent a decentralized system from reaching Pareto-optimal positions (Akerlof (1970), Stiglitz and Weiss (1981)), thus giving rise to market failures.

The Arrow–Debreu works established conditions to have a Pareto optimum: the information need not be perfect; it can be incomplete provided it is exogenous, that is, the beliefs must not change as a result of the agents' actions. In short, there must be no direct interaction. The case in question is represented by a central actor (the auctioneer) and the connections going from him to all agents. Instead, when information is imperfect the single agents will come into direct contact, that is, there will be links between agent and agent.

It must be recognized that if there is information asymmetry, the agents interact directly with each other outside the market, stimulated by profits. In that case, however, the Walrasian star type of network presents serious difficulties. And of course the idea of a representative agent has to be abandoned. Which is not only a problem of fallacy of composition, or of aggregation: it is that with interaction aggregate behaviour is no longer a linear summation, but a nonlinear process that emerges from the individual one and as such is endowed with properties that are different from that of the single constituent parts. The ABM approach aims precisely to describe, in a reduced scale, the behaviour of single individuals and bring out the aggregate properties.

Chapter 1 will analyze in detail the ABM approach compared to the traditional one mentioned above. The idea of this chapter is to give a set of tools necessary to understand the construction of two economic models developed in Chaps. 2 and 3. The chapter opens with a discussion on the problems of aggregation of macroeconomic models. To be honest, such a discussion would not be strictly essential in the ABM models which implement a bottom-up approach that takes into account the distribution of the agents in each period. Aggregation is performed at the end of each period by simply adding or calculating the per capita values. It is, however, important to be aware of this problem which must, instead, be solved in the construction of traditional models. The chapter continues with a comparison between the traditional models and the ABM approach showing the advantages of the latter in the analysis of distribution evolution regarding the features and choices of agents and in the analysis of economic networks. The second session of the chapter analyzes in detail the "box of tools" necessary to the ABM economist. In particular, it illustrates the choices of consumption and production, the expectations, the matching between demand and supply of credit and the entry–exit of companies from a market.

Chapter 2, using the tools of Chap. 1, describes step by step the construction of an educational version of the agent-based model published in Riccetti et al. (2013). The model analyzes the interaction between the distribution of the companies that produce a homogeneous good with external sources of funding and the banking system which is also heterogeneous. Although this is a "toy model", its description proposes a twofold goal: (1) on the one hand it allows us to show how the tools described in the first chapter can be used to build an existing model in the literature and (2) shows the basics of computer programming.

A few words must be spent about the use of programming languages. When two of the editors of this book were young, virtually every economic model had to be analyzed analytically. Certainly it could be simulated and this was a possible strategy of analysis: simulation was performed in order to understand the properties which later were analytically demonstrated. Today many models, both standard and agent-based, are impossible to be analyzed analytically. The attack strategy to the economic problem has been completely reversed. Maybe one can analytically analyze a very simplified version in order to understand the basic properties, but the one and true model can only be studied numerically. Therefore, it is necessary to strongly invest in one or more programming languages (MATLAB/Octave, R, Fortran, C, C++, Python, etc.). The choice of the second chapter fell on R because it is open-source, with a good learning curve (the language is similar to MATLAB even though Octave is closer) and rich in statistical functions with which to analyze the results of an economic model; functions like those also described in Chap. 4. The chapter is packed with exercises in R that provide a thorough knowledge on programming techniques and on the construction of an economic model which is, of course, the ultimate goal of this book.

In Chap. 3, instead, we chose to use the most classic and fastest programming language, C. This is because we believe that for the most complex economic models the choice of fast programming languages (as well as Fortran and C++) is hardly avoidable. Investing in one or more of these compiled languages is a choice, perhaps not necessary, but which we strongly recommend to students, graduate students, young researchers who are interested in the subjects of this book. Chapter 3 presents the construction of a simplified agent-based model drawn from the publications of Tedeschi et al. (2009), Tedeschi et al. (2012b). The model represents, in a stylized form, the operation of a financial market in order to reproduce the most important statistical regularities we observe in financial time series. The main mechanism of the model is the endogenous mechanism of imitation, via a preferential attachment rule (Barabási and Albert 1999) in which the agents are more likely to imitate the choices of others who have generated higher profits in the past. The aims of this chapter are (1) to show how using the classic and fast programming language C it is possible to build an agent-based model for financial markets; (2) how agent-based modelling allows to analyze direct interaction phenomena that generate financial networks and make them evolve.

