Modeling Environmental Processes with Soft Computing Methods[1]

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Abstract: The greatest challenge of environmental management is to create balance between increasing civilisation demands and decreasing natural resources. There is an essential need of the of information about the current state of the environment and tools for predicting how this state would be change due to different effects. We propound the requirements of evaluation of the state of the environment, then review three Soft Computing methods and their feasibility in modelling environmental processes. The GRID based CNN, FUZZY RULES and CA seem to be promisable for modelling complex, highly nonlinear processes and able to ground tool-kit for supporting environmental decision making.

Keywords: environmental management, environmental modelling, cellular neural networks, fuzzy logic, cellular automata

1 Introduction

The state of the environment is continuously changing. Partly due to the never-ending or recurring geomorphologic and biosphere-forming events, partly due to impacts of activities of – today already prevailing – anthropogenic (social and economic) origin. So the balance between the increasing civilization demands and the natural resources has to be created. This is the duty of environmental management. In order to reach all these aims, the management has to be organized i.e. such environmental policy should be established in that environmental

[1] Supported by the National Science Foundation OTKA T 43177, and KvVM

management makes environmental protection part of the activities so separate “environmental policy” disappears. Generative research has begun at the Department of the Environmental Engineering, cooperating with the Institute of Information Technology and Electrical Engineering of the Széchenyi István University. The central topic of this research is modelling and controlling extremely complex, non-linear and non-deterministic/non-causal environmental processes.

2 Requirements of the evaluation of the state of the environment

In order to handle the emerging tasks it is indispensable to get to know the changes forming the quality of the environment, to explore the causes of the changes and the expectable consequences thereof. It is necessary to have information:

- provides the actual state of the environment,

- explores the causal connections,

- indicates the probable trends of the changes.

All these mean that the determination of environmental policy objectives and tools and the elaboration of an actual environmental policy are not possible without exploring the state and the changes thereof, the more and more exact evaluation of the environmental resources and the knowledge of the background social information. So the first, basic step is the evaluation of the state of the environment. In order to fulfil this task – since it is a rather complex one – it is necessary to integrate the results of basic and applied research of different sciences in an interdisciplinary way. According to the objective (examination of the sustainability of regional development), the evaluation of the state of the environment is a part of the comprehensive environmental management.

Within the frame of this, it is necessary to perform the analysis of the changes in state occurring in the environmental media and systems (soil, water, and air) and the economic and social processes causing them. Knowing all these occurring processes can be understood and characterized so the effects may be calculated and forecast.

Since the data sources and the information sets are wide-ranging, their simultaneous illustration and analysis, the derivation of the models requires information systems and GIS within this [1, 2].

Adequate aspects – where the selection of criteria includes value selection – are necessary to the state evaluations supporting the decision-making as well as application of evaluation methods (professional systems). So the evaluation aspects also have to be elaborated. The requirements according to the evaluation aspects are those on whose basis any states of environment or environmental process can be considered as “good”, “bad”, etc. So these are the reference bases of evaluation. In this classification system we consider long-term human biological and economic-social demands against the environment as evaluation criteria. As a matter of course, the validation of these aspects makes necessary the common, optimized consideration of many, relatively well separated aspects.

In the evaluation aspects there are well-formulated requirements towards the state and the quality of environment. These three: ecology, human ecology and economy evaluation aspects cover the whole spectrum of adequate demands against the environment.

The applicability in the evaluation of the state of the environment of these aspects provides the solution of three further tasks.

First of all, a set of parameters suitable for classification of the change according to the given aspects can be specified (and the actual values of these parameters can always be obtained!).
Secondly, a value scale has to be constructed for the chosen parameters so that the environmental state can not only be described but also evaluated.
Thirdly, evaluation algorithms need to be implemented, which can carry out a reconstruct able and objective evaluation. These will allow for the investigation of more alternative scenarios and interactions described by a large number of parameters. They will also increase the reliability of decisions.

Together with all these, it is also necessary to build in highlighting processes into the algorithms.

We deal with the establishment and development of suitable expert systems based on proper mathematics that is suitable to evaluate the state of the environment in a wider sense. The aim is to analyse the relationship of state changes as consequences of (adverse) impacts on the environment, as well as the relationship of social, economic and technological processes being the sources of these impacts.

