CONTRIBUTIONS TO ECONOMICS

Francesco C. Billari · Thomas Fent
Alexia Prskawetz · Jürgen Scheffran
Editors

Agent-Based Computational Modelling

Applications in Demography, Social, Economic and Environmental Sciences

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(Editors)

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With 95 Figures and 19 Tables

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To our children

Preface

This book is the outcome of a project that started with the organisation of the Topical Workshop on "Agent-Based Computational Modelling. An Instrument for Analysing Complex Adaptive Systems in Demography, Economics and Environment" at the Vienna Institute of Demography, December 4-6, 2003. The workshop brought together scholars from several disciplines, allowing both for serious scientific debate and for informal conversation over a cup coffee or during a visit to the wonderful museums of Vienna. One of the nicest features of Agent-Based Modelling is indeed the opportunity that scholars find a common language and discuss from their disciplinary perspective, in turn learning from other perspectives. Given the success of the meeting, we found it important to pursue the purpose of collecting these interdisciplinary contributions in a volume. In order to ensure the highest scientific standards for the book, we decided that all the contributions (with the sole exception of the introductory chapter) should have been accepted conditional on peer reviews. Generous help was provided by reviewers, some of whom were neither directly involved in the workshop nor in the book. All this would not have been possible without the funding provided by the Complex Systems Network of Excellence (*Exystence*) funded by the European Union, the Vienna Institute of Demography of the Austrian Academy of Sciences, Università Bocconi, and ARC Systems Research GmbH, and the help of the wonderful staff of the Vienna Institute of Demography (in particular, Ani Minassian and Belinda Aparicio Diaz). Agent-Based Modelling is important, interesting and also fun—we hope this book contributes to showing that.

Milano
Zurich
Vienna
Champaign

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Thomas Fent
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Agent-Based Computational Modelling: An Introduction

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Summary. Agent-based models (ABMs) are increasingly used in studying complex adaptive systems. Micro-level interactions between heterogeneous agents are at the heart of recent advances in modelling of problems in the social sciences, including economics, political science, sociology, geography and demography, and related disciplines such as ecology and environmental sciences. Scientific journals and societies related to ABMs have flourished. Some of the trends will be discussed, both in terms of the underlying principles and the fields of application, some of which are introduced in the contributions to this book.

1 Agent-Based Modelling: An Emerging Field in Complex Adaptive Systems

Since Thomas C. Schelling's pathbreaking early study on the emergence of racial segregation in cities [32], a whole new field of research on socioeconomic systems has emerged, dubbed with a diversity of names, such as social simulation, artificial societies, individual-based modelling in ecology, agent-based computational economics (ACE), agent-based computational demography (ABCD). Accordingly, the literature on agent-based modelling in social sciences has flourished recently, particularly in economics[5], political science[6],

[5] See i.e. the special issue on agent-based computational economics of the Journal of Economic Dynamics and Control [34], especially the introduction by Leigh Tesfatsion, as well as the website maintained by Tesfatsion http://www.econ.iastate.edu/tesfatsi/ace.htm.
[6] See i.e. the review paper by Johnson [23].

and – to a lesser extent – sociology[7]. During the 1990s, this computational approach to the study of human behaviour developed through a vast quantity of literature. These include approaches that range from the so-called evolutionary computation (genetic algorithms and evolution of groups of rules) to the study of the social evolution of adaptive behaviours, of learning, of innovation, or of the possible social interactions connected to the theory of games.

Different to the approach of experimental economics and other fields of behavioural science that aim to understand why specific rules are applied by humans, agent-based computational models pre-suppose rules of behaviour and verify whether these micro-based rules can explain macroscopic regularities. The development in computational agent-based models has been made possible by the progress in information technology (in hardware as well as software agent technology), and by the presence of some problems that are unlikely to be resolved by simply linking behavioural theories and empirical observations through adequate statistical techniques. The crucial idea that is at the heart of these approaches is to use computing as an aid to the development of theories of human behaviour. The main emphasis is placed on the explanation rather than on the prediction of behaviour, and the model is based on individual agents.

As outlined in Axelrod ([1, p.4]), agent-based computational modelling may be compared to the principles of induction and deduction. "Whereas the purpose of induction is to find patterns in data and that of deduction is to find consequences of assumptions, the purpose of agent-based modelling is to aid intuition". As with deduction, agent-based modelling starts with assumptions. However, unlike deduction, it does not prove theorems. The simulated data of agent-based models can be analysed inductively, even though the data are not from the real world as in case of induction.

