# Studying population dynamics from the bottom-up: the crucial role of agent-based computational demography

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**Abstract**

In this paper we argue that Agent-Based Computational Demography (ABCD) from now onwards has an important role in understanding demographic behaviour. More specifically, we argue that modelling population processes from the bottom up, although historically neglected within the hardcore of demography, provides an opportunity to exploit interdisciplinary links that characterize the study of demographic behaviour. Moreover, ABCD helps in discussing micro-micro link, the emergence and/or persistence of population-level phenomena such as norms. We then discuss types of demographic behaviours for which the use of ABCD may be particularly fruitful, also reviewing the relevant literature.

## 1 Introduction

Recently, the literature on agent-based modelling in social sciences has flourished. This has particularly been the case in economics[1], political science[2], and – to a lesser extent – sociology[3]. During the 1990s, this computational approach to the study of human behaviour developed through a vast quantity of literature. These includes approaches that go 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

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[1]See i.e. the special issue on agent-based computational economics of the Journal of Economic Dynamics and Control [28], especially the introduction by Leigh Tesfatsion, as well as the website maintained by Lesfatsion `http://www.econ.iastate.edu/tesfatsi/ace.htm`.

[2]See i.e. the review paper by Johnson [20].

[3]See i.e. the recent review paper by Macy and Willer [23], or the review of Halpin [16].

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 important 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, that is, *agent-based modelling*. In this paper, we argue that demographers and other scholars interested in population studies should consider *Agent-Based Computational Demography (ABCD)* as a stream of research that can improve our understanding of demographic behavior. The above-mentioned emphasis on individual agents and the traditional centrality of description and prediction in demography might explain the currently limited presence of demographic experts in this field.

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 of agent-based modeling 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, however the data are not from the real world as in case of induction.

We will take a look in this paper at the issue of the use of simulations based on agents for theoretical purposes in a demographic perspective. We will place special emphasis on the link between hypotheses on micro-founded behaviour and macro-level demographic outcomes. We will show how the experience of scholars from other disciplines can be useful to demography but also how the experience of population scholars can be useful in a field that has autonomously developed quickly and in very broad terms.

In Section 2, we will start with the gap between macro and micro demography also looking at disciplines that are strictly linked to demography and that have attempted at micro-founding the study of specific types of behavior. Section 3 discusses the potential role of computer simulation, and in particular agent-based computational demography to bridge the gap between micro and macro. In Section 4, we point towards the added gains of agent-based computational demography. We shall then look at demo-

graphic applications and review some of our own work in this field. In the final section, we present a critical reflection on the function of agent-based simulation for theoretical purposes in demography. It will also examine the possibility of a role for establishing agent-based computational demography as a stream of research.

## 2 Macro-Micro: modeling population processes from the bottom-up

Demography can be simply defined as the study of human populations (Caselli et al. [9]). Populations are by definition aggregates of individuals, and as such they constitute entities at the aggregate or "macro" level of analysis. In the past, demography could be said to be a "macro-demography", as individual lives entered in formal analysis when contributing to numbers of events, persons years and survivors  also the statistical analyses used to be located at the macro-level. 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.

The gap between macro-demography and micro-demography has since then undoubtedly widened, and is rightly seen as a problem. Let us discuss the answers to the challenges posed by macro-micro links in other disciplines, and then focus on recent proposals to bridge this gap and avoid a "soccer game" between macro-demography and micro-demography.

Some hints on the reasons why micro-demography has emerged can be found by having a look at disciplines that are strictly linked to demography, and that have attempted at micro-founding the study of specific types of behavior using some type of "methodological individualism" approach. We look at three disciplines in particular: ecology, sociology, and economics. In *ecology*, what is defined as "individual-based modeling" (IBM) for the study e.g. of animal and plant populations, has emerged starting from the mid-1970s as a research program that has lead to significant contributions – in a review, Grimm [14] discussed fifty IBMs of animal populations published mostly during the 1990s. According to Grimm and Railsback [15], 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 build 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 ([15]).

In *sociology*, the approach proposed by James Coleman (see [10] Ch.

