The missing link: AB models and dynamic microsimulation

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Abstract In this note I pay tribute to two early works by Barbara Bergmann and Gunnar Eliasson which, though firmly grounded in the dynamic microsimulation literature, can be considered as the first examples of large-scale agent-based models. These attempts at building complete micro-to-macro computational models of the economy are important not only in a history of economic thought perspective, but also to encourage convergence of the two approaches in developing credible alternatives to DSGE models.

1 Introduction

Agent-based (AB) models are characterized by three features (Gallegati and Richiardi, 2009): (i) there are a multitude of objects that interact with each other and with the environment, (ii) these objects are autonomous, i.e. there is no central, or "top-down" control over their behavior and more generally on the dynamics of the system, and (iii) the outcome of their interaction is numerically computed. AB models are generally identified as *theoretical exercises* aimed at investigating the (unexpected) macro effects arising from the interaction of many individuals —each following possibly simple rules of behavior— or the (unknown) individual routines/strategies underlying some observed macro phenomenon (Richiardi, 2012). As such, the typical AB model is a relatively small "toy" model, which can be used to understand relevant mechanisms of social interaction. The roots of AB modeling can be traced down to the study of cellular automata.[1] AB models further developed

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[1] See von Neumann and Burks (1966); Gardner (1970) and, for a first application to social issues, Schelling (1969).

within the evolutionary economics approach[2] and the so-called Santa Fe perspective on the study of complex systems[3].

However, an earlier antecedent of AB modelling can be identified in the dynamic microsimulation (DMS) literature, and in particular in two almost forgotten works: Barbara Bergmann's microsimulation of the US economy (Bergmann, 1974) and Gunnar Eliassons microsimulation of the Swedish economy (Eliasson et al., 1976; Eliasson, 1977).

While there has been a recent surge of interest for AB modeling in the DMS literature, this is considered more as a promising direction for future research, than as the continuation of a tradition that dates back to thirty-five years ago (Morand et al., 2010; Li, 2011). The infatuation of dynamic microsimulationists for AB modeling is not corresponded by AB practitioners, who not only are not aware of their intellectual debt, but seem not to recognize the convergent paths the two literatures have embraced, with a new vintage of large AB macro-models claiming increasing empirical content.

Both Bergmann and Eliasson developed a macro model with production, investment, and consumption (Eliasson also had a demographic module). They introduced two basic innovations with respect to the DMS literature that was emerging at the time —and in which they were firmly grounded: they explicitly considered the interaction between the supply and demand for labor, and they modeled the behavior of firms and workers in a structural sense. On the other hand, the standard approach to microsimulation —or, as Guy Orcutt called it, the "microanalytic approach for modeling national economies" (Orcutt, 1990)— was based on the use of what he considered as a-theoretical conditional probability functions, whose change over time, in a recursive framework, describe the evolution of the different processes that were included in the model. This is akin to reduced-form modeling, where each process is analyzed conditional on the past determination of all other processes, including the lagged outcome of the process itself.

Bergmann and Eliasson had a complete and structural, although relatively simple, model of the economy, which were calibrated to replicate many features of the US and Swedish economy, respectively. However, their approach —summarized in (Bergmann et al., 1977)— passed relatively unnoticed in the DMS literature, which evolved along the lines identified by Orcutt mainly as reduced form, probabilistic partial equilibrium models, with limited interaction between the micro unit of analysis, and with abundant use of external coordination devices in terms of alignment to exogenously identified control totals. On the contrary, the AB approach emerged with a focus on general equilibrium feedbacks and interaction, at the expenses of richer empirical grounding. Hence, the work of Bergmann and Eliasson could be interpreted as a bridge between the (older) DMS literature and the (newer) AB modeling literature, a bridge that however has so far remained unnoticed. The goal of this paper is to bring this bridge back on the map, not only as a tribute to the history of economic thought, but also as a potential useful road for current and future research.