2 From Rational Actors to Agent-Based Models

Established economic theory is based on the rational actor paradigm which assumes that individual actors know their preferences, often measured by a utility function, and the best possible decision, based on complete information about their environment and the supposed consequences. Decision theory deals with the ranking and selection of the options of actors, according to their preferences. Usually a single rational decision-maker maximizes utility (value) under given constraints, where a wide range of methods have been developed to search for and find the optimum. While rational actors may be adequate in environments with a few number of state and control variables, they have limits in complex and uncertain environments and with real human beings of bounded rationality and restrained computational capabilities.

One of the conditions that restrains rationality is the social environment itself, in particular the unpredictable behaviour of other agents. Game theory

[7] See i.e. the review paper by Macy and Willer [26], or the review of Halpin [18].

is trying to extend rational decision-making to two and more players, each pursuing their own preferences and utilities in response to the expected or observed decisions of other players. Game theory becomes more difficult to handle when a large number of players interact in a dynamic environment. Dynamic game models describe the interaction between multiple players according to situation-dependent decision rules and reaction functions. In repeated games players can learn and adapt their behaviour to the strategies of other players, possibly leading to the evolution of cooperation. Evolutionary games analyse the selection among competing populations of game strategies according to their fitness in replication.

Recent years saw a transition from rational actor models to agent-based modelling, and from top-down macro decision-making to bottom-up microsimulation. A common feature of ABMs is that individual agents act according to rules, where utility optimization is just one of many possible rules. Thanks to increasing computational capabilities, it became possible to analyse interactions between multiple agents, forming complex social patterns. Computers turned into laboratories of artificial societies ([12], [13]). Simulations have now the character of experiments in virtual worlds, often with demanding computational requirements.

In cellular automata models, agents behave like insects in virtual landscapes [41]. For a large number of homogenous agents, methods from statistical physics, non-linear dynamics and complexity science are applicable [17], describing self-organization or phase transitions when observed macroscopic properties emerge from the behaviour and interactions of the component agents. Approaches to collective phenomena have been transfered to interdisciplinary fields such as socio-physics and econo-physics, with applications ranging from moving crowds and traffic systems to urban, demographic and environmental planning ([22],[39],[33]).

Key challenges are to find a conceptual framework to structure the diverse field of ABMs, to calibrate the models with data and to integrate ABMs into real-world applications. The selection of strategies and decision rules in computer-based simulation models can be based on observation and include real-world actors and stakeholders, offering a wide field of experimental games for educational and research purposes as well as for decision support and policy advice. Special modelling-simulation environments or toolkits of various kinds are available for performing experiments, which abstract from the details and can be duplicated by other researchers.

3 Structure, Behaviour and Interaction of Agents

Agent-based models are usually based on a set of autonomous agents capable to interact with each other as well as with the environment according to rules of behaviour, which can be simple or complex, deterministic or stochastic, fixed or adaptive. An agent can be any organisational entity that is able to act according to its own set of rules and objectives. All agents can be of the same type (homogenous) or each agent can be different from the other (heterogeneous).

One core question is related to the structure of agents: should agents be simple or should they be complex? Proponents of the simplicity of agents, such as Robert Axelrod [1], support the so-called KISS principle (keep it simple, stupid), and point out that the most interesting analytical results are obtained when simple micro-level dynamics produce complex patterns at the macro level. This approach is analogous to mathematical models where complex dynamics may arise from simple rules. Proponents of the complexity of agents base their views especially in economics, sociology and cognitive psychology, assuming that agents are possibly guided by a set of behavioural rules and objective functions which evolved as a result of interaction and learning in complex environments and shape the individual structure of each agent. Reality tends to be between simplicity and complexity, and agents should be kept as "simple as suitable". Real agents seek to reduce complexity according to their needs and adjust to their social environment, sometimes leading to rather simple collective behaviour, despite the potential for individual complexity.

Agents can include many details matching reality, at different spatial and temporal scales. Depending on the agents' number, their attributes and behavioural rules in their respective environments, ABM's can be of great variety and complexity, making them hard to analyse or predict. Using sensors, agents can perceive their local neighbourhood and receive or send messages ([14]).

Cognitive agents may have cognitive capabilities "to perceive signals, react, act, making decisions, etc. according to a set of rules" ([9]). Their intended actions are shaped by what they think to know about the world (beliefs), based on experience and perception, and what they would like to achieve (desired goals), both represented by an internal model of the external environment. Agents can be autonomous and act independently of any controlling agency, or they can directly interact with or depend on other agents. In their environment agents need information to react and adapt to their observation and to respond to changes in the environment, and they can communicate with other agents via a language. Pursuing goals, agents need to be pro-active, and they can be rational by following a well-defined and logical set of decision rules to achieve these goals.