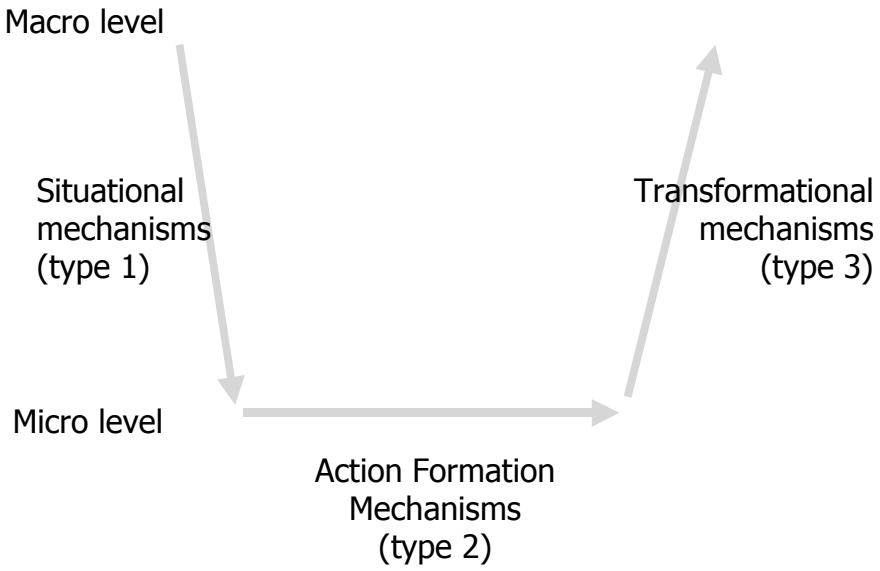


Figure 1: Coleman's conceptual framework in terms of social mechanisms (adapted from Hedström and Swedberg, 1999)

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. Figure 1 represents Colemans conceptual framework, as embedded in the notion of "social mechanism" as the key concept to explain behavior in the social sciences, proposed by Hedström and Swedberg [19], 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 [12] in a review on the macro-micro link.

The micro level is now the natural point of departure in *economics*, also when pointing to the macro level as the important outcome. As noted by van den Bergh and Gowdy [31](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 home economics approach that exactly applies the toolkit of neoclassical economics to demographic choices has been a key success of the work of Gary Becker (see e.g. Becker [7]). This approach has now reached a level of maturity that can be attested from looking at recent textbooks on the subject (Ermisch [**?**]) and at the importance of the literature on population economics (see e.g. Zimmermann and Vogler [35]). That we ought to start from the micro 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 determinantsat the level of individuals, households, farms, firms, and public sector providers of goods and servicesof population changes and of the interactions between population and development is essential"(Behrman [8]).

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 behavior 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. Behrman, [8] for objections to critiques concerning populationdevelopment relationships). Of particular interest for the reasoning of this paper we see 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 [21]). Kirman's point is that even if individuals are all utility maximizers (an idea that has also been criticized by several scholars, but that we shall not discuss here), the assumption that the behavior of a group of heterogeneous and interacting agents can be mimicked by that of to 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 [28]). We shall come back to this point in relationship to demography in the following section.

# 3 From micro to macro: the role of agent-based models

The missing part of the micro-macro gap concerns transformational mechanisms. How do we get from the findings and the ideas of "micro-demography" back to the macro level? This is perhaps the key issue raised by authors who consider that demography should give answers about population processes at the macro level.

In Section 2 we have mentioned the debates that are often pervading neighboring disciplines, and in particular in economics, about aggregation problems. 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, an household). For these reasons, and for the natural links to current micro-demography, computer simulation provides a way to transform the micro into macro without having to impose assumptions on the micro level one would not like to impose (among those homogeneity, lack of interaction). This is the way some scholars in neighboring disciplines have chosen, as we saw in Section 2, when introducing for instance individual-based modeling in ecology.

Agent-based computational demography (ABCD) is a set of tools that models population processes, including their macro level dynamics, from the bottom up, that is starting from assumptions at the micro level (Billari and Prskawetz [**?**]). 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 behavior that describe micro-level decisions and for which we are also interested in macro-level outcomes.

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 (Hammel et al. [17]; Wachter [33]; Ruggles [27]; Hammel and Wachter [18]; Tomassini and Wolf [30]). Microsimulation has also been widely used in the study of human reproduction and fecundability (Ridley and Sheps [26]; Nakazawa and Ohtsuka [24]), migratory movements (Courgeau [11]) or whole populations (Land [22]), and its role has been discussed in the general context of longitudinal data analysis (Wolf [34]). Evert van Imhoff and Wendy Post [32] provide a general overview of the topic. Microsimulation has been used to study and predict the evolution of 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.