[2] Dosi and Nelson (1994).

[3] Anderson et al. (1988); Arthur et al. (1997); Blume and Durlauf (2006).

The structure of the paper is as follows. In section 2 DMS is briefly presented; sections 3 and 4 are devoted to Bergmann's and Eliasson's models, respectively; section 5 describes how the recent literature on DMS has approached the challenge brought forward by these two precursors; section 6 depicts a convergent evolution of AB models toward increasing complexity and empirical content; finally, section 7 discusses how the emerging approach to estimation of AB models diverges from the one which is dominant in the DMS literature, and suggests that cross-fertilization of techniques might be fruitful.

2 Dynamic microsimulation

Broadly defined, microsimulation is a methodology used in a large variety of scientific fields to simulate the states and behaviors of different units —individuals, households, firms, *etc.*— as they evolve in a given environment —a market, a state, an institution. Very often it is motivated by a policy interest, so that narrower definitions are generally provided. For instance, Martini and Trivellato (1997) define microsimulation models as "computer programs that simulate aggregate and distributional effects of a policy, by implementing the provisions of the policy on a representative sample of individuals and families, and then summing up the results across individual units" (p. 85).

The field of microsimulation originates from the work of Guy Orcutt in the late 1950s (Orcutt, 1957). Orcutt was concerned that macroeconomic models of his time had little to say about the impact of government policy on things like income distribution or poverty, because these models were predicting highly aggregated outputs while lacking sufficiently detailed information of the underlying micro relationships, in terms of the behavior and interaction of the elemental decision-making units. However, if a non-linear relationship exists between an output Y and inputs X, the average value of Y will indeed depend on the whole distribution of X, not on the average value of X only.

Orcutt's revolutionary contribution consisted in his advocacy for a new type of modeling which uses as inputs representative distributions of individuals, households or firms, and puts emphasis on their heterogeneous decision making, as in the real world (Orcutt et al., 1961). In so doing, not only the average value of Y is correctly computed, but its entire distribution can be analyzed. In Orcutt's words, "this new type of model consists of various sorts of interacting units which receive inputs and generate outputs. The outputs of each unit are, in part, functionally related to prior events and, in part, the result of a series of random drawings from discrete probability distributions".

Two things are worth noting. First, the deficiencies of aggregate macro-models identified by Orcutt are still on the table today, more than 50 years later —the recent financial crisis has clarified that the king is naked, exposing all shortcomings of dynamic stochastic general equilibrium (DSGE) models, the workhorse tool in macroeconomics.[4] Second, DMS appears very similar indeed to the AB approach to economic modeling. The main differences can be traced down to the following (i), microsimulations are more policy-oriented, while AB models are more theory-oriented; (ii) microsimulations generally rely on a partial equilibrium approach, while AB models are most often closed models.

As it turns out, in their struggle to replace DSGE models, AB models are becoming more empirically oriented, while microsimulations are becoming more complex, by including more behavioral responses and general equilibrium feedbacks. Bergmann's and Eliasson's models were precursors in the latter respect.

