Application of System Dynamics to Climate Policy Assessment

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Summary. To provide useful scientific advice to climate policymakers, a paradigm shift in mathematical economics is needed from general equilibrium concepts to agent-based system dynamics. For effective communication, the simulation models should be simple. This can best be achieved by developing models as a hierarchy, progressing from simple to more complex versions. Examples are given of work currently being carried out in the EU project "Global System Dynamics and Policies".

1 Integrated Assessment of Climate Change

Through the persistent efforts of the UN Intergovermental Panel on Climate Change (IPCC), [5], and the mounting observational evidence, the reality of human induced climate change is today no longer seriously disputed. Governments worldwide are committed to implementing effective climate mitigation policies. However, in contrast to the central role of IPCC in bringing the climate problem to the attention of the public and policymakers, the impact of IPCC in developing effective policies to combat climate change has been marginal [3]. This can be largely attributed to the reliance on general equilibrium macroeconomic models in the assessment of climate policies [1]. The general equilibrium approach is unable to capture the basic dynamic processes that must be invoked to transform our present fossil-based socio-economic system to a sustainable carbon-free system. It ignores also other important aspects of globalization that cannot be separated from the problem of global climate change, such as widespread poverty and growing rich-poor inequalities, with associated migration pressures and increases in conflict potential. Similarly excluded are shorter-term processes such as business cycles, recessions and financial instabilities, which although traditionally disregarded in economic growth models, represent important considerations in the unavoidable short-term/long-term trade-off decisions of policymakers.

A central goal of the EU networking project "Global Systems Dynamics and Policies" is to overcome these shortcomings by creating a network of

A.D. Fitt et al. (eds.), *Progress in Industrial Mathematics at ECMI 2008*,
Mathematics in Industry 15, DOI 10.1007/978-3-642-12110-4_27,

researchers cooperating in the development of a new generation of integrated assessment models based on dynamical agent-based models. The standard general equilibrium paradigm of main-stream neo-liberal economics is based on Adam Smith's famous "invisible hand": although the economy is governed by the diverse actions of innumerable competing players, the net outcome is nevertheless an optimal equilibrium state in which the integrated welfare of all players is maximized. In contrast, the multi-agent paradigm views the economy as a nonlinear system with many degrees of freedom that is inherently chaotic, exhibiting random fluctuations and major instabilities (dramatically exemplified by the most recent global financial crisis). An approximately stable growth path can be maintained only if the instabilities are understood and counteracted by appropriate government policies. The inherent dynamics of the socio-economic system and the important role of governments becomes particularly relevant in the context of climate change.

2 The Model Hierarchy MADIAMS

The attainable complexity of a multi-actor model is limited by two natural constraints: the available data, and the difficulty of distinguishing between competing hypotheses if the model contains too many free parameters. To ensure that one remains within these limitations, it is useful to develop models as a model hierarchy, beginning with the simplest model at the lowest level, and successively introducing more processes at higher model levels, until one reaches a limiting level of complexity determined by the data and parameter constraints.

As illustration, we consider a model hierarchy MADIAMS (Multi-Actor Dynamic Integrated Assessment Model System) developed from an earlier single-level model MADIAM [8](see also [2]). The hierarchy is divided into three model levels M1, M2 and M3, each of which can be further sub-divided into sub-levels M1a, M1b, ..., M2a, M2b, ..., M3a, M3b, ... depending on the number and type of sectors, regions, actors, etc. The lowest-level model M1 describes a macroeconomic system governed by the actions of three representative actors: firms, households and banks. Governments are included in the next model level M2, while the highest model level M3 contains also a climate module.

The lowest model level M1 is similar to the core macroeconomic model of the original MADIAM model, but with an important difference: instead of filtering out faster variations in the supply and demand of consumer goods by regarding these as equilibrated with respect to the slower time scales of the mean growth of physical and human capital, all three production outputs, including consumer goods, are treated in M1 as dynamic, non-equilibrated stock variables. This enables a combined investigation of both fast and slow dynamic processes. The model is thereby able to simulate business cycles, recessions and the impact of the counteracting stabilization policies of a central bank. This provides the necessary background for the investigation of the combined impact of long-term climate mitigation measures and short-term monetary and fiscal stabilization policies in the higher model levels M2 and M3.