# 4 The Added Gains of Agent-Based Computational Demography

There are some reasons for which ABCD may help bridging the macro-micro gap in demography. Some of them can be mentioned in particular in this context (see Billari et al. [4] for a full discussion).

First, it is relatively easy to include feedback mechanisms and to integrate micro-based demographic behavioural theories (and results from individual-level statistical models of demographic behaviour such as event history models) with aggregate-level demographic outcomes. This ability to include feedback is possibly the most important gain of ABCD models. In such models, space and networks can be formalised as additional entities through which the agents will interact.

Second, compared to mathematical modelling, it is relatively easy to introduce heterogeneous agents that are not fully rational. Hence, the paradigm of the representative, fully rational agent that has and often still penetrates many economic and sociological applications can easily be relaxed in agent-based modelling.

Third, when building agent-based computational models, it is indispensable to adopt simple formulations of theoretical statements. Although agent-based modelling employs simulation, it does not aim to provide an accurate representation of a particular empirical application. Instead, the goal of agent-based modelling should be to enrich our understanding of fundamental processes that may appear in a variety of applications. This requires adhering to the KISS principle, which stands for the slogan keep it simple, stupid (Axelrod [1]).

Fourth, using agent-based approaches, it is possible to construct models for which explicit analytical solutions do not exist, for example social interaction and generally non-linear models. Agent-based models are used to understand the functioning of the model and the precision of theories need not be limited to mathematical tractability. Simplifying assumptions can

then be relaxed in the framework of an agent-based computational model. But as Axtell [2] notes, even when models could be solved analytically or numerically, agent-based modelling techniques may be applied since their output is mostly visual and therefore easier to communicate to people outside academia. In general, we can see formal modelling of population dynamics using differential equations and agent-based computational models as two ends of a continuum along the macro-micro dimension (Rahmandad and Sterman [25]).

Finally, it is possible to conceive artificial societies that need not necessarily resemble present societies; such artificial societies can be seen as computational laboratories or may allow to reproduce past macro-events from the bottom-up.

# 5 Agent-Based Models in Demography

An example of macro-demographic issue that can be addressed using ABCD is the dynamics of marriage. Billari [3] has proposed to derive what has been long known within demography as the shape of the hazard rate of marriage (that is, a macro-level empirical regularity that has been sometimes modelled using "demographic laws") by simulating a marriage market at the micro level. Todd et al. [29] present a series of such models. Figure 2 shows the shape of the hazard rate of marriage derived from a model in which individuals marry after a period of "learning" during adolescence (which is distributed according to a normal distribution) as long as they find an acceptable partner who accepts to marry them. The shape of the curve is qualitatively similar to the ones observed in reality.

A further topic of broader interest in sociology is the persistence of cultural norms. In Billari et al. [5] we address the issue of the cultural evolution of age-at-marriage norms. The issue of age-norms is of central importance in research on the life course, where the debate focuses on whether such norms may resist in the presence of a general individualisation process pervading post-modern societies. In this paper we developed an agent-based simulation model to study the evolution across generations of age-at-marriage norms. In our definition, norms are constraints built in the programming of agents, and they can be transmitted to the next generation only by those agents who are able to marry and thus have children. Social influence may also play a role, because agents can derive their norms in conformity to the majority of the population. The paper shows, with this highly stylised model, that under certain conditions, the long-term persistence of age-at-marriage is assured. It also shows the importance of path dependence in this type of processes, because the initial

In a recent paper (Billari et al. [6]) we build an agent-based model of marriage based on social interaction. More specifically, we build a popula-

