Simulation methods in the social sciences
1: Models, simulation, and micro simulation

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These slides can also be found at
http://www.uni-koblenz.de/~kgt/SMABS.pdf

Overview

- What is a model? Why do we simulate?
  - Model, theory and simulation
  - Steps in model building
  - Validation
- How do we simulate?
  - A short history of simulation approaches
  - From System Dynamics to agent-based models
- Microanalytical simulation
  - Principles
  - Tools

Ostrom’s idea of three symbol systems

- Computer simulation is a third symbol system — beside natural language and mathematics — in its own right and an alternative to mathematical formalization of social science theories.
- “Any theory that can be expressed in either of the first two symbol systems can also be expressed in the third symbol system.” [Ostrom 1988, 384]
- Thus, there might be verbal theories which cannot be adequately expressed in the second symbol system of mathematics, but can be in the third.

Models as representations of real-world systems

- If the representation is in the form of verbal argumentation,
  - only rather simple target systems may be analyzed, and
  - hidden antecedents may perhaps fail to be detected during the argumentation.
- If the representation is in mathematical form, there are no hidden antecedents, but still we have the case that only simple representations have their mathematical solutions:
  - If we have a complicated function with several parameters we cannot easily tell which consequences parameter changes will have for the behaviour of the function.
- Even simulation may fail in finding all of the possible conclusions — visualization may help here.

Observation and simulation as models of a theory

- Structuralism as defined by Balzer, Moulines and Sneed sees both simulation models and observations as models of a theory.
  - **Theory:** a mathematical structure consisting of (among others) three sets of models: full models, potential models, and partial potential models all of which are defined as lists of terms and functions and (in the case of full models) invariants.
  - **Observations:** intended applications of a theory, a subset of the set of its partial potential models in a sense that we can talk about them in terms which are non-theoretical with respect to a theory **T** in question.

Structuralism, T-theoretical terms …

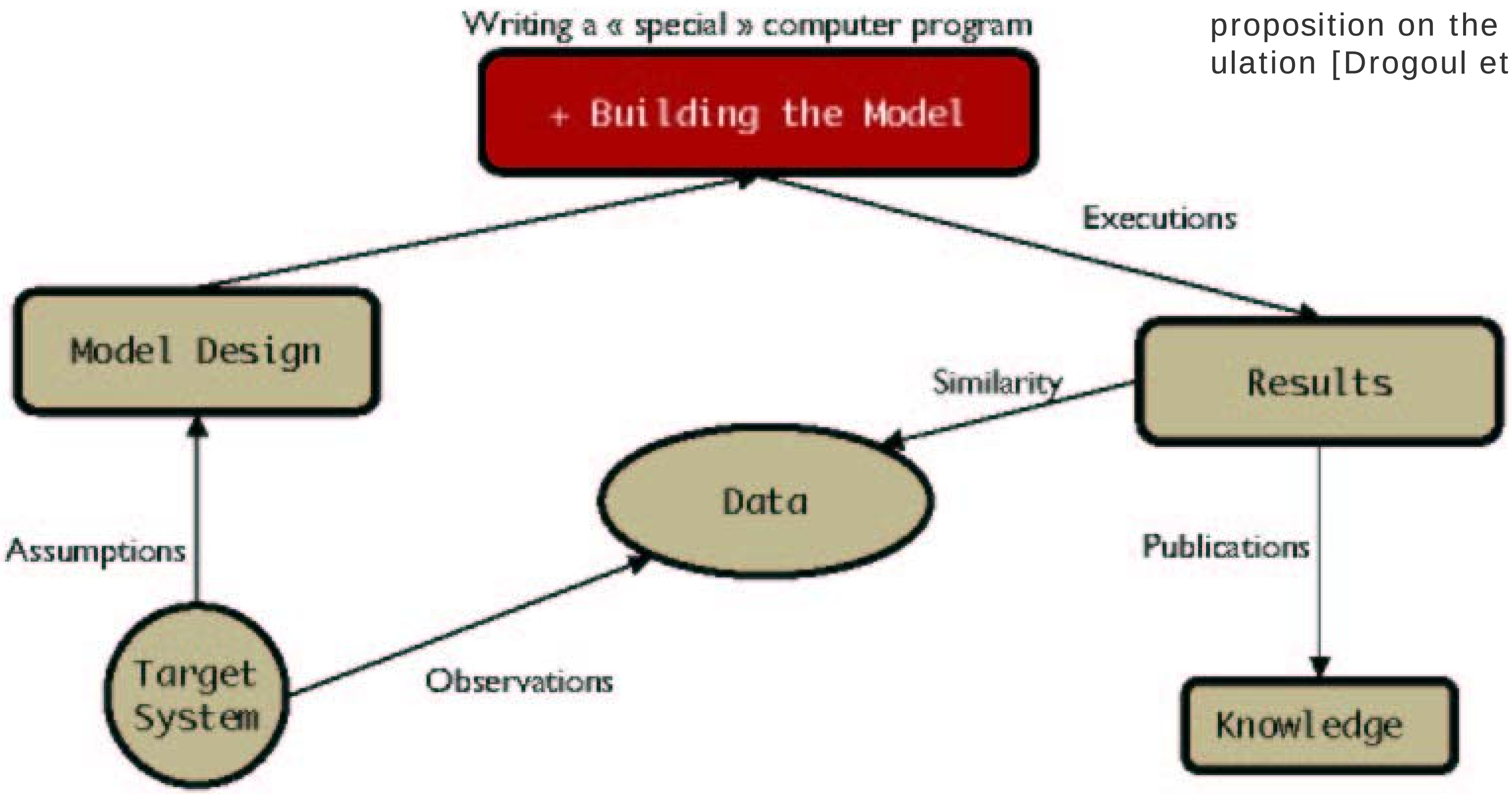
- **T-non-theoretical terms:** those we can use for talking about the target system irrespective of whether the theory is validated or not, as opposed to
- **T-theoretical terms:** those which are only introduced by the theory, "in the sense that their meaning depends on **T**".

  - [Sneed 1979; Balzer et al. 1987]

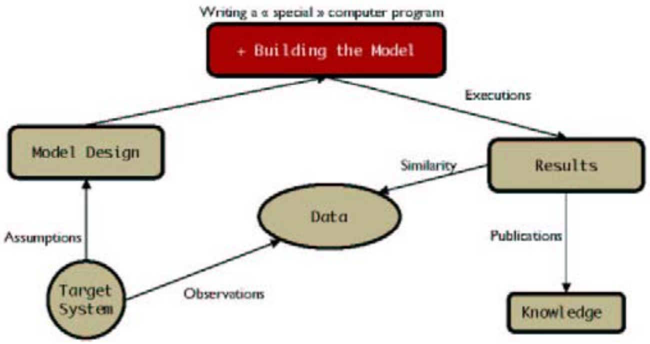
Simulation and theory reconstruction

- A simulation model *"of a theory"* is "analogous to a structuralist reconstruction of this theory", and such reconstructions can easily be translated into simulation models and vice versa, provided the simulation language is object-oriented and functional (in other simulation languages the translation might be less straightforward).
  - [Troitzsch 1994]
- Simulation models would then be translated into full models in so far as they contain both T-non-theoretical terms, T-theoretical terms and, thirdly, the axioms or invariants the theory postulates — whereas observations (or rather: intended applications, to keep to the terminology of structuralism) are only partial potential models listing just the terms which are non-theoretical with respect to this theory.
- Thus, simulation is "richer" than observation.

The role of a model



Drogoul's and his colleagues' interpretation of Gilbert's and Troitzsch's methodological proposition on the role of simulation [Drogoul et al. 2003:5]



The role of a simulation model

- A model is built by abstraction from a target system,
- it is translated into a computer programme
- which can then be run and
- delivers results in the form of simulated data
- which can, and have to, be compared to data gathered
- from the same kind of target systems in the real world from which the model was abstracted.

Theory, simulation, observation and stylised facts

- Observation (as contrasted to just looking around in the world) presupposes at least some primitive form of theory (which tells us which entities and which of its properties to observe and which relations between them to register to find out whether there are some regularities).
- Our assumptions and our observation are not independent from each other.
- In most cases computational (and other) models do not directly start from observation data but from a theory which in turn should build on, but often does not refer explicitly to observation data.
- Instead, we often start from a verbal theory which expresses our (or other authors') belief in how reality works, comparing simulation results with stylised facts instead of observation data.

Steps to simulation

- identify some part of reality as a 'real system' consisting of elements of different 'natural kinds' [Bunge 1977, p. 143] and represent them by model objects,
- identify relations defined on the 'natural kinds' of these elements ('what depends on what?'),
- identify their properties and represent them by model object attributes.
  - These three steps — steps two and three are easily interchangeable — are, by the way, also covered by the static entity-relationship approach to database modelling[Chen 1976] in computer science.

Simulation steps (continued)

- detect — or rather reconstruct — the laws governing that part of reality we are about to model (‘what are the dependences like?’,
- combine our notions of the laws governing reality into a model written down in a formal language (a computer programming language), thus representing real world elements and their properties with (programming language) objects and their attributes, and empirical laws with program invariants;
- run the simulation program.

Views on simulation can be quite different

- Sugarscape:
  - the question “can you explain it?” is interpreted as “can you grow it?”, and
  - “a given macrostructure [is] ‘explained’ by a given microspecification when the latter’s generative sufficiency has been established.”
    - [Epstein and Axtell 1996:177]
- Microanalytical simulation:
  - starts from a large collection of observational data on persons and households and the population as a whole,
  - is initialised with empirical estimates of transition probabilities, age-specific birth and death rates and so on,
  - tens of thousands of software agents are created with data from real world people.
  - And all this aims at predicting something like the age structure or kinship networks of this empirical population in the far future

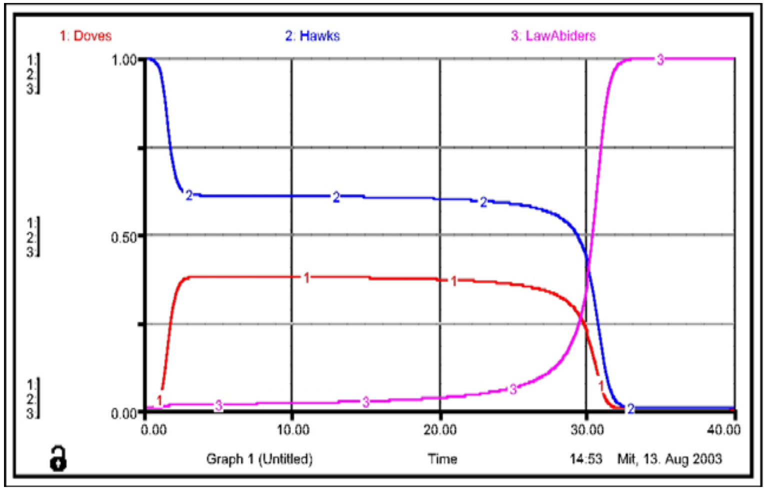
Simulation as a thought experiment

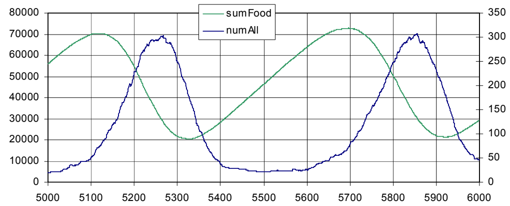
- Simulation may be seen as a thought experiment which is carried out with the help of a machine, but without any direct interface to the target system: We try to answer a question like the following.
- Given our theory about our target system holds (and given our theory is adequately translated into a computer model), how would the target system behave?
- The latter has three different meanings:
  - Which kinds of behaviour can be expected under arbitrarily given parameter combinations and initial conditions?
  - Which kind of behaviour will a given target system (whose parameters and previous states may or may not have been precisely measured) display in the near future?
  - Which state will the target system reach in the near future, again given parameters and previous states which may or may not have been precisely measured?