With the help of this analysis the state changes depending on the changes of environmental loading can be forecasted and the environmental and impact assessments can be expanded and developed further. In the course of the regional programmers and development the expected impacts of political programmers aiming at the regulation of the users of the environment can be predicted, so they can be implemented. Regarding the costs it is possible to choose and elaborate the most favourable and suitable ones. This way a policy-supporting system can be implemented, whose establishment totally harmonises with the objectives and priorities of the 6th R&D Framework Programme of the EU, since it supports the sustainable management of the (European) environmental resources.

The system is intended to highlight

- Environmental protection: impacts of chemicals, noise etc. on the environmental systems (soil, water, air, etc.)

- The evaluation of the applicable technologies from the point of view of supporting (initiating and helping with) environmental policy decisions, in particular, to efficient and at the same time cost-effective enough technological solutions in compliance with the environmental regulations (etc.)

It is meant to be deployed mainly in the elaboration of environmental policy regulation tools complying with the aforementioned criteria.

In the next chapters three interrelated techniques will be briefly introduced, which will be suitable for modelling and controlling the above mentioned processes, and this way serving as tools for the construction of the policy supporting system. They are all soft computing techniques: cellular neural networks, fuzzy logic based rules and cellular automata. They are applicable separately and in combinations as well [3].

3 Application of CNN (Cellular Neural Networks) for modelling environmental processes

The CNN paradigm has been playing an important role in digital signal and image processing during the past decade. CNN is a special technology within the broader field of neural networks [4, 5]. Any physical implementation of the CNN can be considered as a multidimensional array of processors, in which the processing units are connected only to their neighbouring processors. So the communication of the processors is limited to their immediate neighbours. The weights of the coupling between the neighbouring processors are expressed by the elements of so called template matrices. In the case of a classic rectangular grid where the radius of neighbourhood is defined as one unit, the template matrix contains 9 weight elements. The state equation of the state-output in the so called full range CNN and the expression of the limitation which follows each integration step is given in the following equations:

$$\begin{aligned} \dot{x}_{ij}(t) &= -x_{ij}(t) + \sum_{W^x_{rij}} \mathbf{A}_{kl} x_{ij}(t) + \sum_{W^u_{rij}} \mathbf{B}_{kl} u_{ij} + z_{ij} \\ x'_{ij}(t) &= \frac{1}{2}\left(|x_{ij}(t)+1|\right) - \left(|x_{ij}(t)-1|\right) \end{aligned}$$

Here $x_{ij}(t)$ is the time-dependent state-variable, $x'_{ij}(t)$ is the limited state, u_{ij} is the input variable, z_{ij} is a constant, which does not depend on time. **A** and **B** are the *template matrices*. The domains of summing W_{rxij} and W_{rui} represent the *r* radius neighbourhood of x_{ij} and u_{ij} respectively. One of the most promising directions of the application of CNN models is the numerical integration of partial differential equations of physics. Since the transport processes in the environment protection are described by spatio-temporal equations, a multilayer CNN approach is proposed for model generation, recombination and transport processes, such as drift and diffusion. As an example, consider the continuity equation for a pollutant, in a single layer CNN model. The continuity equation describes the time dependence on the concentration of a given pollutant in a particular point of space, assuming generation, recombination, drifting in a given direction and diffusion.

$$\dot{c} = g - r + h\, div\mathbf{D} + k\, div\mathbf{grad}c$$

c is the concentration, *g* is *the* generation rate, *r* is the recombination rate of the pollutant, **D** is the drift vector moving the pollutant, *h, k* are constants. On a grid of a two-dimensional plane the components lead to spatial discretisation. The expressions describing drift and diffusion of the right side of the equation can be expressed by two template matrices as follows:

$$h\ div\ \boldsymbol{D} \rightarrow T_{ij}^{D}\ ,\ k\ div\ \boldsymbol{grad}\ c \rightarrow T_{ij}^{c}$$

where

$$T_{ij}^{D} = \begin{matrix} h & 0 & 0 \\ 0 & -h & 0 \\ 0 & 0 & 0 \end{matrix}\ ,\ T_{ij}^{c} = \begin{matrix} k & k & k \\ k & -8k & k \\ k & k & k \end{matrix}$$