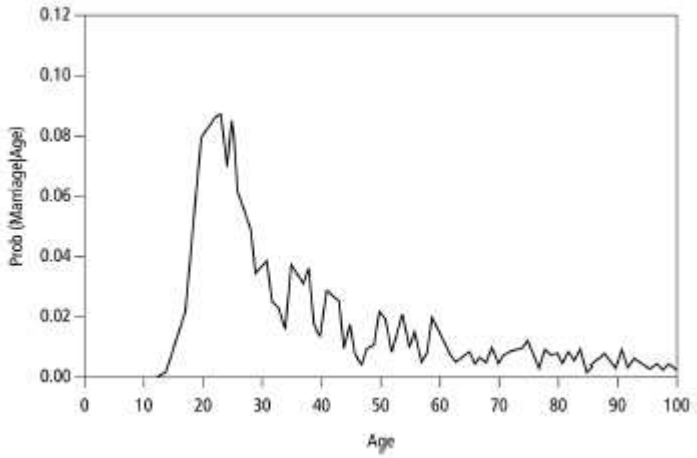


Figure 2: Hazard rate for marriage from an agent-based simulation of marriage.
Source: Todd et al. [29]

tion of agents whose willingness to marry depends on the share of relevant others who are already married and on the availability of partners. Agents live on a circular space. Our simulations show that age-at-marriage curves of realistic shape can emerge from micro-level hypotheses and social interaction.

## 6 Discussion

While the study of the influence of macro-level factors on micro-level demographic decisions, as well as the interaction between macro- and micro-level factors have been pushed by recent developments in demography[4], much less advancement has been done in demography on the problem of transformational mechanism, i.e. the aggregation of micro-level results to obtain macro-level outcomes. If we are not willing to accept the idea of representative agents that has helped economists to micro-found macro-economics also in a formal way, agent-based computational models (including microsimulation) provide an important toolkit to build a bridge from micro-level findings to macro-level dynamics. Future models may also be developed in a more statistical "fashion", by estimating the simulation parameters more directly from actual data.

[4]The life course approach has provided a theoretical framework on demographic decision-making; multilevel statistical models possibly applied to event histories have been developed as key analytical tools; data collection efforts with true multilevel dynamics have started and are currently planned

To build the final bridge between micro and macro-demography, we need to accept that computer programming, and specifically programming aimed at building simulation models, becomes again part of mainstream technical tools in demography. As in the case of other approaches, learning and interacting with disciplines that are close to demography will constitute an important advantage rather than a disadvantage. Demographers ought not to create a gap between micro and macro, and the existing gap needs to be bridged.

## References


[1] Axelrod, R. (1997): The Complexity of Cooperation. Agent-Based Models of Competition and Collaboration. Princeton University Press, Princeton

[2] Axtell, R. (2000) Why agents ? On the varied motivations for agent computing in the social sciences. - Washington, The Brookings Institution, Center on Social and Economic Dynamics, 22 p. (CSED Working Paper, n 17). Available online at: http://www.brook.edu/dybdocroot/es/dynamics/papers/agents/agents.htm).

[3] Billari, F.C. (2000) Searching for mates using 'fast and frugal' heuristics : a demographic perspective, in : Grard BALLOT and Grard WEISBUCH (ed.), Applications of simulation to social sciences, p. 53-65. - Oxford, Hermes Science Publications, 461 p.

[4] Billari, F.C., Ongaro, F. and Prskawetz, A. (2003) Introduction : agent-based computational demography, in : Francesco C. Billari and Alexia Prskawetz (ed.), Agent-Based Computational Demography. Using Simulation to Improve our Understanding of Demographic Behaviour, p. 1-17. - Heidelberg, Physica/Springer, X + 210 p.

[5] Billari, F.C., Prskawetz, A., and Fürnkranz J. (2003) On the cultural evolution of age-at-marriage norm, in : Francesco C. Billari and Alexia Prskawetz (ed.), Agent-Based Computational Demography. Using Simulation to Improve our Understanding of Demographic Behaviour, p. 1-17. - Heidelberg, Physica/Springer, X + 210 p.

[6] Billari, F.C., Prskawetz, A., Aparicio Diaz, B. and Fent, T. (2005) The "Wedding-Ring": An agent-based marriage model based on social interaction, mimeo, Vienna Institute of Demography.

[7] Becker, G.S. (1981): A treatise on the family. Cambridge (Mass.), Harvard University Press, XII + 288 p. (2nd edition 1991, XII + 424 p.).

[8] Behrman, J.R. (2001) Why micro matters, in : Nancy Birdsall, Allen C. Kelley and Steven W. Sinding (ed.) Population matters. Demographic change, economic growth and poverty in the developing world, p. 371-410. - Oxford, Oxford University Press , XVI + 440 p.

[9] Caselli et al. (2005) xxxx

[10] Coleman, J.S. (1990) Foundations of Social Theory. Cambridge (Massaschussetts), Belknap Press, XVI + 993 p.