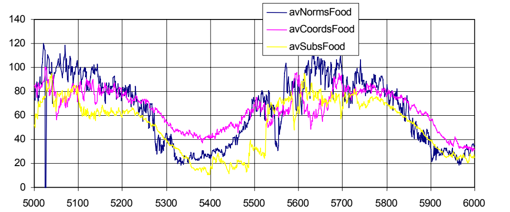
Qualitative prediction

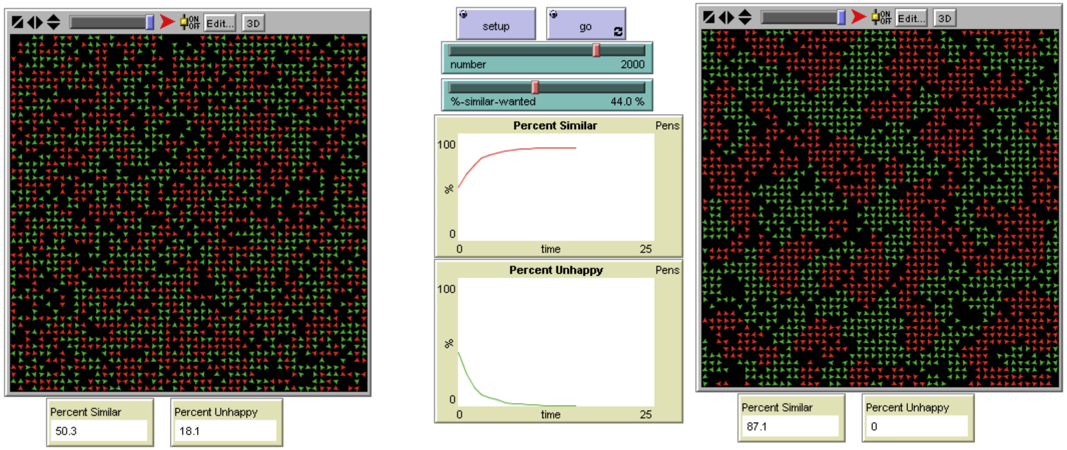
- This is either the prediction
  - which modes of behaviour are possible for a given type of systems or
  - which of several possible modes of behaviour a particular target system will have in the near future,
- provided the theory we have in mind holds for this kind of target systems or for this particular target system.
  - Will this system stabilize or lock in (and in which of several stable states will it do so), will it go into more or less complicated cycles, will it develop chaotic behaviour (such that long-time quantitative predictions are impossible)?
  - Will this system display some emergent structures like stratification, polarization, or clustering?
- Note: Most quantitative social simulation aims only at qualitative prediction. And: Most qualitative prediction is done by quantitative simulation.

Qualitative predictions





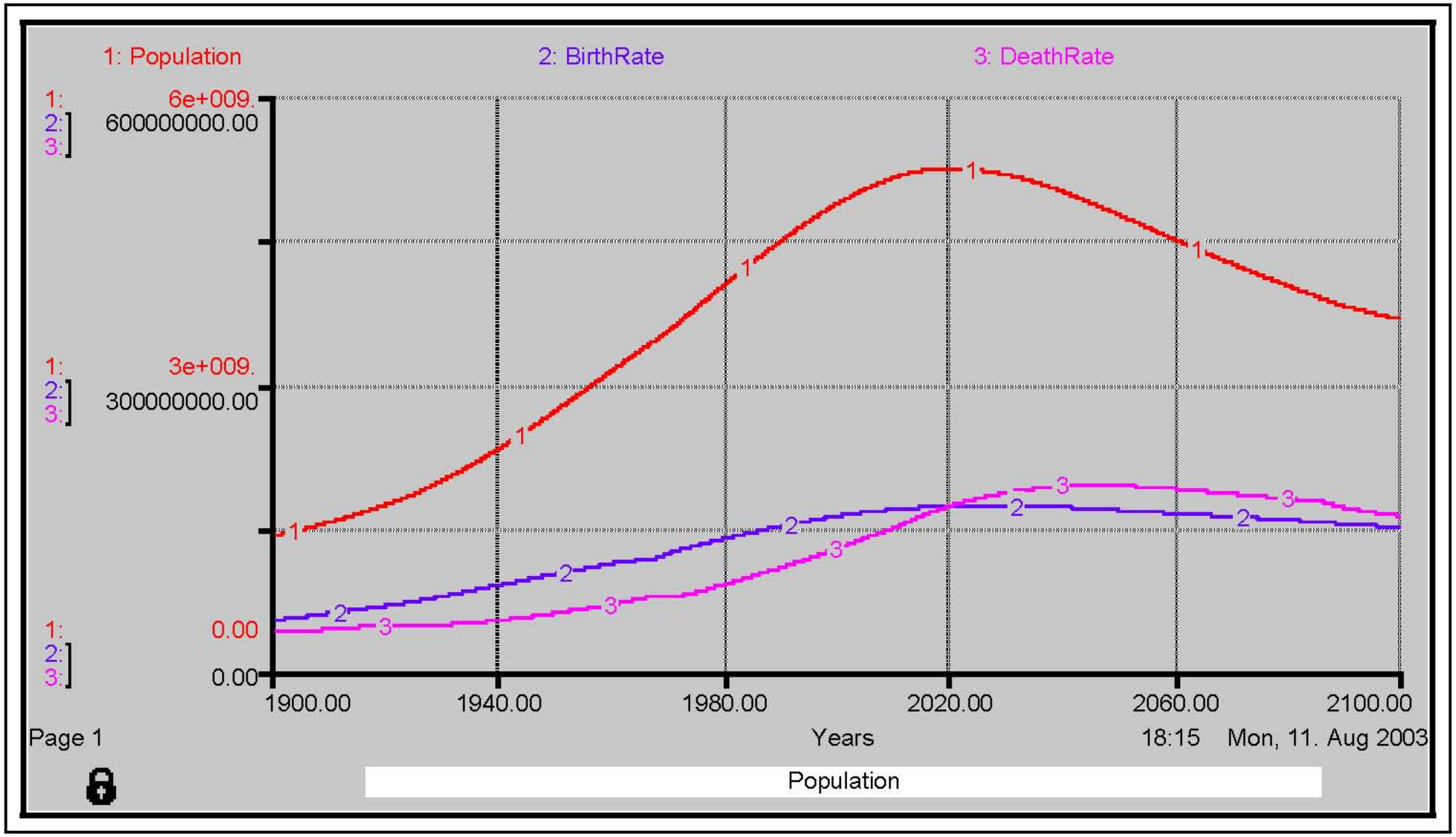




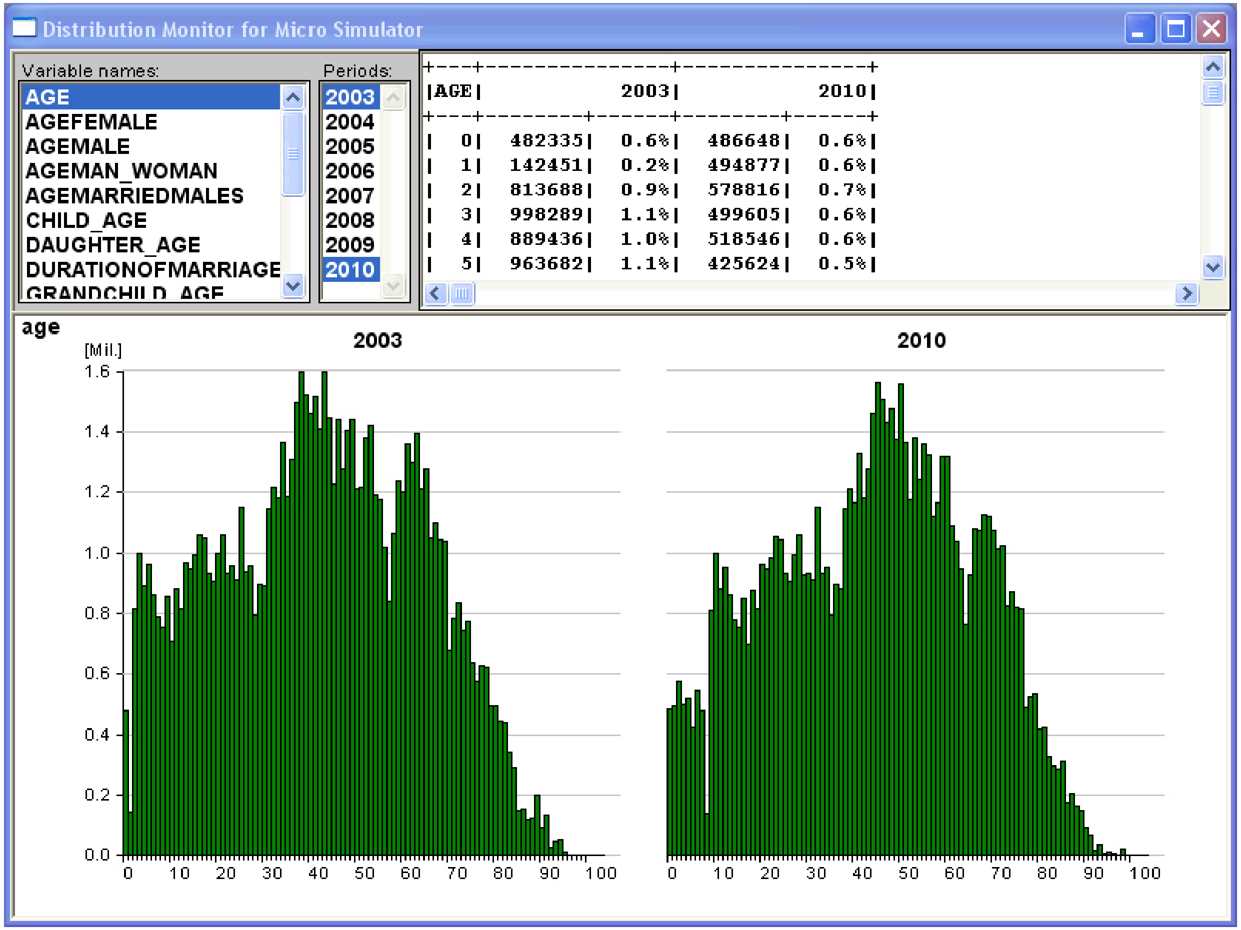
Quantitative prediction

- This is the prediction
  - which state the system will reach after some time, given we know its actual state precisely enough.
  - which state the system will acquire if we change parameters in a certain manner, i.e. if we control parameters to reach a given goal.
- Here it is only possible to calculate trajectories starting from the measured initial state of the target system and using the parameters of the target system (which, too, must have been measured or adequately estimated beforehand).
- Quantitative prediction is the field of microanalytic simulation models which are very often used for prediction in demography and policy making.

A quantitative prediction



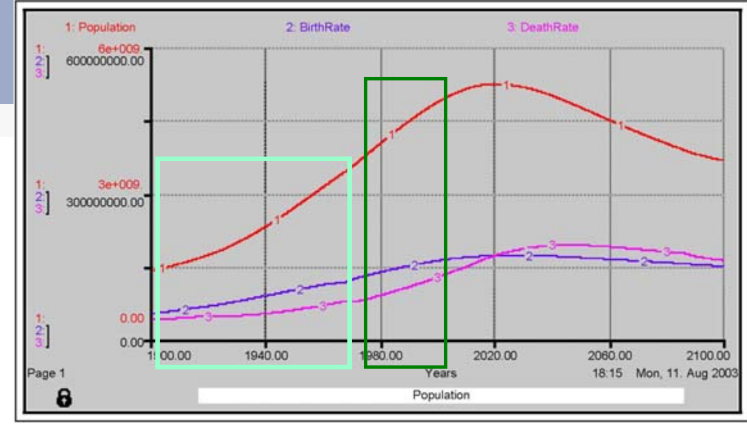
Another quantitative prediction



Quantitative prediction: problems

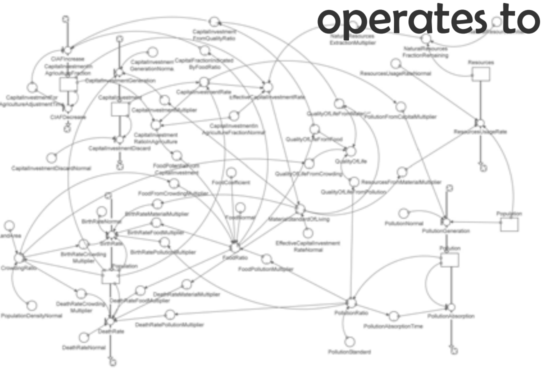
- Two additional problems have to be kept in mind here:
  - If sensitivity analysis has yielded the result that the trajectory of the system depends sensitively on initial conditions and parameters, then quantitative prediction may not be possible at all (which is a very valuable result!).
  - And if the model is stochastic, then only a prediction in probability is possible, i.e. confidence intervals can be estimated from a large number of stochastical simulation runs with constant parameters and initial conditions.