Using these templates, the CNN-like form of the continuity equation is as follows:

$$\dot{c}_{ij} = g_{ij} - r_{ij} + \sum_{w_{ij}} T_{kl}^{D} c_{kl} + \sum_{w_{ij}} T_{kl}^{c} c_{kl}$$

Here w_{ij} is the unity radius environment of point *ij* which assigns the following matrix:

$$\begin{matrix} c_{(i-1)(j+1)} & c_{i(j+1)} & c_{(i+1)(j+1)} \\ c_{(i-1)j} & c_{ij} & c_{(i+1)j} \\ c_{(i-1)(j-1)} & c_{i(j-1)} & c_{(i-1)(j-1)} \end{matrix}$$

The simplest numerical integration in time of the CNN form of the continuity equation is the forward Euler:

$$c_{ij}(t + \Delta t) = c_{ij}(t) + \Delta t \left(g_{ij} - r_{ij} + \sum_{w_{ij}} T_{kl}^{D} c_{kl}(t) + \sum_{w_{ij}} T_{kl}^{c} c_{kl}(t) \right)$$

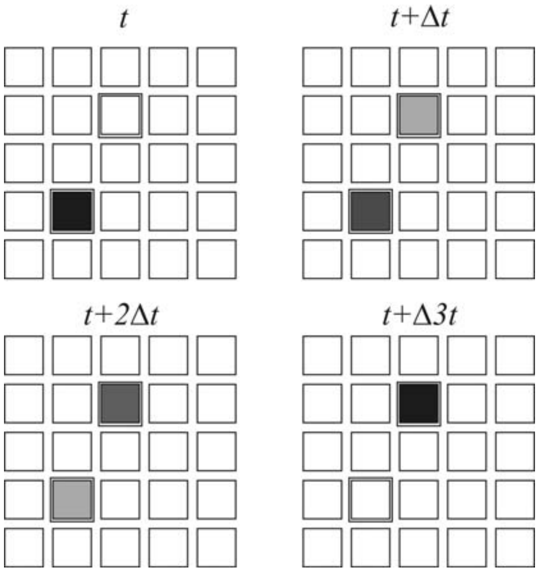


Fig. 1. Generation and recombination. Generation: the grey points of the grid in time ***t*** *will be darker from time to time. Recombination: The dark (black) points of the grid in time* ***t*** *will be lighter from time to time.*

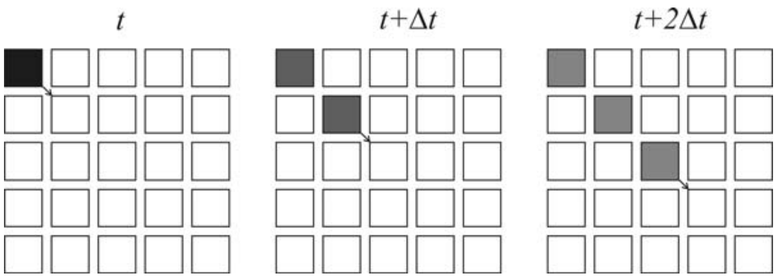


Fig. 2. Drift from a dark (heavily polluted) point to south-east direction

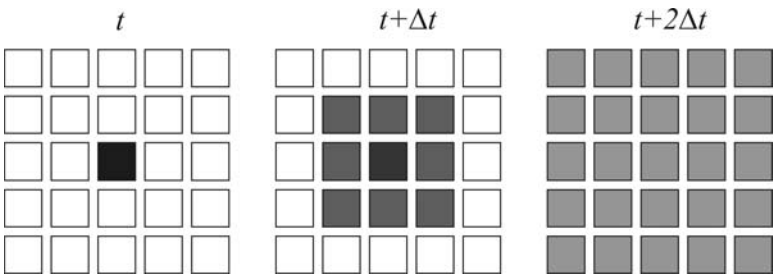


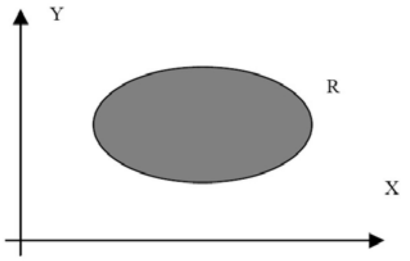
Fig. 3. Diffusion from the black (heavily polluted) point of the grid to all directions