[11] Courgeau, D. (1995) Migration theories and behavioral models, International Journal of Population Geography, vol. 1, n 1, p. 19-27.

[12] Courgeau, D. (2003) General introduction, in : Daniel COURGEAU, Methodology and epistemology of multilevel analysis. Approaches from different social sciences, p. 1-23. - Boston, Dordrecht and London, Kluwer Academic Publishers, 235 p.

[13] Ermisch, x. (2003) xxx.

[14] Grimm, V. (1999) Ten years of individual-based modeling in ecology. What have we learned, and what could we learn in the future ? Ecological Modelling, vol. 115, n 2-3, p. 129-148.

[15] Grimm, V. and Railsback, S.F. (2005) Individual-based Modeling and Ecology. - Princeton, Princeton University Press, XIII + 412 p.

[16] Halpin, B. (1999): Simulation in Society. American Behavioral Scientist 42(10), 1488-1508

[17] Hammel, E.A., McDaniel, C.K. and Wachter, K.W. (1979) Demographic consequences of incest tabus : a microsimulation analysis, Science, vol. 205, n 4410, p. 972-977.

[18] Hammel, E.A. and Wachter, K.W. (1996) Evaluating the Slavonian Census of 1698. Part II : A microsimulation test and extension of the evidence, European Journal of Population, vol. 12, n 4, p. 295-326.

[19] Hedström, P. and Swedberg, R. (1999) Social mechanisms. An analytical approach to social theory. - New York and Cambridge (UK), Cambridge University Press, VIII + 340 p.

[20] Johnson, P.E. (1999): Simulation Modeling in Political Science. American Behavioral Scientist 42(10), 1509-1530

[21] Kirman, A.P. (1992) Whom or what does the representative individual represent?, Journal of Economic Perspectives, vol. 6, n 2, p. 117-136.

[22] Land, K.C. (1986) Method for national population forecasts: a review, Journal of the American Statistical Association, vol. 81, n 347, p. 888-901.

[23] Macy, M.W., Willer, R. (2002): From Factors to Actors: Computational Sociology and Agent-Based Modeling. Annual Review of Sociology 28, 143-166

[24] Nakazawa, M. and Ohtsuka, R. (1997) Analysis of completed parity using microsimulation modeling, Mathematical Population Studies, vol. 6, n 3, p. 173-186.

[25] Rahmandad, H. and Sterman, J. (2004) Heterogeneity and network structure in the dynamics of diffusion: comparing agent-based and differential equation models. - Cambridge (Massachussets), Massachussets Institute of Technology, 31 p. (MIT Sloan Working Paper 4512-04).

[26] Ridley, J.C. and Sheps, M.C. (1996) An analytic simulation model of human reproduction with demographic and biological components, Population Studies, vol. 19, n 3, p. 297-310.

[27] Ruggles, S. (1993) Confessions of a microsimulator, Historical methods, vol. 26, n 4, p. 161-169.

[28] Tesfatsion, L. (Eds.) (2001): Special Issue of Agent-based Computational Economics. Journal of Economic Dynamics & Control 25, 281-654

[29] Todd, P.M., Billari, F.C. and Simao, J. (2004) Modeling the emergence of social marriage patterns produced by individual mate-search heuristics. - Berlin, Max Planck Institute for Human Development, 32 p.

[30] Tomassini, C. and Wolf, D. (2000) Shrinking kin networks in Italy due to sustained low fertility, European Journal of Population, vol. 16, n 4, p. 353-372.

[31] van den Bergh, J. C.J.M. and and Gowdy, J.M. (2003) The microfoundations of macroeconomics: an evolutionary perspective, Cambridge Journal of Economics, vol. 27, n 1, p. 65-84.

[32] van Imhoff, E. and Post, W.J. (1998) Microsimulation methods for population projection, Population: An English Selection, vol. 10, n 1, p. 971-938. (Special issue on "New Methodological Approaches in the Social Sciences").

[33] Wachter, K.W. (1987) xxx

[34] Wolf, D. (2001) The role of microsimulation in longitudinal data analysis, Canadian Studies in Population, vol. 28, n 2, p. 313-339.

[35] Zimmermann, K.F. and Vogler, M.(ed.), 2003. Family, Household and Work. - Berlin, Springer, XIV + 427 p.