The book ends with Chap. 4, a valuable chapter for those who study agent-based economic models, but not only. This chapter describes density and probability functions which are useful to represent empirical distributions of individuals and businesses depending on their characteristics. Also illustrated, and implemented in R, is their estimation procedure. They are all "heavy-tail" distributions in the sense of having heavier tails than normal and than their derivatives. This is one of the most robust stylized economic facts that agent-based models must and can explain. In reality the probability of extreme events is higher, and often much higher, than that implied by Gaussian distributions.

Alessandro Caiani
Annarita Colasante
Antonio Palestrini
Alberto Russo
Mauro Gallegati

Chapter 1
Getting Started: The Aggregation Conundrums and Basic Toolkits of Agent Based Modeling

Ermanno Catullo, Antonio Palestrini and Gabriele Tedeschi

1.1 Understanding Heterogeneity and Interaction in Economic Models

1.1.1 Aggregate Models with Boundlessly Rational Agents

From the very beginning macroeconomics analysis tried to understand aggregate relationships (GDP, Consumption, Investments, etc.). The most famous one is the Keynesian relation between aggregate consumption at time t, C_t and aggregate income, Y_t

$$C_t = F(Y_t) = \bar{C} + cY_t \tag{1.1}$$

where $\bar{C}$ is the autonomous component of consumption and c is the marginal propensity to consume.[1]

[1]These aggregate relation was later modified by Friedman (1957) and Ando and Modigliani (1963) in $C_t = F(Y_{pt})$ where Y_p is permanent income.

E. Catullo (✉) · A. Palestrini
Dipartimento di Scienze Economiche e Sociali, Università Politecnica delle Marche,
Piazzale Martelli 8, 60121 Ancona, Italy
e-mail: ermanno.catullo@gmail.com

A. Palestrini
e-mail: a.palestrini@univpm.it

G. Tedeschi
Departament d'Economia, Universitat Jaume I de Castellon,
Avenida de Vicent Sos Baynat, s/n, 12071 Castellón, Spain
e-mail: gabriele.tedeschi@gmail.com

A. Caiani et al. (eds.), *Economics with Heterogeneous Interacting Agents*,
New Economic Windows, DOI 10.1007/978-3-319-44058-3_1

These kind of relationships were motivated by behavioral rules such as the Keynes' observation that marginal consumption of a family/individual is a fraction of disposable income.[2]

The problem with this starting approach to macroeconomic analysis is that, because of the lack of micro data, such behavioral rules were not motivated by empirical or experimental analysis[3] but just common sense. Furthermore, was not clear at the very beginning the aggregation problem we face in analyzing aggregate variables (see next section).

During the 70s, the discussion in macroeconomics stressed the necessity of a micro-foundation of macroeconomic theories. In other words, the economic relations have to be specified at the micro-level, then there is the aggregation step and finally the computation of the (determinate) rational expectation solution of the aggregate model. This approach produced a huge amount of literature but with important limitations: first, the theoretical assumptions at the base of modern neoclassical macroeconomic models (such as, DSGE models) have been increasingly challenged. Secondly, the use of representative agents prevent to analyze the joint distributions of individual characteristics/choices and the network topology of agents decisions, which can be crucial both in an explanatory and normative perspective.[4]

This latter aspect also implies that the aggregation procedure employed in the standard literature is logically valid only under particularly restrictive hypothesis, as we discuss in the next section.

The first set of criticisms instead challenges one of the milestones of neoclassical macroeconomic: the idea that agents are perfectly informed, perfectly rational, and take their decisions through an optimization process of some objective function. In this respect, the agent-based approach, in a sense, is a continuation of the mid of the past century analysis recognizing the problems of the concept of *perfect rationality*. In the 1950s there was the first attempt to discredit the assumptions of the Neoclassical Economic theory. Without any doubt, Herbert Simon and Maurice Allais were the first authors who shed light on the inadequacy of the axiomatic approach of the Neoclassical Economics. The main critiques raised by Simon and Allais focused on the idea that in the process of individual decision making two factors should be taken into account: cognition and psychological aspect.

Simon (1957) highlighted the fact that agents have limited capacity of calculus and they have no sufficient computational capability to find the optimal solution. Simon, in fact, introduced the concept of *bounded rationality* which implies that agents are not able to use the optimization process to reach their goal. Assuming that individuals

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[2]In Keynes' words (Keynes 1936) a "psychological law of consumption".

[3]The field of Experimental Economics aims at investigate individual behaviors. In this field data are collected through laboratory or field controlled experiment as in physic or biology in which the phenomenon under observation is the choices of human beings. Running an experiment means to create a controlled environment to examine some questions of interest. This method has a great advantage with respect to the use of existing data set, i.e. researchers are able to isolate the impact of the variable under investigation and, most important, they are able to observe real individual's choices or preferences.