4 Fuzzy logic rule bases

Another very powerful approach for modelling very complex, non-linear and non-deterministic phenomena is the application of fuzzy logic based **If…then…** rules and various algorithms for obtaining conclusions for facts/observations. The starting idea for these techniques was the crucial paper by Zadeh [6], where he suggested the combination of that time classic expert systems rule bases with the idea of linguistic variables and values represented by fuzzy sets over the universes of discourse corresponding to input and output state variables for describing very complex systems. The new element in this approach was that rather than using symbolic logic and discretised state space representation, the ordered and continuous metric structure of the state space allowed the reduction of the actual symbols and terms, which could produce by their partial overlapping an interpolation type approximative calculation technique. Soon Mamdani [7] completed the idea by introducing a projection based representation for fuzzy sets and relations and so he and his collaborators succeeded with a very powerful and efficient controller for a highly non-linear steam engine system. The main idea is that if given an input universe of discourse

$\mathbf{X} = \prod_{i=1}^{k} X_i$, where X_i are the input state variables, and Y is the output universe,

any rule in the form **If** x **is** A **then** y **is** B can be represented as a relation R of the XxY space, cf.



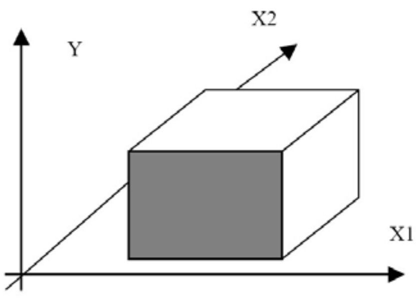


Fig. 4. Relations

In Mamdani's approach the structure of the possible fuzzy relations is more restricted as only those that can be generated as the Cartesian products of orthogonal projections are allowed – on the other hand however, this restriction allows a much better computational complexity. The rule base in this approach has the following structure:

If 1 *x* **is** 1 *A* **and** 2 *x* **is** 2 *A* **and … and** *k x* **is** *k A* **then** *y* **is** *B.*

Based on Mamdani's algorithm a series of commercial applications were implemented and the so called „fuzzy boom" started especially in Japan. However, it turned out soon that no real implementation was possible for more than 5-10 input dimensions because of the high computational complexity of the model: $O(t^k)$, where t denotes the (maximum) number of terms for each dimension. Further advance towards larger dimensionality was offered by the rule interpolation algorithm introduced in [8] and finally by the combination of hierarchical structuring the rule base combined with the sparse approach in the rule interpolation technique [9].

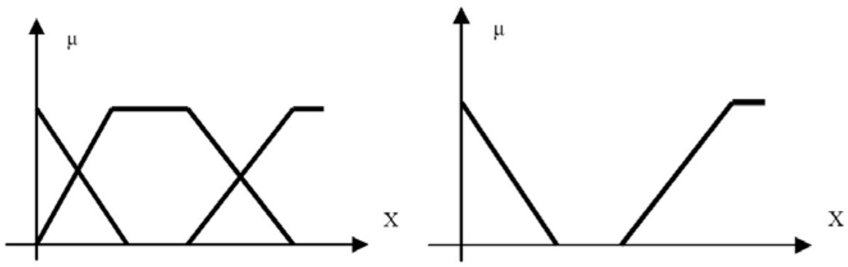


Fig. 5. The difference between the Mamdani-approach and the interpolative sparse technique.

The hierarchical method deals with a multilevel rule structure where meta-level rules have symbolic output: R_0: **{ If** z_0 **is** A_i **then** R_i **}.** Where each R_i is of the type R_i: **{ If** x_i **is** A_{ij} **then** y **is** B_j **}.**

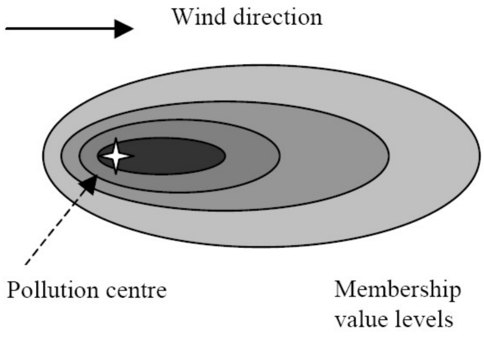


Fig. 6. Spatial air pollution model

This latter type of rule base allows dealing with very complex systems with a reasonable accuracy. We suggest that pollution drift, expansion, etc. is dealt with by applying the last, more complex but more effective technique. If there is a reasonable way to group variables according to one or more key variables (z_i), it will be possible to segment the model and this way effectively reduce the value of k locally. The extension of various pollutants in a geographic area will be well described by fuzzy sets whose time behaviour can be modelled by the rule bases as suggested above.