Types of Validity



- With Zeigler we should distinguish between three types of validity and three different stages of model validation (and development):
  - replicative validity: the model matches data *already acquired* from the real system (retrodiction),
  - predictive validity: the model matches data *before* data are acquired from the real system,
  - structural validity: the model "not only reproduces the observed real system behaviour, but truly reflects the way in which the real system operates to produce this behaviour."

– [Zeigler 1976:5]



A first conclusion ...

- It should have become clear by now that social science simulation has at least two very different types of purposes.
  - One of them might be called explanatory — this includes also teaching —, while
  - the other comprises different types of prediction and prescription, including parameter estimation, retrodiction, and decision making.
- In most cases, the explanatory type of simulation — exploring would-be worlds [Casti 1996] — has to be done before the prediction and prescription type of simulation can be accessed.

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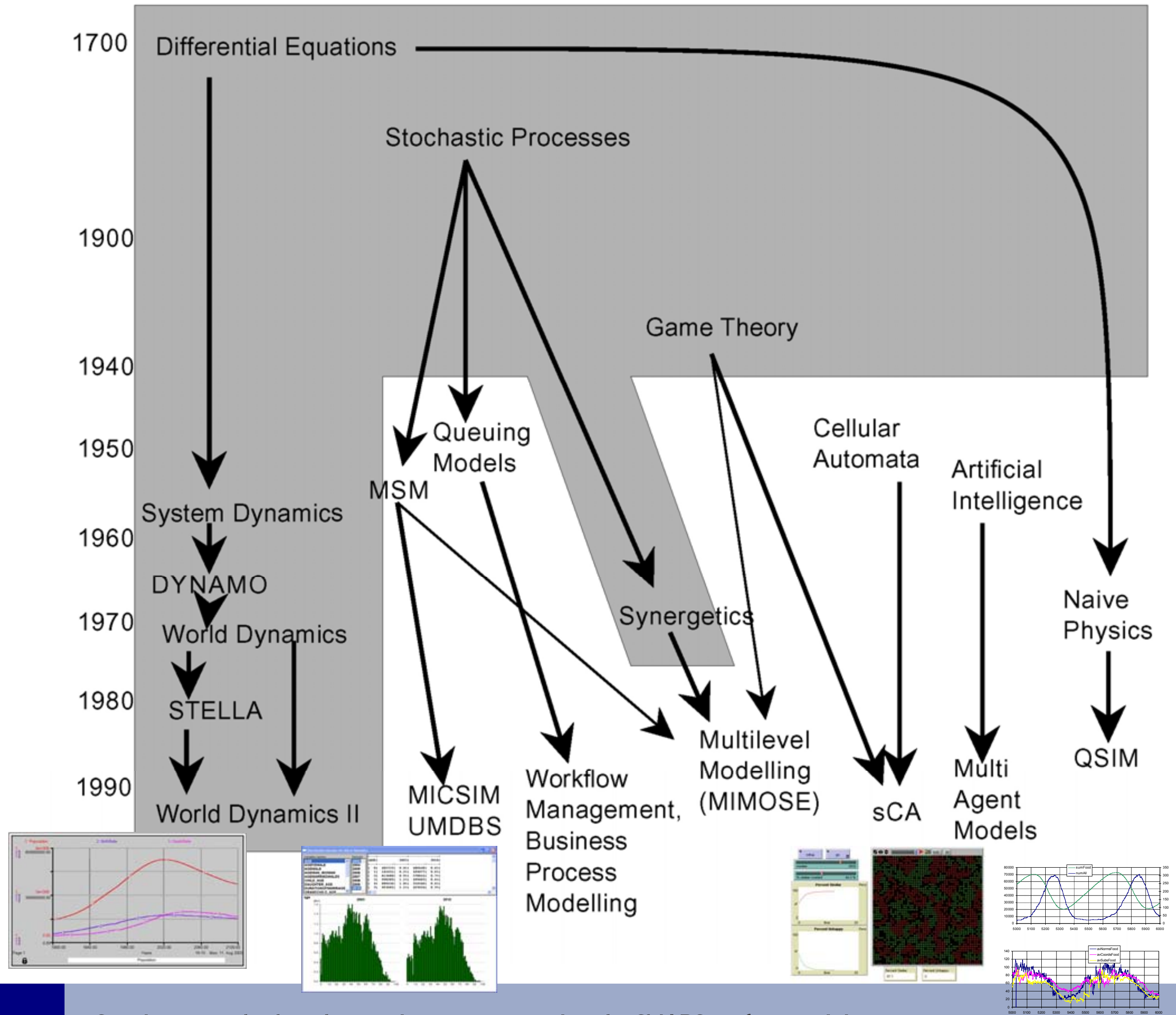
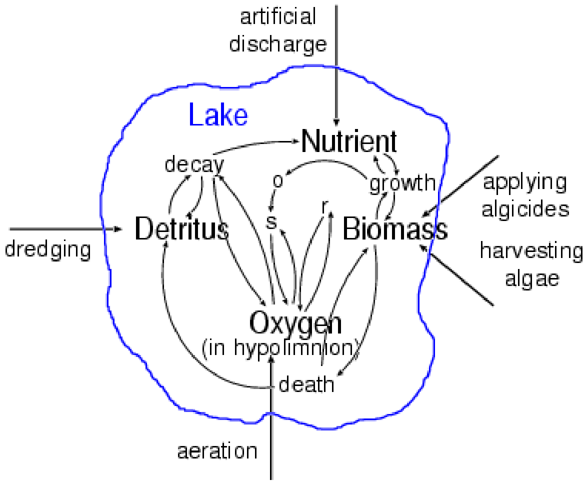
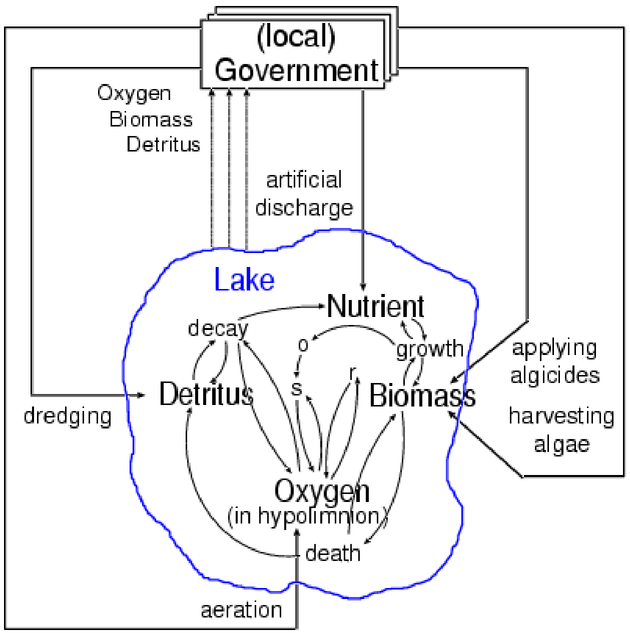
From World Models to Multi-Agent Models



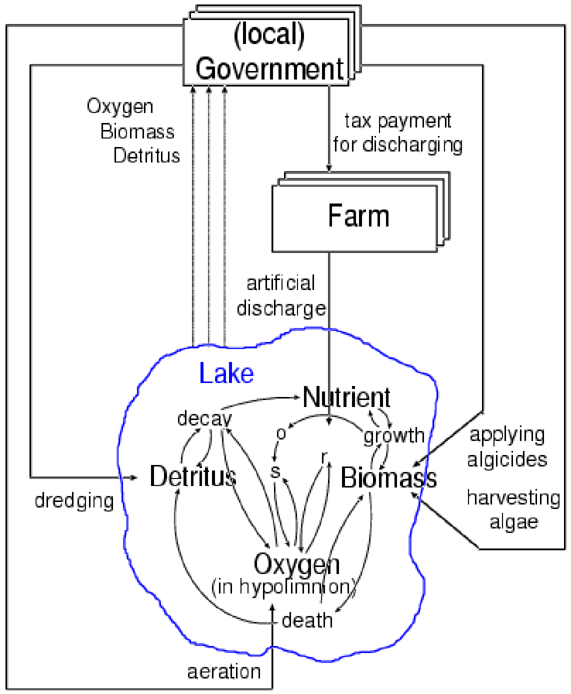
Lake Anderson revisited



Original model, System Dynamics style



Variant 1 with strat-egies applied within the model



Variant 2 with feedbacks on sev-eral levels

Anderson's model: variables

- The behaviour of the lake is described in a number of equations for the following main "level" variables:
  - **nutrient:** the amount of fertiliser and other nutrients in the lake, increased by fertiliser discharge, by respiration and decay of the biomass, and decreased by the growth of the biomass,
  - **biomass:** the amount of algae in the lake, increased by their growth, and decreased by their death rate, by respiration and, possibly, by harvesting algae,
  - **detritus:** the amount of sediment at the bottom of the lake, increased by dying algae, and decreased by detritus decay and, possibly, by the dredging the lake ground,
  - **oxygen:** the concentration of oxygen available to the algae for their metabolism; this level variable is composed of two parts, the epilimnion oxygen concentration (which is considered to be constant because oxygen is always replenished from the air above the lake surface) and the hypolimnion oxygen concentration which is increased by the diffusion of oxygen from the epilimnion into the hypolimnion, and decreased by the oxygen consumption (due both to the respiration of the algae and to the detritus decay process) and, possibly, by artificial aeration.

Anderson‘s model: policies

- Anderson describes five policies to avoid eutrophication of the lake:
  - **applying algicides:** the application of algicides can increase the natural death rate of the algae,
  - **dredging the detritus:** the detritus can be dredged from the ground of the lake, which results in a decrease of nutrient (which otherwise would have been produced from the detritus naturally) and in an increase in the hypolimnial oxygen concentration (because less oxygen is consumed in the detritus process),
  - **aeration of the lake:** oxygen can be bubbled into the water of the lake, thus increasing the hypolimnial oxygen concentration,
  - **harvesting algae:** biomass can be harvested, thus decreasing the biomass (and, in consequence, its oxygen comsumption and its conversion into detritus); the harvested biomass can be used for agricultural purposes,
  - **reducing nutrient (fertilizer) discharge into the lake:** Anderson suggests an artificial discharge of fertiliser into the lake which is ten times the natural discharge of nutrient from outside the lake at the beginning of most of his simulation runs; moreover he suggests a yearly increase of the artificial fertiliser discharge of two per cent if no specific measures are taken.

Extensions

- In the original model, these policies are applied by the experimenter;
- in extended models,
  - one or more simulated "governments" or
  - other agents/agencies under the control (tax reduction, fines, ...) of local authorities
- perform the task to apply strategies to avoid or fight eutrophication.

Theoreticity and the Terms of the Lake Example

- Our model of a lake and its socioeconomic environment was based on observation, but it would still contain a number of terms which can only be used within a theory of, say, ecological consciousness:
  - There would be some link between the state of the lake (its smell or colour) and the state of ecological consciousness of a particular person living near the lake (something like "the worse the water smells, the more am I willing to protect the lake from sewage") and the action this person takes, but
  - we could only observe the direct link between the observable smell of the lake and the observable actions taken, so the two "internal" links (as functions with their numerical coefficients, or as fuzzy rules with their membership functions) would remain theoretical with respect to such a theory —
  - but the computer programme used for this simulation would still be a full model of this theory, because it would contain a function or rule representing this link, and that part of the simulation output which could be compared to empirical observational data would be the partial potential model of the theory.

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The microsimulation approach

- Microanalytic simulation models were first developed to predict demographic processes and their consequences for tax and transfer systems (Orcutt 1986). They consist of two levels at least:
  - the level of individuals or households (or in the rare case of simulating enterprises, the level of enterprises)
  - the aggregate level (e.g. national economy level)
- More sophisticated MSMs distinguish between the individual and the household levels, thus facilitating models in which persons move between households and can found and dissolve new households (e.g. by marriage and divorce).

… what the founding fathers said …

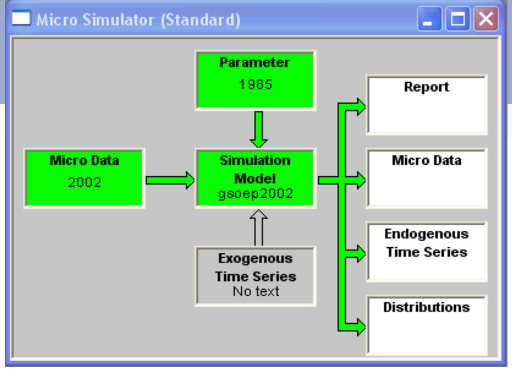
- “. . . in microanalytical modelling, operating characteristics can be used at their appropriate level of aggregation with needed aggregate values of variables being obtained by aggregating microentity variables generated by microentity operating characteristics” [Orcutt 1986, p. 14].