Adaptive agents have the capability to learn, i.e. rather than following a fixed stimulus-response pattern, they continuously adapt to changes in their environment according to their expectations and objectives. They evolve in a learning cycle of acting, evaluating the results of the actions dependent on the response of the environment and updating the objective or the actions. By acting an agent employs resources and directs them onto its environment, in order to achieve the objective. Evaluation compares the results of the actions and their impacts with the expectations and objectives. Searching tries to find better routines for achieving the objective. Adaptive agents can change their objectives and routines.

A general framework for agent-based modelling can be characterized by the following elements (see the contribution by Gebetsroither et al. in this volume):

- Values, targets and objectives
- Resources or production factors
- Observation, expectation and update
- Rules, search routines and actions

These elements occur repeatedly in a cycle of action, evaluation and update. A more comprehensive analysis would consider the complete multi-step process of decision-making, interaction and management, including the following phases [31]:

1. Situational analysis and problem structuring
2. Option identification and scenario modelling
3. Concept development and criteria-based evaluation
4. Decision-making and negotiation
5. Planning and action
6. Monitoring and learning

The different phases are connected by processes such as evaluation, communication, capacity building, information, simulation, validation. Usually ABMs do not apply all phases of this cycle but only selected elements which are of particular relevance for a given problem.

4 From Micro to Macro: Modelling Population Processes from the Bottom-Up

Agent-based simulations are increasingly applied in the social sciences. Artificial computational environments serve in fact as small laboratories to simulate social behaviours and interaction among a large number of actors. This includes the study of the complex dynamics evolving from heterogenous populations. Populations are by definition aggregates of individuals, and as such they constitute entities at the aggregate or "macro" level, whereas individual lives contribute to numbers of events, person years and survivors, which are used in the statistical analysis of populations. Demography as such is concerned with the study of populations, and has been traditionally focusing on the macro side of population dynamics, on "macro-demography". However, during the last decades of the Twentieth Century a "micro-demography" emerged with a specific emphasis on the unfolding of individual-level demographic trajectories and on the consequences of individual heterogeneity for the study of population dynamics.

Perhaps surprisingly, other disciplines than the one focusing on population per se have attempted at micro-founding the study of specific types of behaviour using some type of "methodological individualism" approach. In particular, we refer to ecology, sociology, and economics, disciplines that are in particular represented in this book.

In *ecology*, "individual-based modelling" (IBM), e.g. for the study of animal and plant populations, has emerged starting from the mid-1970s as a research program that has led to significant contributions (for a review see [15]). According to Grimm and Railsback [16], individual-based models in ecology fulfill, to a certain degree, four criteria: first, they explicitly consider individual-level development; second, they represent explicitly the dynamics of the resources an individual has access to; third, individuals are treated as discrete entities and models are built using the mathematics of discrete events rather than rates; fourth, they consider variation between individuals of the same age. Individual-based models in ecology are aimed at producing "patterns" that can be compared to patterns observed in reality. The sustainable use and management of natural resources is an important issue but difficult to model because it is characterized by complexity, a high degree of uncertainty, information deficits and asymmetries.

There are not many examples of agent-based models concerning the management of natural resources. A complete agent-based model would have to comprise both social and natural systems and respective agents, which is a challenging task.

In *sociology*, the approach proposed by James Coleman (see [8] Ch. 1) proposes to found social theory ultimately on the micro-level decisions of individuals. Coleman proposes to use a three-part schema for explaining macro-level phenomena, consisting of three types of relations: 1) the "macro-to-micro transition – that is, how the macro-level situation affects individuals; 2) "purposive action of individuals" – that is, how individual choices are affected by micro-level factors; 3) the "micro-to-macro transition" – that is, how macro-level phenomena emerge from micro-level action and interaction.

Colemans conceptual framework is embedded in the notion of "social mechanism" as the key concept to explain behaviour in the social sciences, proposed by Hedström and Swedberg [21], who see the three types of relationships as 1) situational mechanisms, representing the case in which "The individual actor is exposed to a specific social situation, and this situation will affect him or her in a particular way"; 2) action formation mechanisms, representing "a specific combination of individual desires, beliefs, and action opportunities (that) generate a specific action"; 3) transformational mechanisms, specifying "how these individual actions are transformed into some kind of collective outcome, be it intended or unintended". The framework is very similar to the one presented recently by Daniel Courgeau [11] in a review on the macro-micro link.

