Hierarchical Asymmetric Cellular Automata for Multiple-scale Modelling of Ecological and Socio-economic Systems

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Abstract

Complex ecological and socio-economic systems often have to be modelled spatially explicitly. Therefore, cellular automata (CA) are a widely used method for such applications. But CA in its original form do not allow to model processes on different time scales and also define a common grid for all processes. This problem can be overcome by an extension of CA called HACA, introduced in this short paper. HACA allow multiple-scale modelling of spatially explicit processes based on a formally defined extension of CA. HACA can be used for practical applications by extending a C++-framework that allows a maximum of freedom to define local dynamics of cell's behaviour.

1. Introduction

Cellular automata (CA) [Toffoli and Margolus, 1987; Wolfram, 1986] are well known and often used in spatially explicit modelling of ecological systems (see e.g. [Thulke et al., 1999]), environmental systems (see e.g. [Berjak and Hearne, 2002]), or socio-economic systems (see e.g. [Wang and Zhang, 2001]). The dynamics of such systems is usually very complex as the underlying processes are based on different scales in time and space (see e.g. [Levin, 1992]). The concept of ordinary CA doesn’t support these multiple-scale models which has been addressed as an open problem e.g. in [Chen et al, 2002]. We propose the modelling technique HACA (hierarchical asymmetric cellular automata) that is based on an extension of cellular automata but introduces a formal distinction of these scales, which leads to well-structured and clearly defined spatially explicit multiple-scale models.

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2. Overview on the modelling framework

In contrast to our discrete event-modelling framework EcoSim [Lorek and Sonnenschein, 1998], HACA models are discrete time specified networks (see [Zeigler, 1976] for the terminology). Our generalisation of CA to hierarchical asymmetric cellular automata (HACA) is characterised as follows:

- The cells of the different spatial scales are hierarchically organised in levels: a cell on one level is defined by an aggregation of cells on the level beyond.
- Each level of cells has its own time scale for state changes in this level. The time scales of different levels are synchronised by a common clock to model temporal dependencies in the dynamics of these levels.
- The state change of cells in one level may depend not only on the cells in this level but also on the state of the neighbouring levels.
- The structure and the dynamics in one level of cells are based on the extensions proposed for asymmetric cellular automata (ACA) defined in [Sonnenschein and Vogel, 2001]: asymmetric shaped cells, irregular neighbourhood relations, and external influences to cells.

Each level of an HACA can be interpreted as an ACA influenced by external effects determined by the state of the cells in the levels above and below. This supports different views of a system on different levels of granularity. So, the hierarchy of cells can also be interpreted as a further dimension of the model.

The state change of a cell $c$ of an automaton (level) $A$ of an HACA at time $t+1$ depends on:

- the state of the static attributes (constants) of $c$,
- the state of the dynamic attributes (variables) of $c$ at time $t$,
- the external influence of environmental values (input parameters) of $A$ at time $t$,
- the observable influence of neighbouring cells of $c$ on the same level at time $t$,
- the state of the cell embedding $c$ on the next level above at time $t$,
- the states of all cells aggregated by $c$ from the next level below at time $t$.

Dynamics of the cell's behaviour, i.e. rules for the state change from time $t$ to $t+1$, can be defined by an arbitrary computable function on these values, in particular by random functions or fuzzy rules. The behaviour function of cells is fixed for each level. Consequently, all cells on one level behave equally and synchronously, as usual for CA. Cells on different levels on the other hand may follow different rules of behaviour.

The modelling framework of HACA has been formally defined in [Sonnenschein and Vogel, 2002] Such a formal definition allows clearly defined semantics of the models, which is - in our opinion - essential for the communication of unambiguous models. For reasons of compact semantics, HACA do not allow to change the cell's topology dynamically. For more complex models of landscape dynamics, e.g. the domain-specific framework SELES [Fall and Fall, 2001] has been proposed.
3. Example

As an example from ecology, consider plants which spread by seeds over long distances but also locally by tillers. The dynamics of the vegetative reproduction happens on a fine-grain scale in time and space, while the production and distribution of seeds takes place on a much coarser scale of space and only for some specific time slices in the year. So, we model this example by a HACA with two levels: Figure 1 illustrates this by two cells of an upper HACA level which each aggregate four cells of a lower level automaton. The cells on the upper level may model the spread of seeds of plants by wind while the lower level may model the vegetative expansion of local patches of plants. Figure 1 shows the interactions of cells in the same level (seed transportation by wind and tiller growth, resp.) as well as between levels (emission of seeds) by arrows.

![Figure 1: HACA with two levels](image)

4. Implementation of HACA

Based on the formal semantics, a C++ programming framework for modelling and simulation with HACA is being implemented, and will be ready for use in a first version by October 2002. In particular, the framework will support the spatial modelling by predefined topologies as well as by user-defined topologies. The integration of vector-based Geographical Information System (GIS) will allow using geometrical data to facilitate the initialisation of the cells’ spatial extent as well as thematic data to initialise their attributes. Visualisation of single levels of HACA will also be made possible by using the tool I-EpiSim [Köster et al., 2002]. The framework will be used to evaluate the concept of HACAs.

Interesting questions for future research can be found in formal analysis of HACA behaviour, visualisation of the dynamic behaviour of HACA in three or rather four dimensions, and in the definition of some standard topologies of HACA for ecological and socio-economic models.
Bibliography