The main advantage of this kind of procedure is that

- “available understanding about the behaviour of entities met in everyday experience can be used … to generate univariate and multivariate distributions” [ibid.].

Types of micro simulation

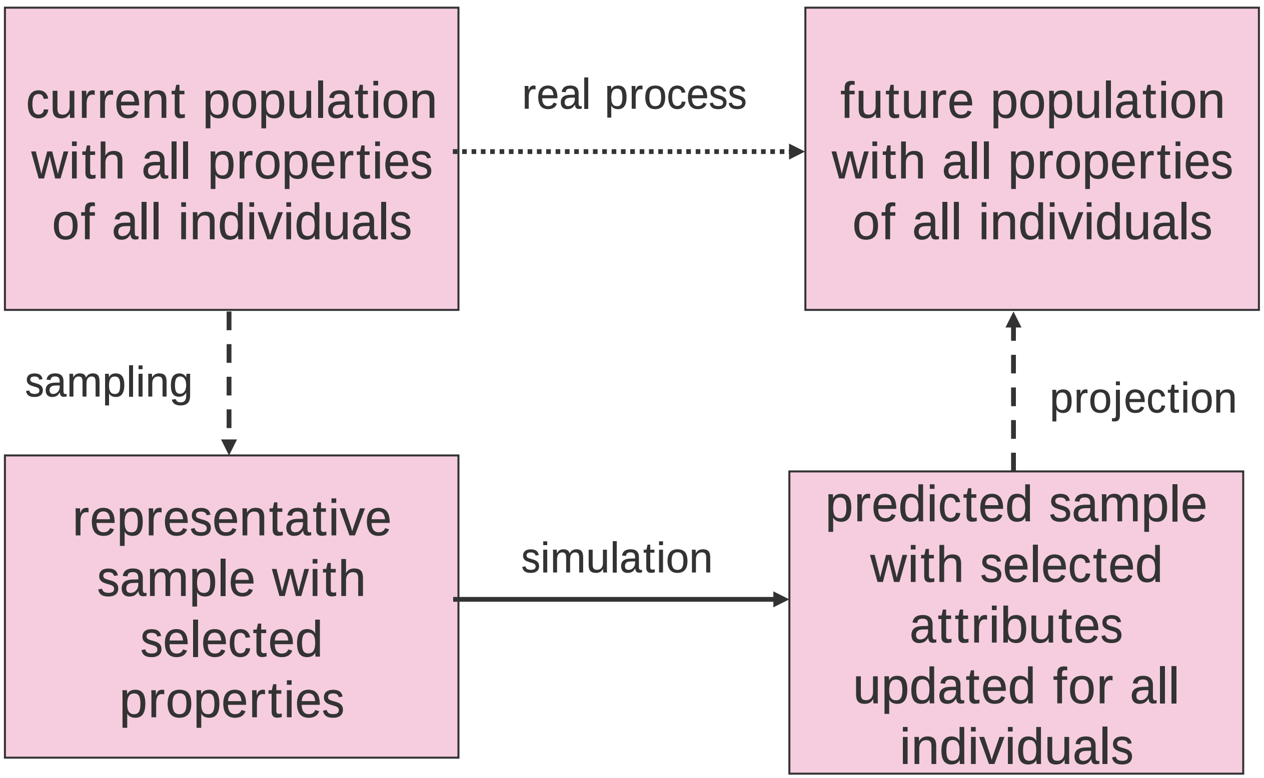
- The classical micro simulation comes in three different types, the first of which is most common, but does not actually describe a stochastic process:
  - "static micro simulation": change of the demographic structure of the model population is performed by reweighting the age class according to external information;
  - "dynamic micro simulation": change of the demographic structure of the model population is performed by ageing the model persons individually (and by having them give birth to new persons, and by having them die) according to life tables;
  - "longitudinal micro simulation": simulation is done on an age cohort and over the whole life of this cohort, thus omitting a population's age structure (but children of the cohort members may still be simulated).



How it proceeds

- All types of micro simulation, in contrast to many other simulation approaches, are data driven instead of concept driven:
  - Starting from data of a population or rather a sample from some population, normally on the nation state level,
  - this approach models the individual behaviour in terms of reproduction, education and employment,
  - simulates this individual behaviour and
  - aggregates it to the population level in order to generate predictions about the future age or employment structure.

How it proceeds



Subprocesses

- To realise the simulation, several subprocesses have to be modelled:
  - demographic processes: ageing, birth, death, marriage, divorce, regional mobility, household formation and dissolution
  - participation in education and employment, employment income
  - social transfers
  - taxes and social security
  - consumption
  - wealth

Data availability

- The initial states of MSMs are read from databases in which individual and/or household and/or enterprise characteristics are stored from an empirical sample.
- It is difficult to get contiguous data for both household and enterprise sectors at the same time,
  - every closed sample of individuals and households will contain persons employed by any number of firms,
    - to arrive at a contiguous sample,
      - one would have to include at least a sample of the other individuals in these firms,
        - » which would then have new employees
        - » who are not in the individual sample and so forth;
  - moreover, this sample of firms will not necessarily be representative even if the household and/or individual sample is.

Panels

- Over the years, it has become easier and easier to get contiguous data for individuals and households, as in most developed countries there are long term panels available (e.g. the German Socio-Economic Panel since 1984).
- In the case of panels, it is, at least in principle, possible to calibrate model parameters and algorithms to panel data.

Birth and death and what they depend upon

- In biology, birth-and-death processes are usually modelled for a homogeneous population.
- For the case of human populations (and many animal populations), this model of the birth-and-death process is much too simple, as …

Birth process

- the probability that a child is born by a woman (within a certain period of time) does not only (and in the case of a modern society: not at all) depend on the current size of the population,
- but rather on (biological and socially attributed) individual and other social properties, such as
  - age and health (as examples of biological and individual properties),
  - education and employment (as examples of socially attributed individual properties) or
  - marital status, kinship and friendship network (as examples for social attributes).

Death process

- The same is true for the probability that a person dies within a certain period of time;
- this probability depends on age, sex, health as well as on education and employment (at least in so far as health partly depends on these) and
- on the state of the society he or she lives in (war and peace, wealth and poverty and so forth).

Search for parameter estimates

- In micro simulation births and deaths will always be simulated with transition probabilities which depend on the named attributes of the model individuals.
- This makes it necessary to collect data about property-dependent birth and death rates and to make assumptions about their future development.

Estimates of the changes of parameters

- As even the short history of the developed nations in the last half century shows,
  - death and (even more so) birth rates are by no means constant on the population level,
  - life tables change from decade to decade (due to the progress in medical treatment), and
  - even age-dependent probabilities of giving birth to first and further children have changed in the past five decades.
- It might still be an open question if this change is only due to a hidden and changing heterogeneity (for instance in the structure of education and employment of women in their second to fifth decades) or due to a long-term process which extends to all subgroups of women (for instance as a consequence of the availability and acceptance of contraceptives at least in Western societies).

Other transitions

- Other demographically relevant properties and transitions must also be taken into account.
  - Beside marriage and divorce we have, for instance, to think of
  - the transition from primary to different types of secondary and tertiary education and
  - the transition from education to employment,
  - the transition between different types and places of employment,
  - migration
  - and so forth.

Programming easy, estimating coefficients difficult!

- For designing simulation models which take all these effects into account, these different types of individual state transitions are not the central problem;
- instead, the problem lies in the availability of empirical transition frequencies which can be taken as estimates of transition probabilities

(if we consider the real-world demographic process as inherently stochastic, perhaps probability is only a surrogate of propensities).

… estimating parameters difficult

- Given we have complex life tables, separately for men and women, migrants and indigenous people, speakers of different languages, adherents of different religions and so forth:
- we can easily program a function or method which yields the (empirically estimated or otherwise assumed) probability that a simulated individual with certain values in all these attributes will die during the current simulation period and then execute this death with the given probability.
- The same applies to a simulated individual representing a real-world woman: its probability of initialising a new simulated individual can also be read from a table of estimated or assumed probabilities (even yielding the probability that twins or triplets, boys or girls are born).

Marriage market

- For marriage and divorce, a marriage market has to be set up bringing together (the simulated representatives of real-world) single men and women and having them select among potential partners, according to assumptions which, too, have to be derived from empirical analysis.
- Designing such a simulated marriage market (and, on the other hand, algorithms for divorce, household dissolution etc.) is a little more complicated than in the case of birth and death,
- but still designing the algorithm is the easier task as compared to getting hold of empirically sound assumptions of coefficients and parameters.
- The same applies to processes in education, employment, unemployment and retiring.

Structure of a typical micro simulation model

- Initialise the individuals from an empirical data base
- Link them together according to their current household structure and to other information on networks (kinship or friendship networks, where the latter information will usually not be available)
- Then, for every simulated period
  - organise the marriage market,
  - and for every simulated individual
    - increase its age,
    - decide whether it dies,
    - decide whether, if it represents a woman, it gives birth to one or more children,
    - decide whether, if it represents a person currently married, it is divorced,
    - decide whether and whom it will marry,
    - decide whether it will move from one household to another or form a new household,
    - decide on transitions in education and employment, respectively
  - and execute all these transitions and changes.
  - Store all the data needed for the analysis and interpretation of the simulated history and perhaps output some intermediate results.
- Analyse and interpret the collected data, aggregate them, calculate distributions etc.

A pessimistic view

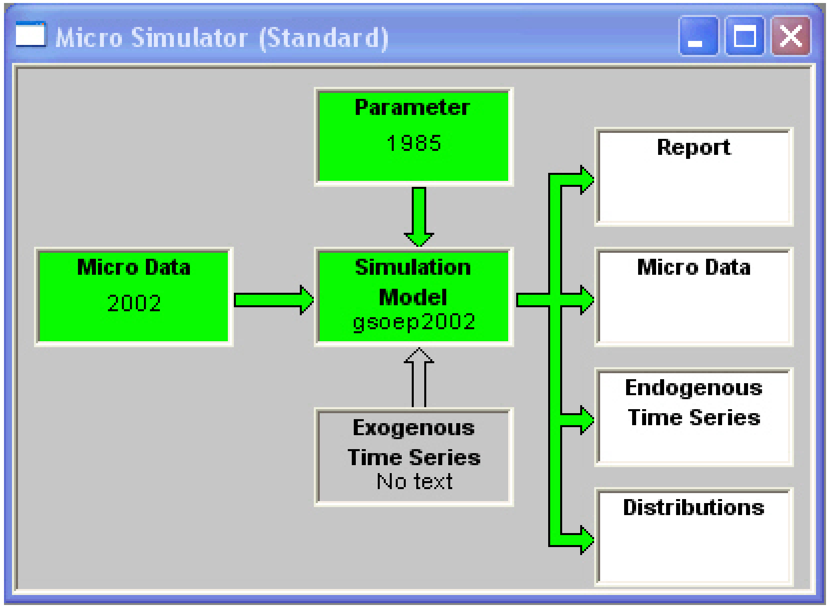
- What such a micro analytical simulation model yields is in a way prediction, but not in the strict sense.
- It is the outcome of one realisation of a stochastic process whose parameters are not exactly known but estimated on the base of more or less reliable empirical data.
- The distribution of the outcome of this stochastic process can only be estimated (as it were, on a higher level of estimation) if a large number of parallel runs of the same model was run; then confidence intervals can be estimated on a Monte Carlo base.
- After this time-consuming procedure we arrive at an estimate of the distribution of, e.g., the age distribution among women ten years from now, or of the distribution of the proportion of people over 65 with living daughters (to nurse them in case of sickness) — but only for the one set of parameters with which we initialised our simulation model earlier on, and not much is then known about the sensitivity, namely the dependence of the distribution of the outcomes of the stochastic process on slight changes on one or several of the large number of input parameters.

… and the optimistic view

- Results of micro analytical simulation models have their value as they show possible paths into the future,
- and Monte Carlo simulations of this type even show the reliability of the predictions, while multiple runs of similarly parameterised models give a first glance at the validity of the model:
- if there is no sensitive dependence on initial conditions then the problem of estimating parameters is not a hard one.
- And if we happen to have a long panel or a series of cross-sections then we can validate our model in comparing results of simulations of past periods with the empirical data of the same period.