3 Barbara Bergmann's model of the US economy

Barbara Bergmann was deeply influenced by Orcutt's lessons while a graduate student at Harvard (Olson, 2007). However, her microsimulation (Bergmann, 1974) departs from Orcutt's approach in significant ways. The behavior of all actors is modeled in a structural sense: workers, firms, banks, financial intermediaries, government and the central bank act based on pre-defined decision rules, rather than being described in terms of transition probabilities between different states. Each period (a week), (i) firms make production plans based on past sales and inventory position; (ii) firms attempt to adjust the size of their workforce; wages are set and the government adjusts public employment, (iii) production occurs, (iv) firms adjust prices, (v) firms compute profits, pay taxes and buy inputs for the next period, (vi) workers receive wages, government transfers, property income; they pay taxes and make payments on outstanding loans, (vii) workers decide how much to consume and save, choose among different consumption goods and adjust their portfolios of assets, (viii) firms invest, (ix) the government purchases public procurement from firms, (x) firms make decisions on seeking outside financing, (xi) the government issues public debt, (xii) banks and the financial intermediaries buy or sell private and public bonds; the monetary authority buys or sells government bonds; interest rates are set. In the early 1974 version, only one bank, one financial intermediary and six firms, "representative" of six different types of industrial sectors / consumer goods (motor vehicles, other durables, nondurables, services and construction) were simulated. In the labor market, firms willing to hire make offers to particular workers, some of which are accepted; some vacancies remain unfilled, with the vacancy rate affecting the wage setting mechanism. Unfortunately, the details of the search process are described only in a technical paper that is not easily available anymore (Bergmann, 1973). Admittedly, the model was defined by Bergmann herself as a "work in progress", and was completed only years later (Bennett and Bergmann, 1986). The assumption of "representative" firms is particularly questionable from an AB perspective, although it is not engraved in the model architecture. However,

[4] See Colander et al. (2008); Solow (2010); Kirman (2010); Krugman (2011); Stiglitz (2011).

the model is noteworthy for its complexity and for the ample relevance given to rule-based decision making.

4 Gunnar Eliasson's model of the Swedish economy

Eliasson et al. (1976) "Micro-to-Macro model", which eventually came to be known as MOSES ("model of the Swedish economy"), is a DMS with firms and workers as the unit of analysis. A concise description of the model can be found in (Eliasson, 1977). The labor market module, which is of central importance in the model, is firm-based insofar the search activity is led by the firms that look for the labor force they require to meet their production targets. Labor is homogeneous, and a firm can search the entire market and raid all other firms subject only to the constraint that search takes time (a limited number of search rounds are allowed in each period). Firms scan the market for additional labor randomly, the probability of hitting a source (another firm or the pool of unemployed) being proportional to its size. If a firm meets another firm with a wage level that is sufficiently below its own, it gets the people it wants, up to a maximum proportion of the other firm's labor force. The other firm then adjusts its wage level upwards with a fraction of the difference observed, and it is forced to reconsider its production plan. If a firm raids another firm with a higher wage level it does not get any people, but upgrades its wage offer for the next trial. Firms then produce, sell their products, make investment decisions and revise their expectations. Individuals allocate their income to savings and consumption of durables, non-durables and services. Each year the population is dynamically evolved with flows into and out of the labor force.

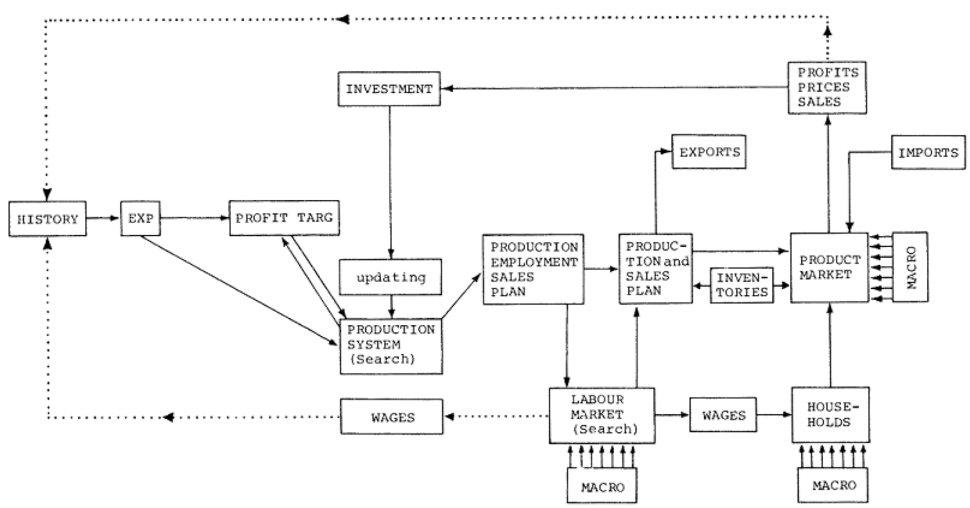

Fig. 1: Structure of the MOSES model of the Swedish economy. Source: Eliasson (1977).