The inclusion of governments in model level M2 enables the consideration of fiscal policy in addition to monetary policy in stabilizing economic growth, thereby illuminating the different assumptions on actor behavior underlying the long-standing debate between post-Keynsians and monetarists. On longer time scales, various model sub-versions simulate the effects of government climate policies in the form of a carbon price, subsidies, or direct emission regulations. Also included as an option at model level M2 is the role of the media in influencing consumer preferences and public support for climate policies.

The third model level M3, finally, is completed to a fully coupled climate-socio-economic integrated assessment model by incorporating the climate sub-module NICCS (Nonlinear Impulse response coupled Climate-Carbon-cycle System) [4] of the original MADIAM model. NICCS computes the greenhouse gas forcing by CO_2 emissions and the resultant climate change in the form of regionally dependent changes in near-surface temperature and sea-level (represented in both cases by the dominant first empirical orthogonal functions). The back-interaction of the computed climate change on the macroeconomic system is expressed in terms of simple aggregate impact functions. Not considered in the original MADIAM version of the model is the interaction between different economic regions via trade, an important extension that still needs to be implemented.

3 Simulation Examples

The following simulation examples illustrate two basic points: (1) long-standing debates over the role of actor behavior in governing macroeconomic dynamics can be readily quantified and illuminated by translation into simple system-dynamics models, and (2) even for very simple models it is nevertheless often difficult to predict a priori the outcome of assumed actor behavior (although this can normally be readily reconstructed a posteriori). Thus system dynamics should be seen primarily as a learning and expository tool.

Figure 1, from a model M1 simulation, shows two different growth paths resulting from two equally plausible supply strategies of firms in response to changing demands for consumer goods. In simulation S, firms strive to maintain a chosen target level of the goods *stock* by adjusting the investments in the consumer goods production sector at a rate proportional to the deviation of the goods level from the target level. In simulation F, in contrast, the adjustment rate was set proportional to the difference between the *flows* into and out of the goods stock. Simulation S favors short term consumption over profits and long-term growth, while the reverse holds for simulation F. The point here is not which of the two hypotheses is closer to reality (a question that

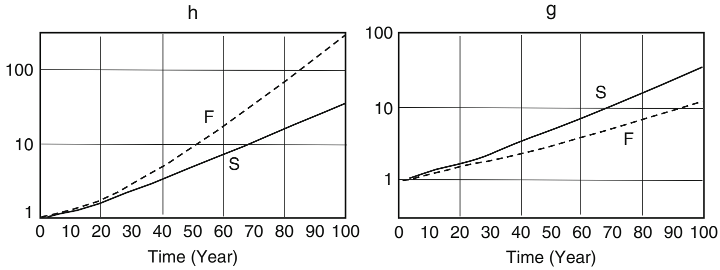

Fig. 1. Growth paths of human capital h (*left panel*) and physical capital k (*right panel*) for two different firm supply strategies S, F, in response to variable consumer goods demand; S (*full curves*): maintainence of target consumer goods stock; F (*dashed curves*): flow balance between consumer goods production and demand

can be decided only by comparisons with data and/or stakeholder interviews) but the signicant differences in growth paths resulting from elementary differences in actor behavior – features that cannot be captured in a traditional actor-independent growth model.

A simple modification of the assumed behaviours of consumers and firms in model M1 gives rise to business cycles (Fig. 2, right panel). The relevant feedback interactions are indicated in the left panel[1]. A decrease in consumption *delcons* (triggered, for example, by a decrease in consumer confidence) induces a slow-down in production *dely*, with an associated reduction in employment by firms, further reducing consumer confidence, and so on. This positive feedback loop alone would result in exponential decay or growth (a recession or boom, depending on the initial conditions). However, the exponential instabilities are converted into a periodic cycle through a stabilizing negative feedback loop (bottom two boxes), representing the willingness of firms to employ more labor once wages *delw* have been sufficiently depressed by the reduced employment level.

There exist, or course, many alternative explanations of business cycles, with numerous associated proposals for their control through appropriate monetary or fiscal policies [6]. The present example underlines the earlier comment that macroeconomic hypotheses can be readily expressed in appropriate system dynamics terms, but the outcome of the model simulations, even for the simple model shown in Fig. 2, is normally strongly dependent on the details of the hypothesized actor behaviour and difficult to forsee. Thus, in the present example, the cycles can have very different amplitudes and periods, or can revert to exponential growth or decay, depending on the values of the feedback coefficients ($fac1, fac2, fac2a, fac3$) characterizing the inter-actor coupling.