UMDBS as one tool for micro simulation

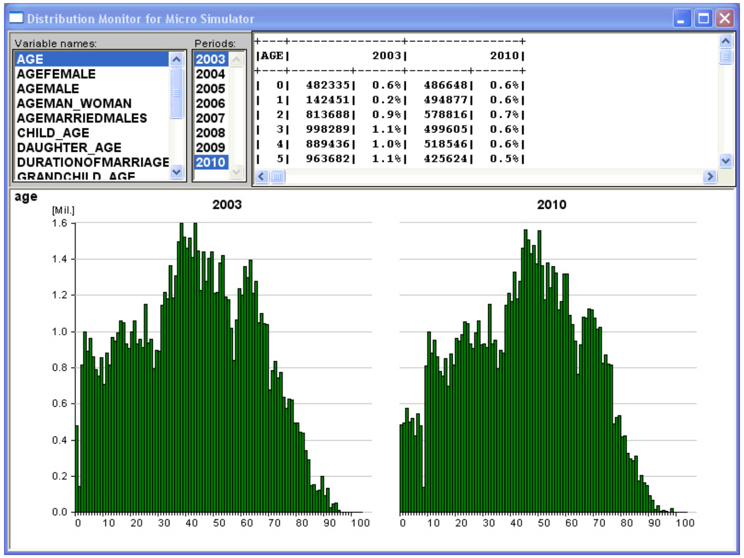
- micro data base
- model
- parameters / coefficients (life tables ...)

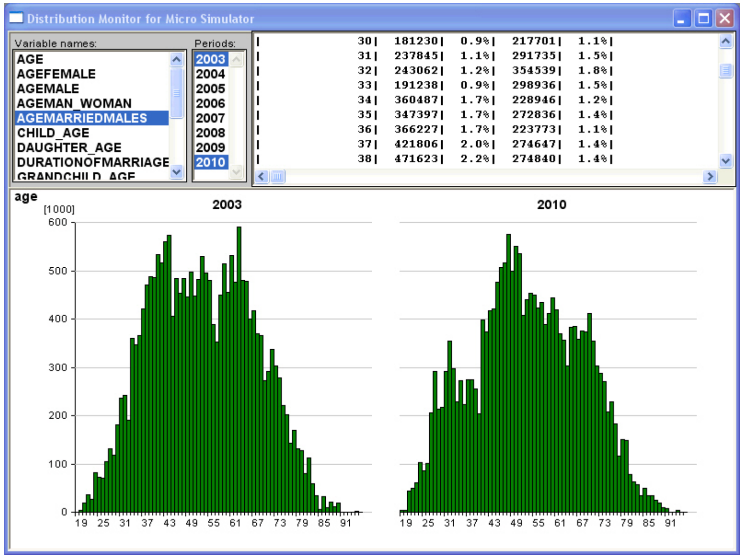


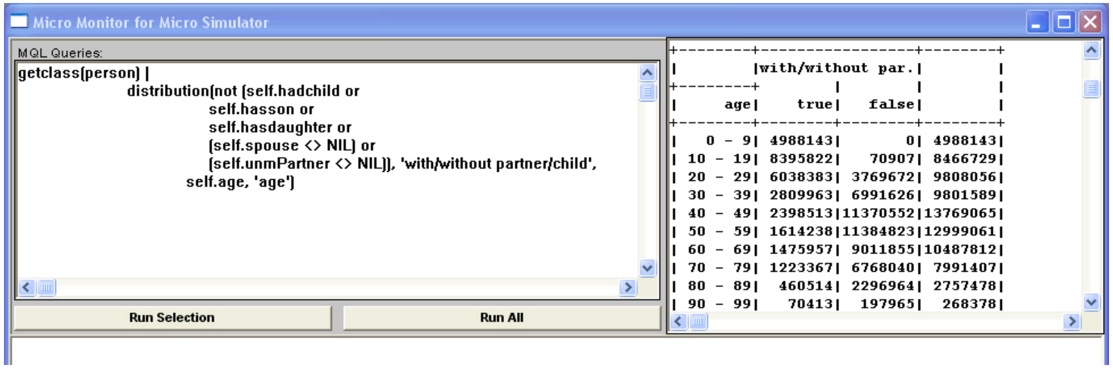
Universal Micro DataBase System UMDBS (Windows) [Sauerbier 2000, `http://www.fh-friedberg.de/sauerbier/umdbs`]

Output

- tables
- graphs
- distributions (one- and two-dimensional)
- queries





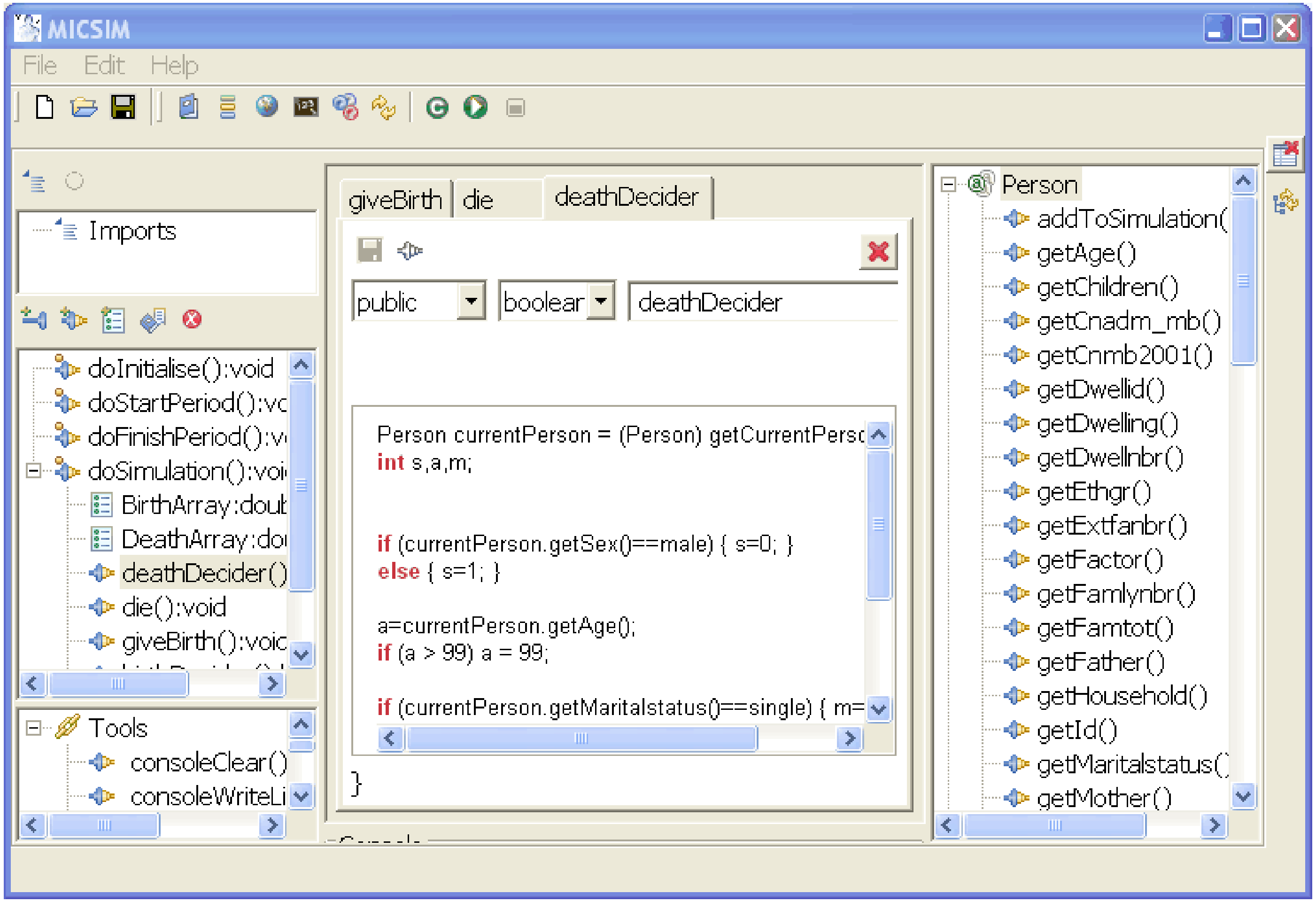


MicSim as an extended approach

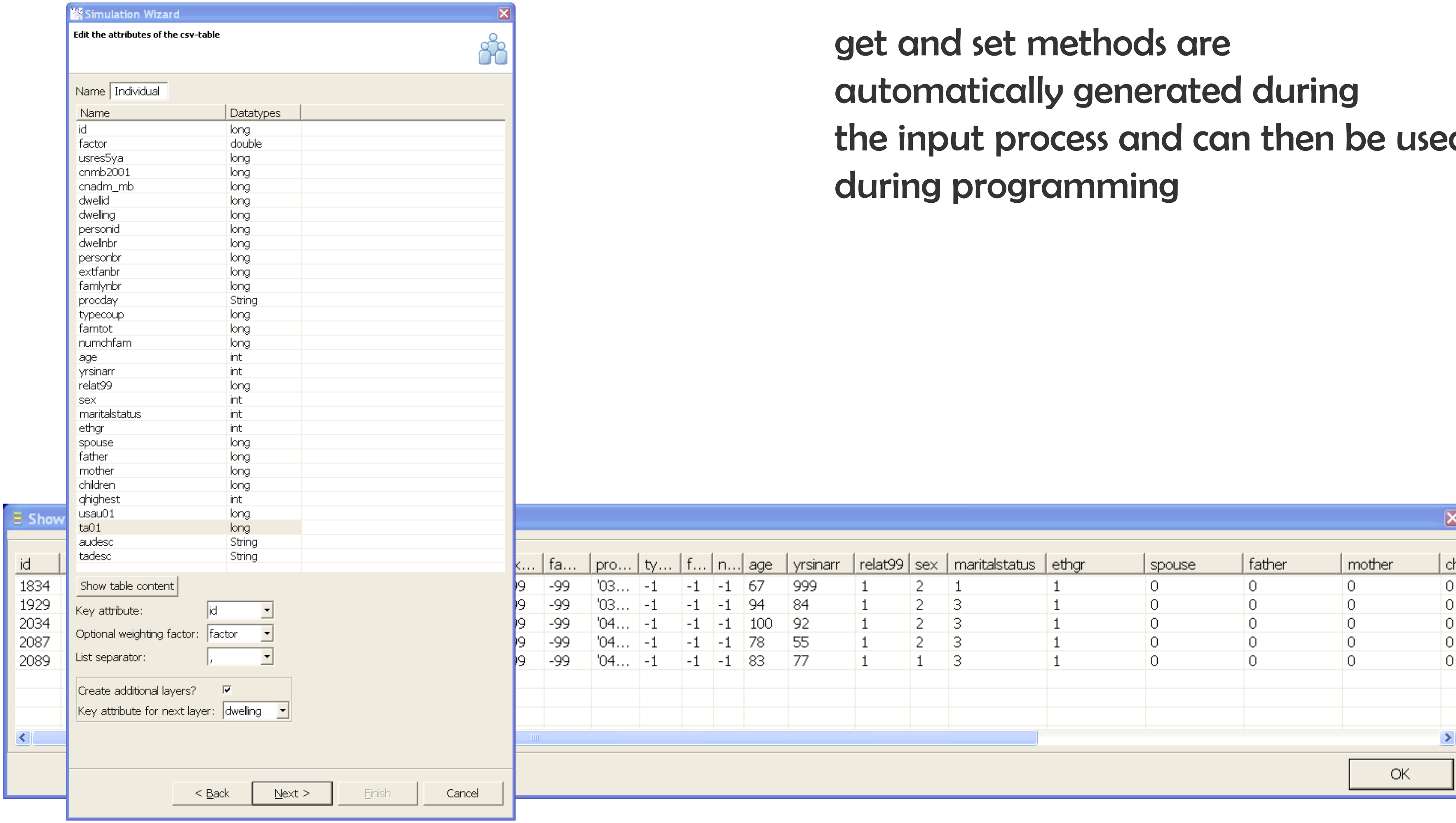
- JAVA based, thus extensible by every (skilled) user
- Facilities for data input (int, float, string, list)
- Multi-layer perspective (person, household, ..., region, ..)
- Immigration possible