The model was designed to address two issues: (i) formulate a micro explanation for inflation, and (ii) study the relationship between inflation, profits, investment and growth. It was populated partly with real balance sheet firms, and partly with synthetic firms whose balance sheets were calibrated in order to obtain sector totals. Since its original formulation, the model has been updated and documented in a series of papers (Eliasson, 1991).[5]

5 Current trends in DMS modeling: linking micro to macro.

Rather than following the strategy of increasing the complexity of microsimulation models and explicitly model general equilibrium feedbacks —along the lines pioneered by Bergmann and Eliasson— the recent literature on DMS has tried to link partial equilibrium microsimulations with computable general equilibrium (CGE) macro models. The underlying idea is to keep the models as simple as possible, and develop different models for different levels of aggregation. Following again Orcutt's insights, these models could then be connected through intermediate variables. Peichl (2009) describes how the approach, labeled *top-down bottom-up*, works: the CGE model produces macroeconomic variables (price level, output growth rates, *etc.*) which are passed as inputs to the DMS; the microsimulation model in turns produces outcomes (elasticities, income, *etc.*) which are passed back to the CGE; the procedure is repeated until convergence.

Simple and appealing as the approach may look, it is plagued by theoretical and empirical inconsistencies, which might preclude convergence or, worse, produce outcomes which are misleading for policy analysis (the Lucas critique once again). The approach is also computationally burdensome, and only few applications have so far been developed.[6]

6 Current trends in AB macro modeling: towards more general models.

Recent years have witnessed a trend in AB macro modeling towards more detailed and richer models, targeting to a higher number of stylized macro facts, and claiming a stronger empirical content.[7] A big push forward has been provided, on the

[5] Of particular relevance here, is the model of the French economy by Gérard Ballot (Ballot, 2002). He models a dual labor market with open-ended and temporary positions. Although the model comprises only 40 firms and 1700 individuals (belonging to 800 households), it is roughly calibrated to the French labor market over the period 1972-1977, that is around the first oil shock. It is able to reproduce the changes in mobility patterns of some demographic groups when the oil crisis in the 1970s occurred, and in particular the sudden decline of good jobs.

[6] See Peichl (2009) for a review.

[7] See Dawid et al. (2013) for a review.

East side of the Atlantic, by two large projects funded by the European Commission: EURACE and CRISIS.[8] The three year (2006-2009) EURACE project had the ambitious goal of creating an integrated AB model of the European economy (Deissenberg et al., 2008), linking real (consumption goods, investment goods and labor) and financial (loans, bonds and stocks) markets. The model was meant to be populated by a very large number of fairly sophisticated agents (in the order of 10^7 households, 10^5 consumption goods producers, 10^2 investment goods producers, and 10^2 banks), each following empirically documented behavioral rules. This very large number of agents allows in principle to discover emerging phenomena and/or rare events that would not occur with a smaller population.

An important feature of the model is its explicit spatial structure: with the exception of the investment goods market and the asset market, all markets are local. For example, there is a local labor market in each NUTS-2 region. Deissenberg et al. (2008) succinctly describe how the model works:

> The market for consumption goods is a decentralized market, with local interaction between the firms and consumers. We assume that the firms send their merchandise to a given set of local shopping malls. All buying and selling occurs at these malls. Firms chose the outlet malls on the basis of expected local demand and profit opportunities. They also take into account the costs involved in servicing a particular mall, such as the transportation costs, the leases for the stores in the mall, and the inventory management costs.
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> The labor market is also a decentralized market. A local search-and-matching process is used to represent the interaction between firms and workers. The firms post vacancies, including the minimum skill level required for the posted job. The potential employees apply to vacancies that have been posted by firms in their local neighborhood. Unemployed workers who do not succeed in finding a job locally can migrate to a different region.