[1]The diagram represent a stocks-and-flows sketch generated by the system-dynamics graphic-modeling tool Vensim. Stocks are represented as boxed variables, rates of change by closed-cross symbols, integrations by double arrows, sources and sinks as clouds, and interdependencies by single-arrow connections.

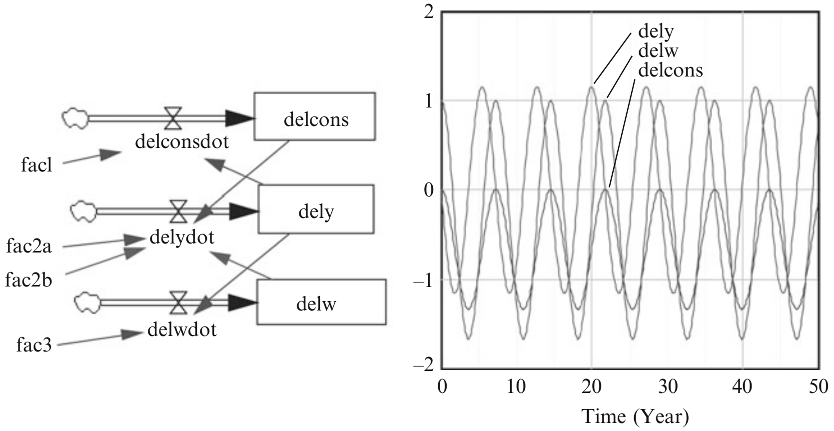

Fig. 2. *Left panel*: Business cycle model of feedbacks between modifications of consumption (delcons), production (dely) and wage levels (delw). *Dashed lines* represent positive feedbacks driving exponential instabilities, dotted lines negative feedbacks leading to oscillations. The variables fac1,. . . , fac3 denote feedback coefficients which control whether the instabilities lead to oscillations or exponential decay or growth. *Right panel*: a resulting oscillation, in normalized units

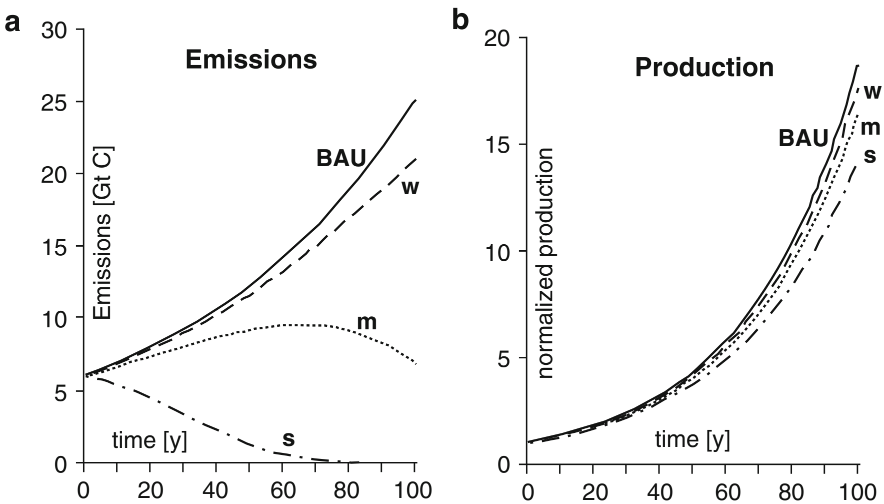

Fig. 3. Impact of various climate mitigation policies (*left*) on economic growth paths (*right*). Significant differences in emissions for weak, medium and strong mitigation policies are seen to have only a minor impact on long term economic growth

The last simulation example, from the third-level model M3 [8] (Fig. 3), illustrates the impact of government climate policies on CO_2 emissions and economic growth. The simulations support the conclusions of the Stern report [7] and other authors that the emissions responsible for global warming can be reduced to acceptable levels at only a minor long-term economic cost of the order of 1% GDP. However, this result is again strongly actor dependent, for example with respect to the assumed response of firms and consumers to government policies.

4 Conclusions

An understanding of the interrelations between climate change and climate change policies requires the application of dynamic models that simulate the behavior of the key socio-economic actors. For an effective communication between scientists and policymakers the models should be as simple as possible. This is dictated also by the inherent uncertainties of human behavior and the unpredictability of future technological developments. Although necessarily simple, simulation models nevertheless represent the only reliable tool for deducing the implications of the assumptions regarding human behavior and future technological developments that are unavoidable in making climate policy decisions.

Acknowledgement

Support for this work through the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under the FET-Open grant agreement GSD, number 221955, is gratefully acknowledged.

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