still under development

MicSim: JAVA based



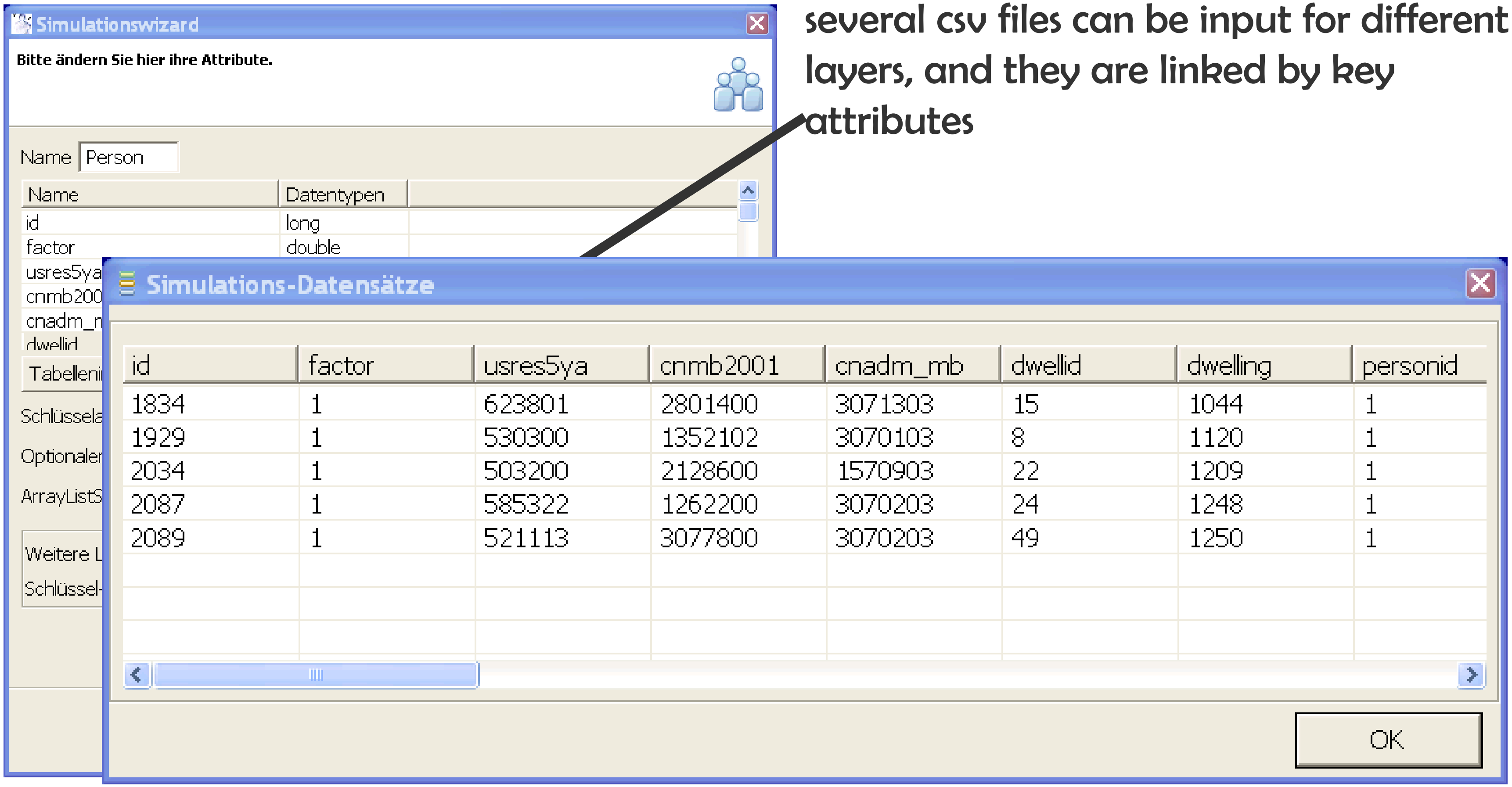
MicSim: Input facilities



get and set methods are automatically generated during the input process and can then be used during programming

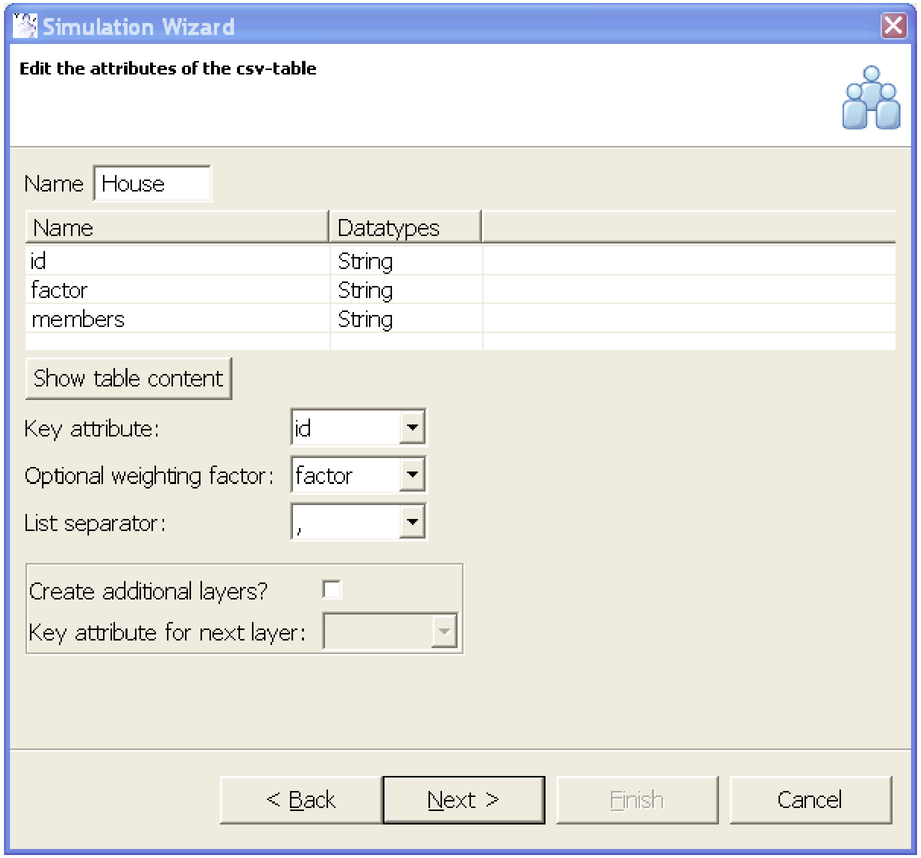
MicSim: Input facilities

several csv files can be input for different layers, and they are linked by key attributes

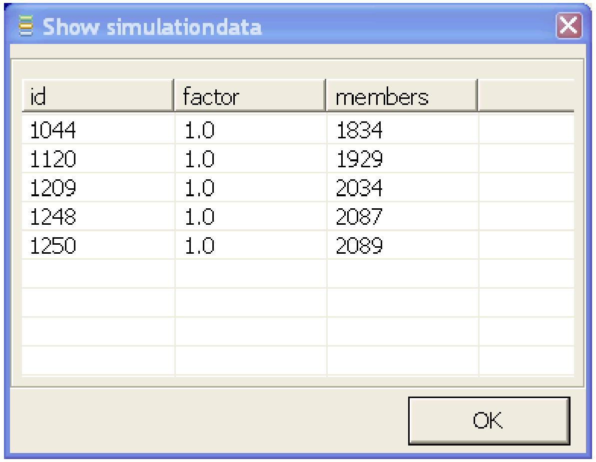


id	factor	usres5ya	cnmb2001	cnadm_mb	dwellid	dwelling	personid
1834	1	623801	2801400	3071303	15	1044	1
1929	1	530300	1352102	3070103	8	1120	1
2034	1	503200	2128600	1570903	22	1209	1
2087	1	585322	1262200	3070203	24	1248	1
2089	1	521113	3077800	3070203	49	1250	1

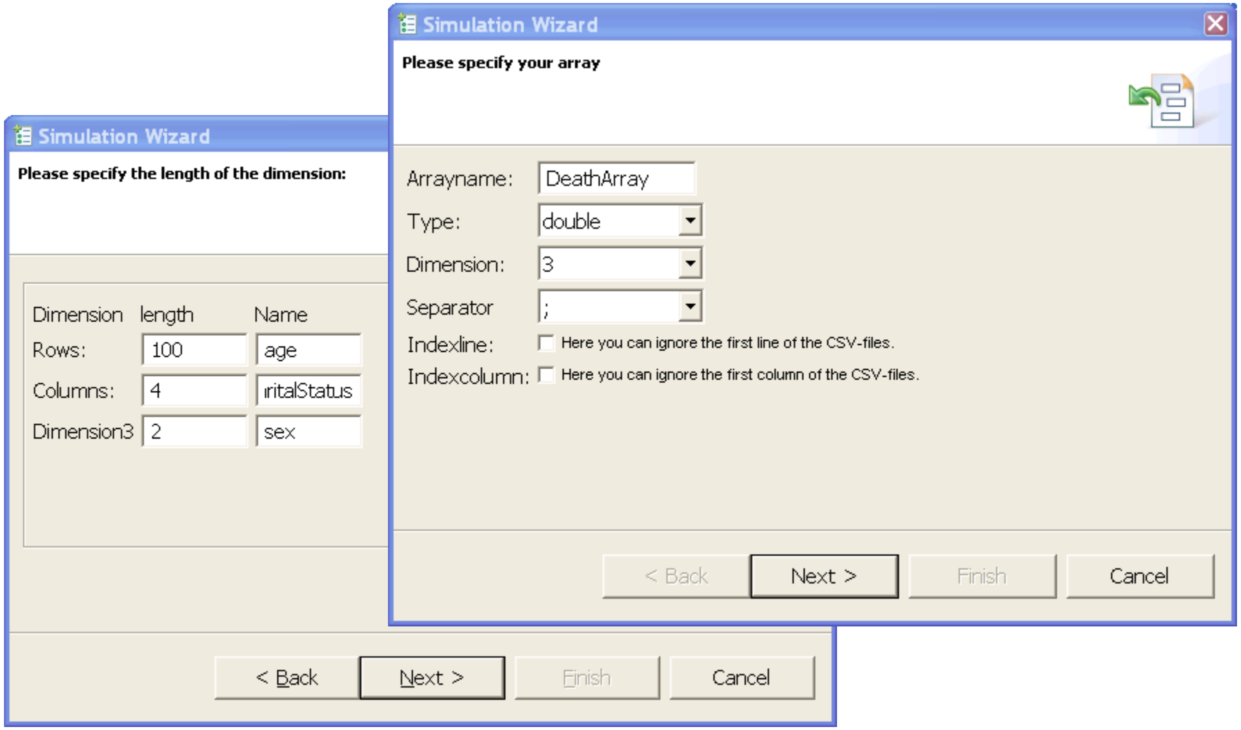
MicSim: Input facilities (second layer)



- preview can be used to find out the appropriate data types

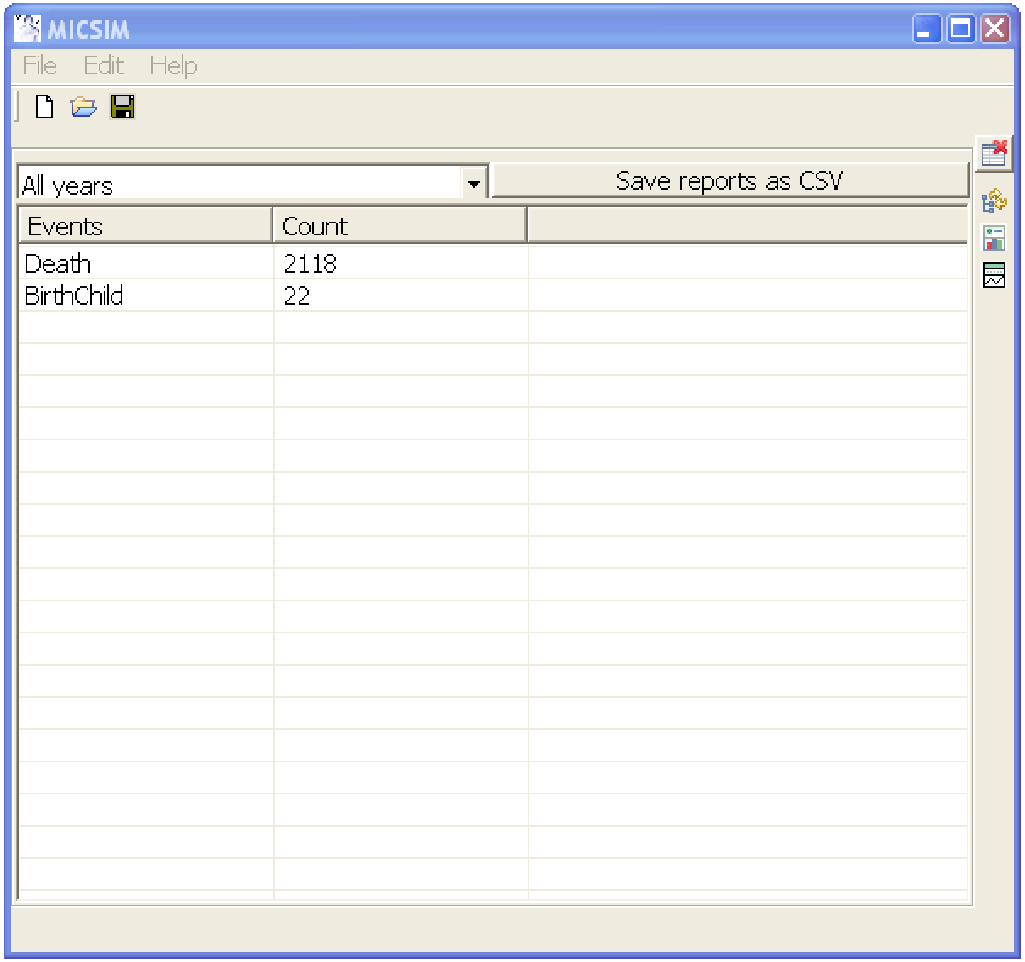


MicSim: Input facilities (parameter arrays)