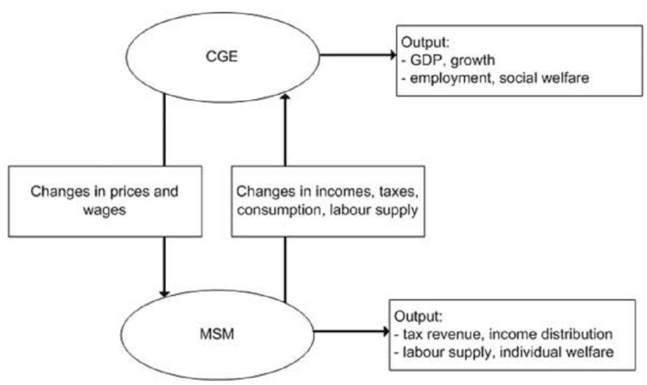

Fig. 2: Linking microsimulation models (MSM) and CGE models: the top-down bottom-up approach. Source: Peichl (2009).

[8] The CRISIS project is still in its initial phase; its goal is to provide "a platform for the development and application of data mining, process mining, computational and artificial intelligence and every other computer and complex science technique coupled with economic theory and econometric methods that can be devoted to identifying the emergence of social and economic risks, instabilities and crises" (Farmer et al., 2012).

> The market for investment goods is a centralized market. There are multiple investment goods producers, each producing a different, vertically differentiated, technology. The investment goods producers invest in R&D to technologically improve the investment goods, leading to oligopolistic competition among them. The producers of consumption goods can invest in one of these technologies to produce a variety of differentiated consumption goods.
>
> On the credit market, the firms interact with banks to obtain loans. The credit market is a decentralized market, with competition between banks setting different interest rates for the business loans. The banks apply credit standards to the firms that apply for the loans. Thus, the firms can be credit constrained.
>
> Finally, the financial asset market links the real side with the financial side. Firms issue equity (common stocks and corporate bonds) to finance investments and production. The households invest in asset portfolios, and the government sells government bonds to finance its budget deficit. The financial market thus consists of a market for corporate and government bonds and a market for firm stocks. The linkage between the financial side and the real side of the economy is provided by the financial policy of the firms on internal and external financing, that is among others, by the dividend, the debt repayment, and the investment decisions.

Figure 3 shows the interactions between producers and consumers in the markets for investment and consumption goods.

Admittedly, EURACE reached a level of complexity rarely seen in an economic model, and proved difficult to manage. As the EU funding run out, the project developed into smaller scale models, each maintained by a different research unit. Herbert Dawid and his team, at the University of Bielefeld, focused on skills formation and innovation; their model was upgraded (Dawid and Neugart, 2011; Dawid et al., 2011) and gave rise to a steady stream of publications.[9] Silvano Cingotti and his team, at the University of Genoa, focused on the credit market and bank regulation.[10] The team lead by Mauro Gallegati and Domenico Delli Gatti, at the Marche Polytechnic University and the Catholic University, adopted another strategy and kept on developing ad-hoc models for specific applications.

7 Microsimulation vs. AB modeling: the challenge of empirical validation

The works by Bergmann and Eliasson were a first attempt at replacing the core of macroeconomics (Caballero, 2010) with an AB alternative. Their goal to provide a structural closed model of the whole economy, to be calibrated empirically, was indeed very ambitious. After more than 30 years, the literature is taking the challenge again. The models reviewed in the previous section are more general and more complex than their overlooked ancestors, but they will ultimately be judged under the same metric : the ability to track real data, simulate policy options and provide policy guidance.

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[9] See Dawid et al. (2009, 2012).

[10] Cincotti and Teglio (2010); Teglio et al. (2012).

