A Parametrized Multi-Actor Model of Technologically Driven Growth - with Application to Climate Change

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Introduction

Combating global climate change is widely recognized as one of the most serious challenges facing humankind today. The mounting evidence of a human induced change in climate, long predicted by climate scientists and summarized in the successive Assessment Reports of the UN Intergovernmental Panel on Climate Change (IPCC, 1990, 1996, 2001, 2007), has finally shifted the public debate from the abstract question of the existence of climate change to the concrete problem of how to transform our present global economy based on fossil fuels to a sustainable carbon-free system.

Unfortunately, in contrast to the clear consensus statements of the IPCC Working Group 1 on the Science of Climate Change, the assessments of IPCC Working Groups 2 and 3 on the impacts, adaptation and mitigation of climate change have not provided policymakers with clear policy recommendations. This is due in part to the chosen scientific rather than policy-oriented stance of IPCC, but is rooted more basically in genuinely divergent views of the scientific community on the appropriate methodology to be applied to the integrated assessment (IA) of climate policy (cf. Hasselmann and Barker, 2008). Thus, it is not surprising that the bold political recommendations of the Stern Review on the Economics of Climate Change (Stern, 2007), although highly influential in the political arena, have generated considerable controversy within the scientific community (Barker, 2008,.).

The origin of much of the controversy lies, in the authors' view, in an ongoing paradigm change in macroeconomic theory brought about by computer simulations (Colander, 2006, Beinhocker, 2006). Traditional macroeconomics has been built on two pillars: mental models and mathematical analysis. Our present understanding of how the economy works is still largely based on the mental models developed by a formidable sequence of classical economic thinkers, extending from Francois Quesnay, Adam Smith, David Ricardo, Karl Marx, John Maynard Keynes and Joseph Schumpeter to Milton Friedman, to name but a few. Attempts to underlay or extend these concepts with rigorous mathematical analysis, beginning in the late 19th century, led to an equally impressive set of theoretical constructs, including general economic equilibrium theory - the central concept of mathematical macroeconomics - the theory of economic growth and game theory. However, it has always been recognized that the macroeconomic system, consisting of a large number of nonlinearly coupled subsystems, and governed by the actions of a large number of notoriously unpredictable human agents, could be made amenable to formal mathematical analysis only by introducing highly restrictive simplifications. Thus the relation between the classical mental models and models derived from mathematical analysis has always been rather tenuous.

With the advent of powerful supercomputers, however, many of the problems restricting the application of formal mathematical analysis, such as the pervasive nonlinearities and large number of degrees of freedom, could be overcome. This has motivated a plethora of new approaches. Most of these fall within the general class of multi-agent simulations, referred to variously as agent-based computational economics (ACE, Tesfatsion, 2006), multi-agent systems (MAS, Axtell, 2006), or, in a more general context, evolutionary economics (...), complexity economics (Beinhocker, 2006), post-Walrasian economics (Colander, 2006) or simply system dynamics (Sterman, 2000). Common to all of these approaches, when applied to macroeconomics, is the goal of deriving the characteristic features of macroeconomic systems as "emergent properties" of microeconomic systems governed by the interactions between (typically a large number of) individual agents. The simulations have been successful in explaining many of the interesting and often puzzling features of macroeconomic systems, such as the large volatilities, non-Gaussian statistical fluctuation properties, major unanticipated instabilities and the emergence of complex networks that modify the behaviour of individual agents. However, the bottom-up approach, to the authors' knowledge, has not yet yielded comprehensive macroeconomic models that can be usefully applied for policy advice.

This must be regarded is a serious shortcoming in the context of climate change, since urgent climate policy decisions cannot wait until science has completed the paradigm shift. Accordingly, most integrated assessments of climate change have perforce been carried out using available general equilibrium models. The limitations of these models - in particular, the inability to capture the dynamic technological-change and adaptation processes characterizing the transition from a fossil-based to a carbon-free global economy

- are well known (cf. Barker, 2008). The present paper is an attempt to close the present gap between conceptual bottom-up multi-agent models and top-down macroeconomic models designed for policy analysis through the development of a parametrized multi-actor model.

Our approach, following Weber et al (2005), is a combination of a traditional macroeconomic model, characterized by a standard state vector $\mathbf{x} = (x_j)$ of aggregated economic variables, and a multi-agent description, in which the dynamic evolution is governed by the actions of a small number of representative agents. We refer to these as "actors", however, rather than "agents", as, in contrast to the usual definition of a multi-agent system (Tesfatsion, 2006), our model is not constructed as an ensemble of interacting agents consisting of distinct objects that can represent either human actors or equally well some other, non-animated entity, such as an economic asset. Instead, we distinguish between the macroeconomic state vector $\mathbf{x}$ in the usual aggregated sense, whose components are not assigned to any particular agent, and a number of independent actors that control the evolution of the system through a set of control algorithms $\mathbf{z} = (z_j)$.

The evolution of the system is accordingly described by a set of coupled differential equations

$$\frac{d\mathbf{x}}{dt} = \mathbf{F}(\mathbf{x}, \mathbf{z}) \tag{1}$$

in which the individual control algorithms $z_j(t)$ are functions G_j of the present and past values of the state vector and a set of control variables: $z_j(t) = G_j\{\mathbf{x}(t'),\ \mathbf{z}(t')\},\ t' \leq t$. The control algorithms can represent either the strategy decisions of individual actors (for example, with respect to investments) or the (parametrized) outcome of negotiations between different actors (for example, with respect to wage levels).

In contrast to most multi-agent models, our model is based on only a small number of actors. These are defined in close correspondence to the representative actors widely invoked in the classical economic literature. Our experience is that this is the simplest and most direct way of translating the rich diversity of classical mental models into a simulation environment enabling both a conceptual clarification and a quantitative test of the underlying actor-interaction hypotheses. By circumventing the mathematical hindrances of a formal analytical approach, numerical simulations thereby focus directly on the central economic problem: the identification of the key actors and behavioural patterns that determine the dynamics of the macroeconomic system.

The representative-actor approach is nevertheless often criticized as being unable to capture the complexity of the multi-agent interactions that ultimately determine the emergent dynamics of the macroeconomic system. We accept this criticism, but attempt to overcome the inherent limitations of our system reduction by the time-honored method of parametrization. In state-of-the-art global climate models, interactions on scales smaller than the grid resolution of the numerical model, such as horizontal and vertical transports by sub-synoptic weather systems and small-scale turbulence, are routinely parametrized in terms of the explicitly resolved larger scales. The parametrizations are based on heuristic assumptions regarding the impact of sub-resolution scale processes on the dynamics of the large-scale system, backed up by comparisons with data and high-resolution numerical experiments designed specifically to test the parametrizations. Similarly, in the present case we parametrize the impact of the non-resolved multi-agent interactions by invoking the heuristic concepts of classical macroeconomic theories. Through numerical simulations with the parametrized multi-actor model, the implications of these assumptions can then be investigated in detail and, if necessary, revised. Further parametrization improvements can then again be achieved through comparisons with data and more extensive individual simulations with a larger number of agents.

Faced with the enormous complexity of the real economic system and the unavoidable limitations of data, a reduced model system is best constructed sequentially in the form of a model tree. If the root model at the lowest level of complexity survives a simple test of plausibility, it can be improved through a first set of generalizations, which can be followed by further refinements, until the model tree reaches a limiting level of complexity beyond which it can no longer be justified by the available data. The paper is structured in the following in accordance with this model-tree concept.