- parameter arrays of arbitrarily many dimensions can be input from a series of two-dimensional csv files

MicSim: Output facilities (report of events)



- all events which were collected are now written into a report

MicSim: Output facilities

- in an easy to use database interface

Show/Search Datasets

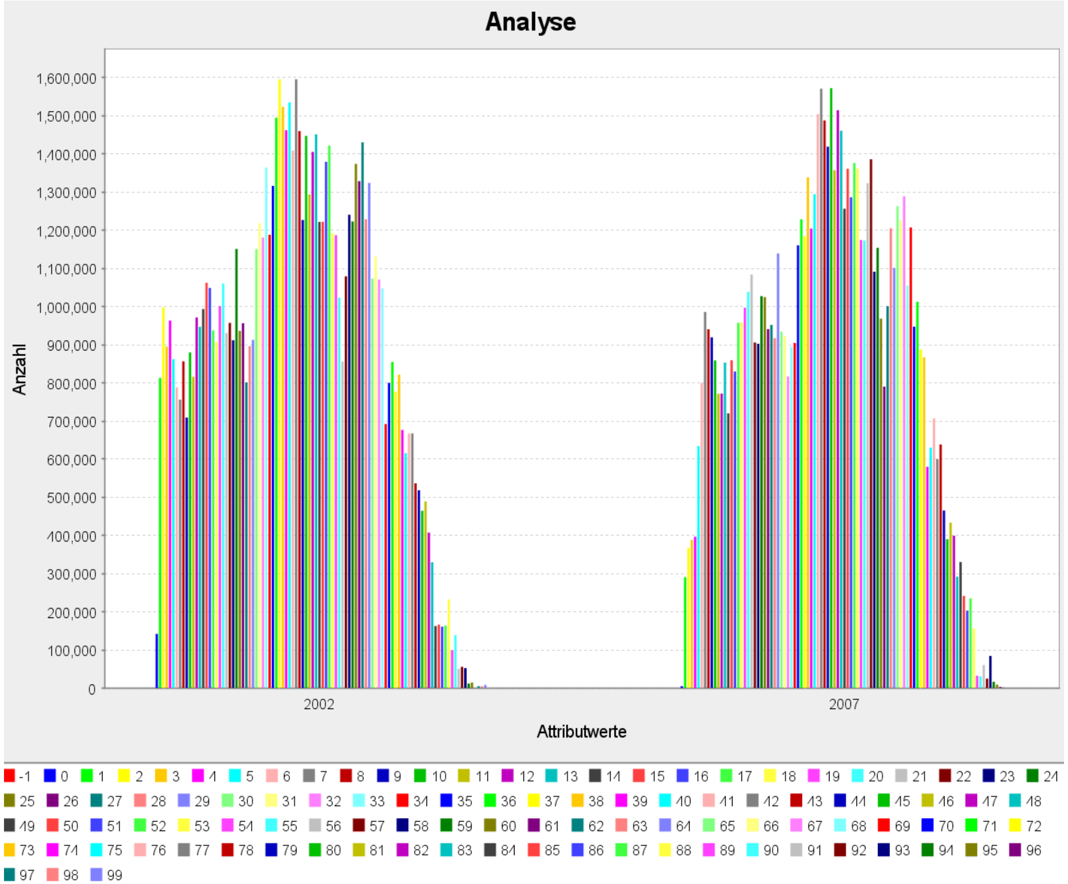
Layer: Person | Year: 2001 | Attributefield: dwelling | Operator: = | Search/Comparative Valu: 29893

id	factor	usres5ya	cnmb2001	cnadm_...	dwellid	dwelling	personid	dwellnbr	personbr
50726	30.89983	600832	1528300	1690504	54	29893	1	29893	0
50727	21.75552	600832	1528300	1690504	54	29893	2	29893	0

2 matches found

Search | Cancel

MicSim: Analytical output



- histograms and age pyramids, weighted and unweighted, for several years at a time

Another example: Co-ordination and sustainability

- Agents who move in a world much like Sugarscape [Epstein/Axtell 1996], feed there, reproduce and perhaps communicate.
- Some agents act as co-ordinators for others: co-ordinators and subordinates co-operate, informing each other about resources.

Example continued ...

- Co-ordinators gather information about available resources from subordinates, forward it as hints to other subordinates and receive a contribution from successful subordinates.
- Resourcs grow on fields, spread to neighbouring fields, and are consumed.

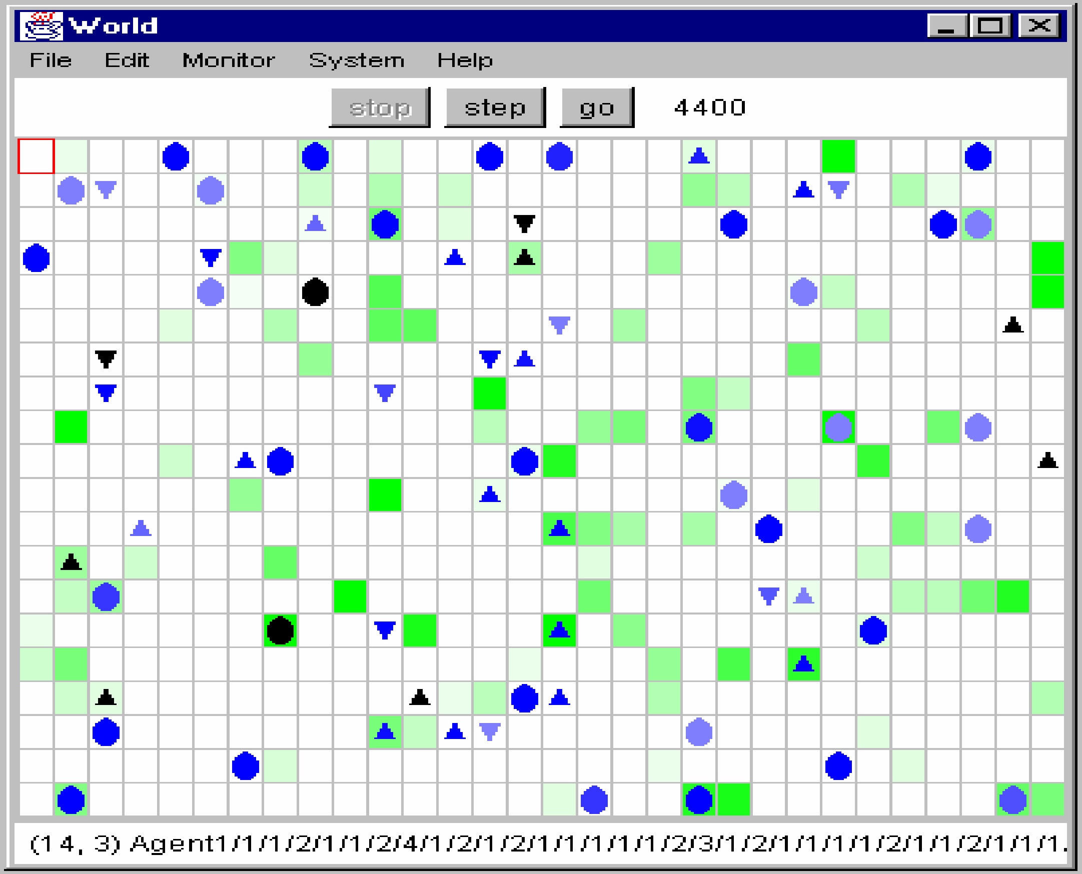
Example continued ...

- If a field is exhausted by harvesting, new crops can grow if seed is spread on it.
- An agent can harvest all or part of the crop in the field (the latter acts in a sustainability mode).
- The simulation programme allows for numerous parameter changes.

Result

- One of the simulation results is that an agent society with co-ordination is more likely to achieve sustainability than a society with isolated agents.

The model



Circles and triangles: agents

▲ : co-ordinators

▼ : subordinates

● : independent agents

colour shade of agents:

degree of saturation

black: dead

colour shade of fields:

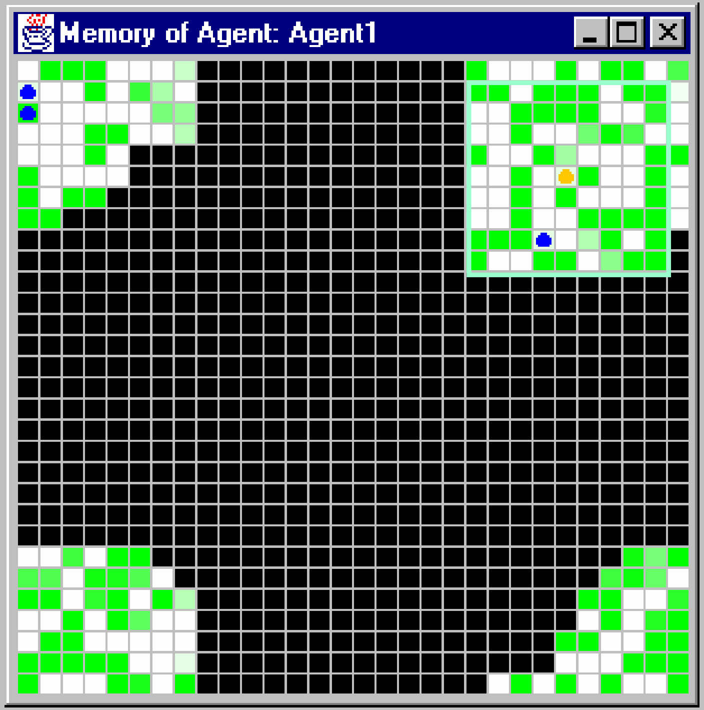
amount of resources

Agents can …

… feed on their individual supply,

… die (either from hunger or from old age),

… recognise the state of neighbouring cells (resources, agents)



and store it in their memories,

… estimate the results of possible actions,

… decide which to apply,

and finally

… act.