[4]Think about the importance, of inter-bank networks or firm-bank credit networks today.

are boundedly rational implies that agents usually simplify the complex problem by decomposing the entire process of choice into sub-problem and, using a step-by-step process, they are able to find the so-called *satisficing solution*. Allais (1953) shed light on the importance of the psychological aspect of choices. He proposed an experiment on individual preferences and the results show that agents systematically violate the independence axiom of the Expected Utility.

For these reasons, the agent-based literature tries to extrapolate simple behavioral rules (such as consumption, production, investment rules) from microeconomic surveys, empirical analysis and experimental economics, rather than deriving agents' choices from the optimization of an a-priori objective function subject to certain types of constraint.

Although econometric estimations techniques, microeconomic stylized facts, direct observations and case-studies still provide a fundamental guide in shaping agents' behavior, as well as in validating models results, over the last decades the Agent Based Modeling literature has increasingly looked at behavioral and experimental economics in order to study the actual mechanisms at the base of agents' decision in a variety of economic context (e.g. financial market operations, investment and production, consumption). The *experimental economics literature* dates back to the seminal work of Vernon Smith[5] (see Smith (1965)) while the 2002 Nobel Prize Daniel Kahneman is considered as the "father" of behavioral economics. Admittedly, as pointed out by Bardsley (2010), the boundary lines between experimental and behavioral economics is thin. However, the field of behavioral economics is broader in that it includes contributions concerning the investigation of human behavior with different technique, i.e. not only through the experimental procedure.

The approach proposed by Smith, which is replicated in many other recent studies like Lei et al. (2001), Stöckl et al. (2010), Haruvy et al. (2007) and Palan (2013), are able to capture the individual behavior in the market. On the other hand, the approach proposed by Kahneman, focuses on the search of the so-called *heuristics* used by agents in making their choices. Heuristics are a *rules of thumb* used as a shortcut for solving the decision problem. These kind of rules emerged from the investigation using lab experiment and, it has been shown, that the adoption of these heuristics brings agents to make predictable errors called *biases*. Some of the well-known heuristics are: (i) availability (Tversky and Kahneman 1973) by which a decision maker relies upon knowledge that is readily available rather than examine other alternatives or procedures; (ii) representativeness (Kahneman and Tversky 1972) which implies a distortion of the probability associated of an event; (iii) framing effect (Tversky and Kahneman 1989) which highlights the importance of the framing within which a situation is presented; (iv) loss aversion (Kahneman and Tversky 1979) that shows that people feel losses more deeply than gains of the same value.

The link between experimental or, more in general, behavioral economics and the agent based model is given by these heuristics. Indeed, the results of experiment are useful to extrapolate behavioral rules which is often used to calibrate or validate agent based model. These models, populated by heterogeneous interactive agents, need a

[5]The Nobel Price in 2002 for his research in experimental economics.

micro-foundation because their results are emergent from the interaction dynamics of many economic units. Unfortunately, one of the important assumption of many agent-based models is that agents are not, and cannot be, perfectly rational and this obviously implies that the micro rules cannot be based on the use of utility functions.

To overcome the problem, it is possible to implement behavioral rules observed in the laboratory. These rules could be useful to calibrate the model and/or to validate the results of the agent based simulation. On the of the first and the most important contribution that show how to use the experimental results to calibrate a model is that by Roth and Erev (1995). In this work authors take into account the results from three well-known experimental game and use these information to construct a dynamic model. One of the significant work on the use of experimental evidence to validate a model is that by Anufriev and Hommes (2012), which focuses on macro experiment on asset and commodity markets and they extrapolate the behavioral rules observed in these fictitious markets to construct an agent based model.

Although an exhaustive survey of the experimental economics literature is beyond the objective of the present book, there is a tighter and tighter relationship between agent based modeling and behavioral experiments. Duffy (2006) is probably the main contribution in this field, providing a significant number of examples of how Agent Based Models can be employed to replicate the properties emerging from experimental data.

The present chapter aims at sketching out a (non-exhaustive) survey of the behavioral rules employed in the ever growing AB literature. These behaviors will be presented and discussed making reference to the different functional block of AB models to which they pertain, such as production, investment, consumption and saving, pricing, expectations, finance behaviors. Then, we will show how to implement some of these behavioral rules into simplified AB didactic models.

Before moving to the core of the book, however, we deserve in the next section some attention to the problem of aggregation in economic analysis with the aim of highlighting the limitations faced by standard approaches in macroeconomics and finance, and how the AB approach presented in the book allow to address them. In the same wake, Sects. 1.1.4–1.1.6 then make a brief comparison of the two methodologies.