With respect to the issue of empirical validation, two approaches can be identified. The first one, which is standard in the DMS literature, is to separately estimate the different processes (education, household formation, labor market participation, *etc.*) as reduced-form equations. This requires to assume that choices are made sequentially, so that all the covariates in every process can be considered as predetermined. This assumption being often untenable, the practical solution is to keep the estimates separate and "adjust" the estimates (via *alignment* algorithms) in order to keep the evolution of some macro-variables of interest in line with exogenously given targets. This also takes care of specification errors, and of the fact that microsimulations generally lack general equilibrium feedback effects. However, the procedure is of dubious validity, from a theoretical point of view. It is considered as a "quick and dirty" solution to deal with complicated models and inadequate data; it can (by construction) succeed in tracking real time series but it has no structural backbone and thus it is likely to fail to predict the effects of policy changes; moreover, it is not able to provide out-of-sample guidance when no external targets are available.

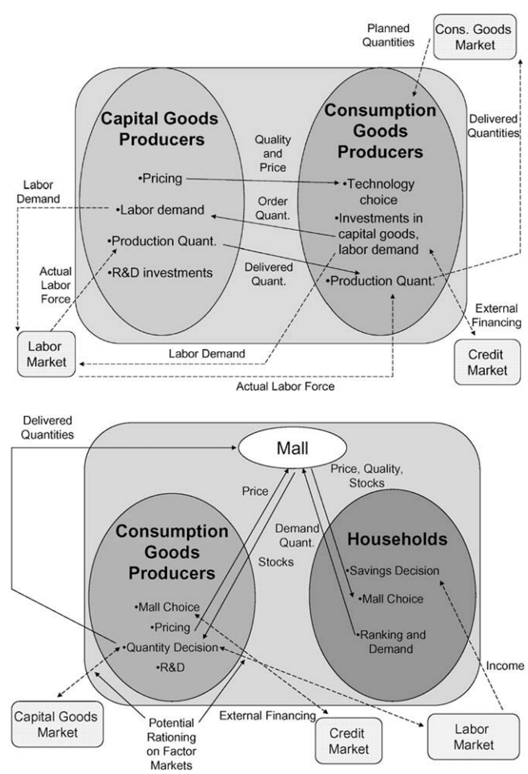

Fig. 3: Interactions in the capital goods market (top panel) and the consumption goods market (bottom panel). Source: Deissenberg et al. (2008).

The second approach is the one followed by DSGE modeling, which has evolved from rough calibration to structural estimation (Tovar, 2008; Fernández-Villaverde, 2010). Notwithstanding the fact that DSGE models are packed with simplifying assumptions, their estimation is by no means straightforward. The most standard technique is ML and requires to linearize the model in order to find a local approximation of the steady state solution (the so-called *policy functions*), then express this solution as a Markov chain (the *state space representation*), then apply filtering theory in order to obtain the likelihood function. Because this likelihood function is generally very flat and quite uninformative about the underlying structural parameters, more curvature is added by introducing Bayesian priors.

As for AB models, empirical validation is still rare, and generally amounts to more or less sophisticated calibration; only a few applications exist where a structural estimation of an AB model is performed, and they normally involve very simple models.[11] The use of simulated minimum distance estimators appear to be a promising approach (Grazzini and Richiardi, 2013), but the feasibility of the approach in a large scale model has still to be proved.

This test will eventually decide the future of macroeconomics. If the structural estimation of large scale AB models remains beyond reach, a sequential approach might become dominant, where —following the standard practice in the microsimulation literature— different submodules are separately estimated. This will however dent the appeal of AB models as an alternative to DSGE models in Economics. If, on the other hand, large scale AB models prove amenable to structural estimation, it is likely that they will eventually encompass DMS and establish their validity —over and beyond DSGE models— not only to explore theoretical possibilities but also to analyze policy relevant issues.

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[11] See Grazzini et al. (2012b,a) and the references therein.

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