As we noticed before, the micro level is the natural point of departure in *economics*, also when pointing to the macro level as the important outcome. While the first generation of economic simulation models was rather focused on stylized empirical phenomena, the emergence of agent-based modelling during the last 10 years has shifted the emphasis from macro simplicity to micro complexity of the socio-economic reality. As noted by van den Bergh and Gowdy [36, p. 65] "During the last quarter century, the microfoundations approach to macroeconomic theory has become dominant". Mainstream economics, also known as "neoclassical" economics traditionally considers a "representative agent" who maximizes a potentially complex utility function subject to potentially complex budget constraints. This and other hypotheses lead to mathematically tractable models of macro-level outcomes. The new economics approach that applies the toolkit of neoclassical economics to demographic choices has been a key success of the work of Gary Becker (see e.g. [6]). This approach has now reached a level of maturity that can be attested from the literature on population economics (see e.g. [42]). That we ought to start from the micro level is also clearly stated by an economist who is particularly interested in population matters, Jere Behrman, who states that "For both good conditional predictions and good policy formation regarding most dimensions of population change and economic development, a perspective firmly grounded in understanding the micro determinants - at the level of individuals, households, farms, firms, and public sector providers of goods and services of population changes and of the interactions between population and development is essential" [7].

The attention on the policy relevance of research on population (including policy implications of results) is undoubtedly the main characteristic that comes to the surface when looking at research on population economics. Micro-based theories of behaviour are thus used to cast "conditional prediction" of reactions to a given policy, with these reactions affecting macro-level outcomes. Within economics, several scholars have objected to the neoclassical paradigm from various perspectives (see e.g. [7] for objections to critiques concerning population-development relationships). Of particular interest are the critiques on mainstream economics that concern the assumption that agents are homogeneous and the lack of explicit interaction between agents (see e.g. Kirman [24]). Kirman's point is that even if individuals are all utility maximizers (an idea that has also been challenged by several scholars), the assumption that the behaviour of a group of heterogeneous and interacting agents can be mimicked by that of a single representative individual whose choices coincide with the aggregate choices of the group is unjustified and leads to misleading and often wrong conclusions.

To overcome this micro-macro "aggregation" problem, that is the transformational mechanism in Coleman's scheme, some economists have proposed to build models that resemble that of IBM in ecology. Models in agent-based computational economics (ACE) explicitly allow the interaction between heterogeneous agents (see e.g. the review by Tesfatsion [34]).

5 Population Dynamics from the Bottom-Up: ABCD

We now document the emergence of the agent-based modelling approach in demography as a specific case-study.

Without the strong paradigm of the "representative agent" that underlies mainstream economics, demography has to solve aggregation problems taking into account that demographic choices are made by heterogeneous and interacting individuals, and that sometimes demographic choices are made by more than one individual (a couple, a household). For these reasons, and for the natural links to current micro-demography, computer simulation provides a way to transform micro into macro without having to impose unnecessary assumptions on the micro level (among those homogeneity, lack of interaction).

Agent-based computational demography (ABCD) has been shaped by a set of tools that models population processes, including their macro level dynamics, from the bottom up, that is by starting from assumptions at the micro level [4]. Agent-based computational demography includes also microsimulation that has been used to derive macro-level outcomes from empirical models of micro-level demographic processes (i.e. event history models), but also formal models of demographic behaviour that describe micro-level decisions with macro-level outcomes.

It is interesting to notice that demography has for a long time been using simulation techniques, and microsimulation has become one of the principal techniques in this discipline, being a widely discussed and applied instrument in the study of family and kinship networks and family life cycle ([19]; [38]; [30]; [20]; [35]). Microsimulation has also been widely used in the study of human reproduction and fecundability ([29]; [27]), migratory movements [10] or whole populations [25], and its role has been discussed in the general context of longitudinal data analysis [40]. Evert van Imhoff and Wendy Post [37] provide a general overview of the topic. Microsimulation has been used to study and predict the evolution of a population using a model for individuals.

What does ABCD add to demographic microsimulation in helping to bridge the gap between micro-demography and macro-demography? The emphasis of demographic microsimulation has been on the macro-level impact of a certain set of parameters estimated at the micro-level from actual empirical data. There has been no particular emphasis on the theoretical side. Agent-based models do not necessarily include only parameters estimated from actual empirical data, but it may include parameters that are relevant for a specific theoretical meaning. In fact, microsimulation is to the event history analysis what macrosimulation (i.e. population projection based on aggregate-level quantities like in the cohort-component model) is to traditional, macro-level, formal demography. On the other hand, agent-based computational demography is the micro-based functional equivalent of mathematical demography.

Some of the reasons why ABCD helps bridging the macro-micro gap in demography are mentioned in this context (see [5] for a full discussion).