1.1.2 The Aggregation Problem

What C_t, and Y_t, of the above sub-section, exactly mean? What is an aggregate variable? Technically, a variable X_t at time t is an aggregate variable if it is a function of the distribution of the micro-variable x_{it} where i is the index of agent-i. That is

$$X_t = h(x_{1t}, x_{2t}, \dots, x_{Nt})$$

The function h, like in the consumption-income example, almost always means sum ($\sum_i x_{it}$) or per capita ($N^{-1} \sum_i x_{it}$). The justification of the aggregate relation is an economic theory at the micro level claiming that individual consumption is a function of income.

Suppose for every individual consumption at time t is $c_{it} = m_{it} y_{it}$; it depends on the income y_{it}, and marginal propensity to consume m_{it}. By assumption there is no autonomous level of consumption. Then, choosing the sum aggregator ($h = \sum$), we have

$$C_t = \sum_{i=1}^{N} c_{it} = \sum_{i=1}^{N} m_{it} y_{it} \tag{1.2}$$

that it is not a functional relation between C_t and Y_t; i.e., C_t depends on the entire distribution of y_{it}. This is known in the literature as the *aggregation problem*. If the distribution is stable and N "big" then we can, using the properties of the sample covariance function $Cov(\bullet, \bullet)$, do the following algebraic computation: start with the definition

$$Cov(m_{it}, y_{it}) = N^{-1} \sum_{i=1}^{N} m_{it} y_{it} - \bar{m}_{it} \bar{y}_{it}$$

where $\bar{m}_{it} = N^{-1} \sum_i m_{it}$ and $\bar{y}_{it} = N^{-1} \sum_i y_{it} = Y_t / N$ are averages. Then multiplying by N

$$NCov(m_{it}, y_{it}) = \sum_{i=1}^{N} m_{it} y_{it} - \bar{m}_{it} Y_t$$

and solving for $\sum_{i=1}^{N} m_{it} y_{it}$, using the consumption definition in Eq. (1.2) we arrive at the aggregate relationship

$$C_t = N\, Cov(m_{it}, y_{it}) + \bar{m}_{it} Y_t.$$

Under the assumption of a stable joint distribution between m and y the relation exists, but

1. is a function of the moments of the distribution. In other words, when the relation exists it depends on properties of agents' distribution. The implication for an economic model, and so for the agent-based framework in particular, is that to have a stable aggregate relationship individuals can change their characteristics over time;
2. is different from the micro-relationships. Provided we have a convergence to an asymptotic distribution the aggregate function may be different from the micro relation. Note that, in the micro consumption-income function there is no constant, whereas we find it in the aggregate relation. Without considering the aggregation problem we may erroneously interpret the aggregate constant as an autonomous consumption that is not present in the micro relation by assumption.[6]

[6]A famous example of the importance of point 2 is the aggregate relation between output and inputs in the basic modern new-keynesian models with sticky prices in a monopolistic competition

The reason to discuss the aggregation problem in this book is to stress an important distinction between standard macroeconomic analysis and the agent-based framework. The former assume the existence of stable aggregate relationships, then specifies preferences (using the utility function representation), payoffs (with an objecting function, usually a profit) and technology and finds the dynamics of the model computing the maximum value in the payoffs/preferences set. In the latter, instead, behavioral rules and technology are specified and then computed the dynamics of the model and the aggregate variables using the appropriate function h (usually the sum). In doing so, in every period is also computed the agents' joint distribution of every characteristics that can be compared with empirical joint distributions.

For the sake of completeness, in the following section we briefly describe the standard approach used in macroeconomics and finance. In other words, following Heathcote et al. (2009) and Guvenen (2011), and the G. Violante's Macroeconomic Theory II course (www.nyu.edu; New York University) we briefly discuss the conditions under which it is possible to obtain the first step of a standard approach; an exact macro-relation between aggregate variables *independent from movements of distributions*.

1.1.3 The Standard Approach and the Aggregation Problem

The simplest macroeconomic model is made of N_f firms and N_c consumers in a *perfect competitive environment*. As said above, the standard approach specifies the objecting function and derive the behavior of the agents computing the maximum value. Let's start with the firm.

1.1.3.1 Firms

Suppose that the production function of the firm is characterized by:*CRS technology* (capital, k_{it}, and labor, l_{it}) and *aggregate uncertainty* Z_t, that is

$$Z_t F(k_{it}, l_{it}).$$

In equilibrium, the production function is also real revenue of the firm. Total cost is

$$w_t l_{it} + r_t k_{it}$$

where w_t is real wage and r_t is the real interest rate. Firms maximize their profits (revenues–costs)

(Footnote 6 continued)
environment. Because of firms setting different prices the aggregate relation between output and input is different from the micro one. Thanks to the Calvo price setting mechanism it is possible to compute the macro function depending also on a price dispersion (see Christiano et al. 2010).