Needs and actions

actions	needs				
	survival	wealth	breeding	influence	curiosity
gather	X	X	D	D	D
move	X	X	D	D	X
breed	X	X	X	D	D
start co-ordinating	X	X	D	X	X
end co-ordinating	X	X	D	X	X
subordinate	X	X	D	D	D
unsubordinate	X	X	D	D	D
rest	D	D	D	D	D

Decision making

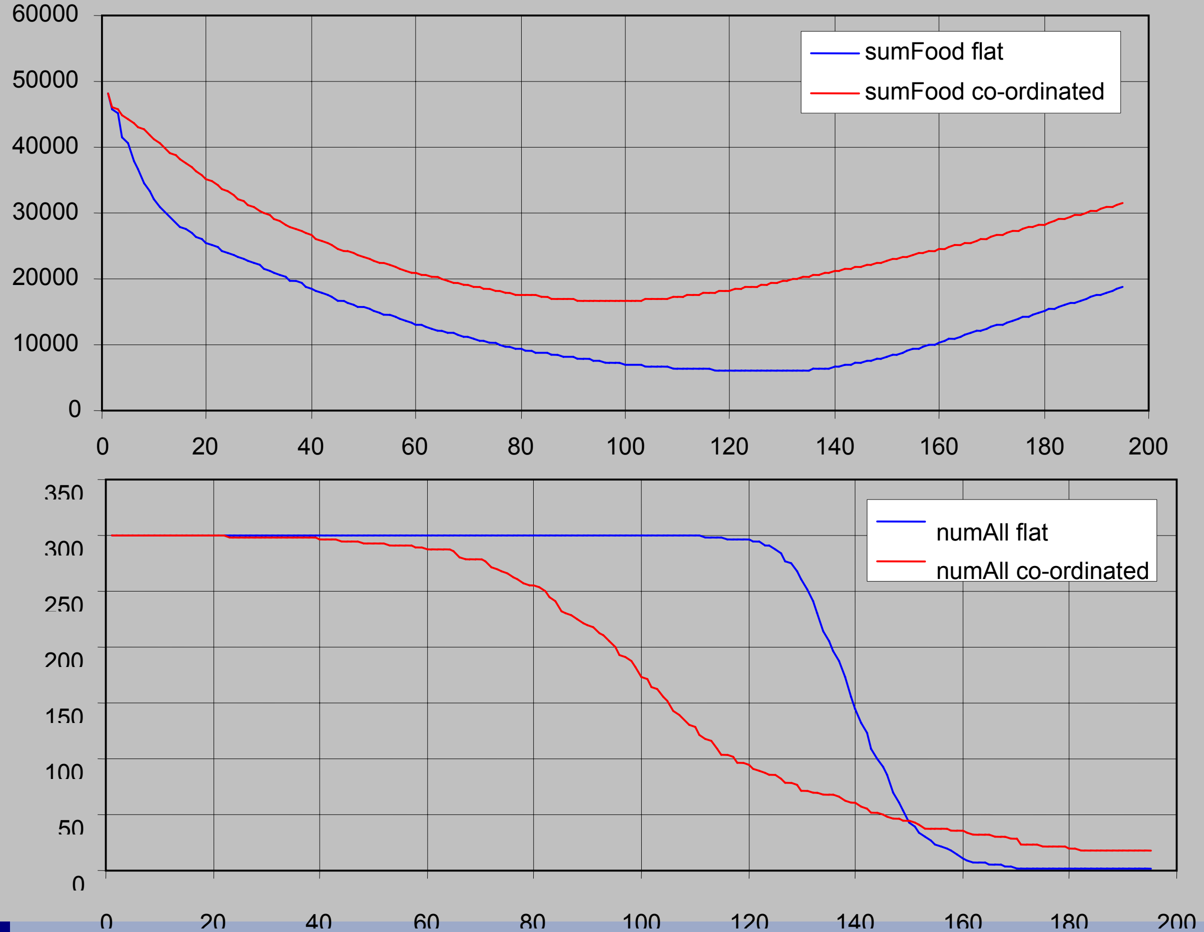
		weight	actions			sum
	needs	α_j	i = 1	i = 2	i = 3	
			D	E	F	D..F
1	j = 1	0.7	0.4	0.6	0.8	
2	j = 2	0.3	0.9	0.6	0.3	
3	$\sum_j \alpha_j sat_{ij}$		0.55	0.60	0.65	
4	$\sum_j \alpha_j sat_{ij} - \min_i \sum_i \alpha_j sat_{ij}$		0.00	0.05	0.10	0.15
5	P(i)		0.00	0.333	0.666	1.00

Actions are taken with a certain probability which depends on the degree to which an action satisfies a need and the weights of the needs for a particular agent.

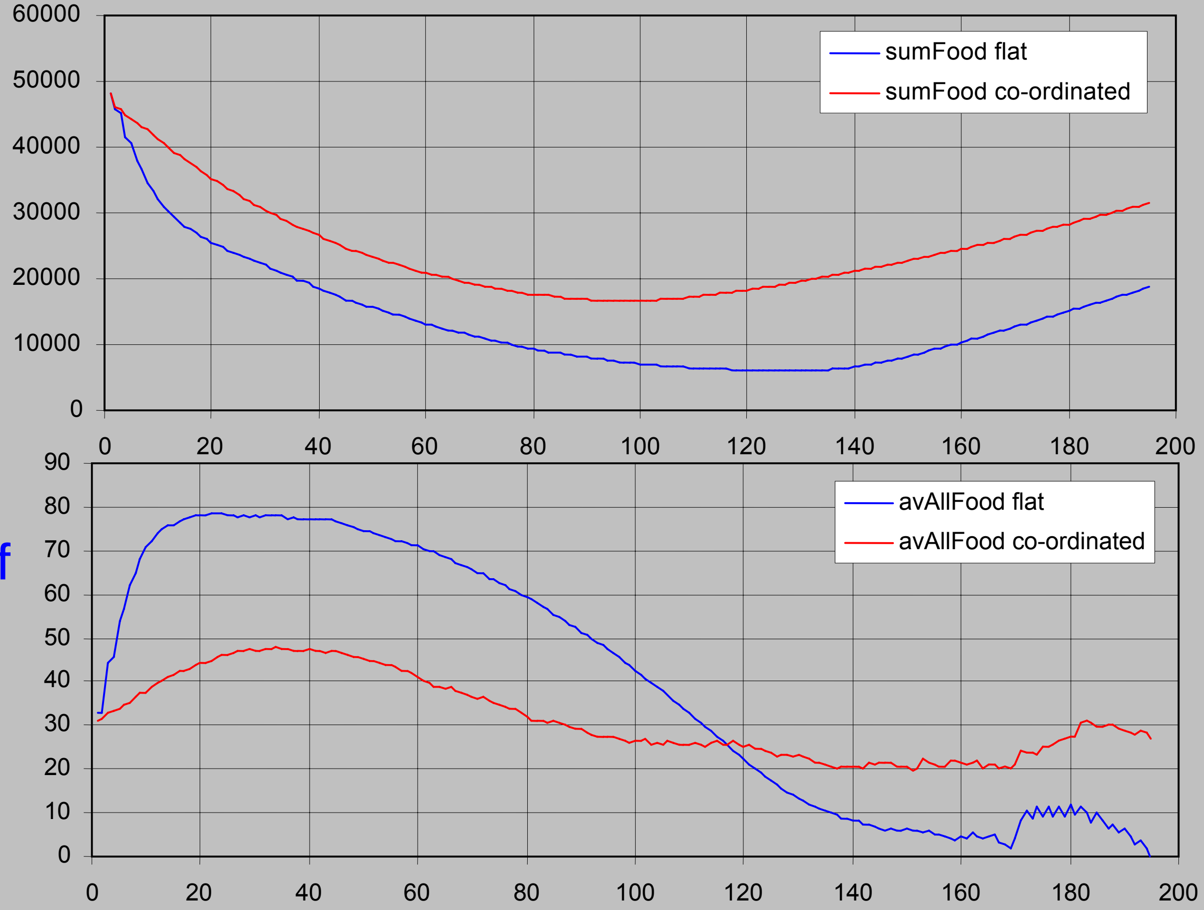
Simulation results

- Populations of isolated agents die out soon,
- those with co-ordinators and subordinates survive for a long time,
- and we find Lotka-Volterra cycles.

A society with co-ordinators survives for a longer time,



... the population with isolated agents dies out.



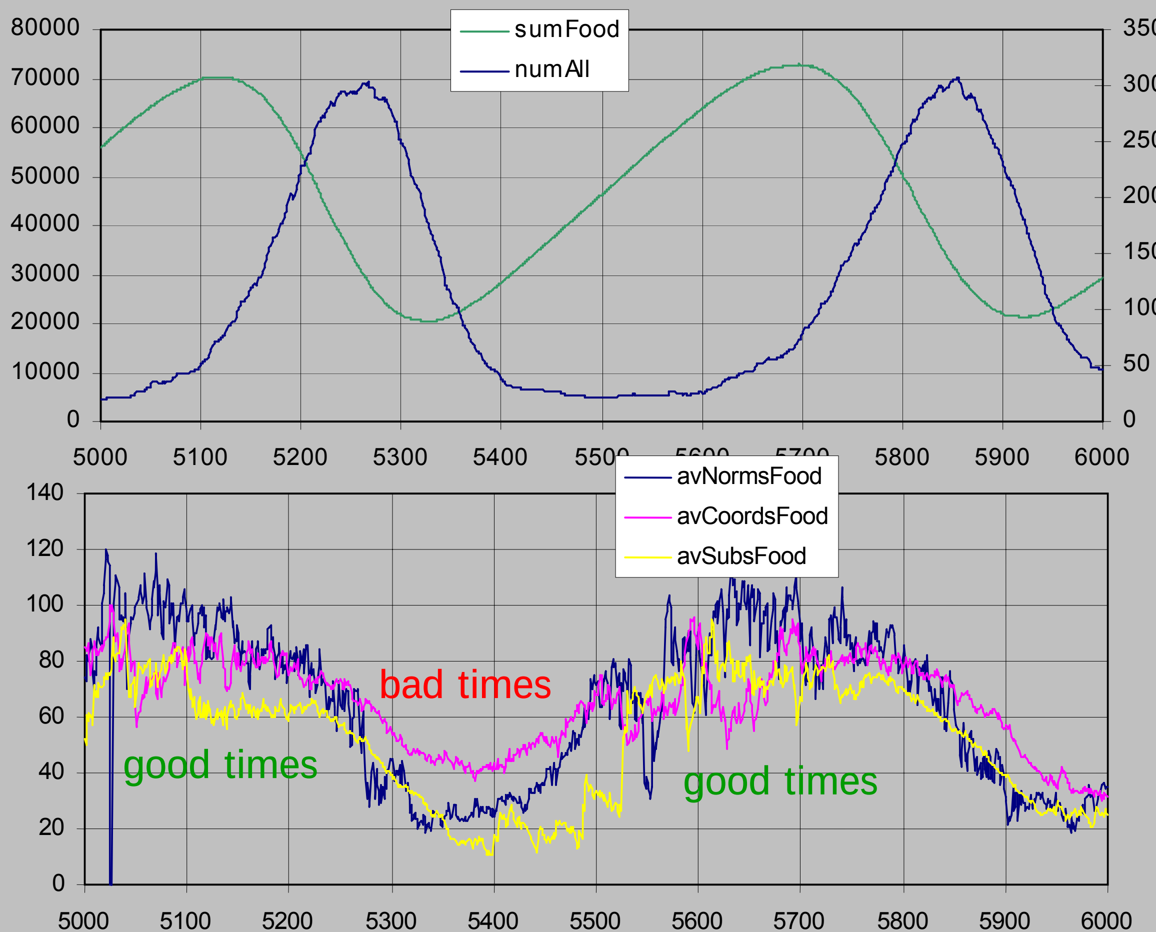
excessive exploitation of resources

reluctant exploitation

survival

extinction

Become self-employed, when times are getting better!



Conclusions drawn from complex antecedents

- Conclusion from a complex set of simple assumptions:
- Co-ordination and subordination in this artificial agent society facilitate sustainability of resources.

replicative validity: the model matches data *already acquired* from the real system (retrodiction),
predictive validity: the model matches data *before* data are acquired from the real system,

- Our conclusion is unlikely to ever be validated empirically:
- real-world human societies have an overwhelmingly more complex structure of co-ordination and subordination than the simple artificial society of our model.

replicative validity: the model matches data *already acquired* from the real system (retrodiction),
predictive validity: the model matches data *before* data are acquired from the real system,

- Indigenous societies, however, show some aspects of the behaviour of our simulation model:
- In a society of herdsmen and farmers in Western Africa, decisions which rest on friendship networks ("friend-priority" decisions) proved to be much more effective then decisions which were made on pure cost deliberations ("cost priority" decisions).
  - [Rouchier et al. 2000, 2001:189].

structural validity: the model "not only reproduces the observed real system behaviour, but truly reflects the way in which the real system operates to produce this behaviour."

- In this respect, the multi-agent model is superior to simpler mathematical models such as
  - a Lotka-Volterra process,
    - either deterministically on the macro level
      - $dx/dt = a\,x - b\,x\,y$
      - $dy/dt = c\,x\,y - d\,y$
    - or stochastically on the micro level
      - $p_{b1}(n_1, n_2) = \alpha\, n_1$ $\qquad p_{b2}(n_1, n_2) = \beta\, n_1 n_2$
      - $p_{d1}(n_1, n_2) = \gamma\, n_1 n_2$ $\qquad p_{d2}(n_1, n_2) = \delta\, n_2$

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