5 Cellular Automata

Cellular automata are flexible tools to approach spatiotemporal dynamics therefore they are widely used in miscellaneous scientific problems (e. g. flow dynamics, biochemical reactions, tumour growth [10, 11] etc.). Their reliability originates from the structure that global behaviour is deduced from local rules.

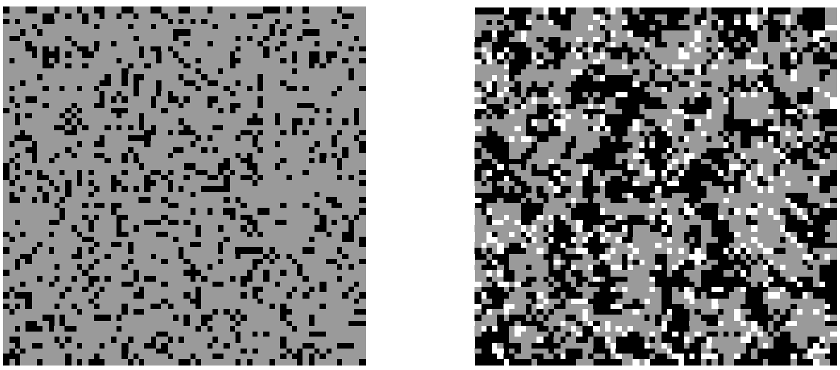
A cellular automaton $\mathrm{A} = \langle L, S, \rho, \psi \rangle$ consists of a cell-space L with a neighbourhood relation ρ, a set of states S and a local transition (or update) function ψ. The cell space is usually a lattice (e. g. a discretized physical space Z^n, $n \in Z^+$ dimensional squared lattice). The most frequently used neighbourhood relations on square grids are the Neumann neighbourhood containing the four adjacent cells (North, East, South and West) and the Moorian neighbourhood consisting of eight adjacent cells (including North-East, South-East, South-West and North-West as well). Each element x of the cell space has a value $s_t(x) \in S$ at a given t, where the time scale is discrete ($t = 0,1,2,\dots$). The state of the cell at the next step $s_{t+1}(x) \in S$ is determined by the update function depending on both the actual state of the cell itself and on its neighbours' state:

$$s_{t+1}(x) = \psi(s_t(x), \{s_t(y) : (x, y) \in \rho\}) \qquad (1)$$

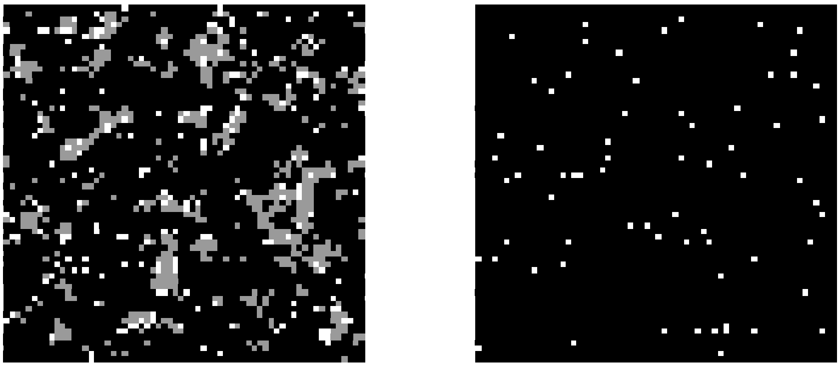
The update function can be either deterministic or stochastic and applied synchronously or asynchronously (one by one cell) to the cell space. The models we investigate are stochastic synchronously updated CA defined on a finite square grid cell space with a torus topology at the edges and with Moorian neighbourhood.

Such models are particularly appropriate for natural dimension of environmental status assessment, because the traditional descriptive methods based on plant communities which can be considered discrete both in time (because of annual reproductive cycle) and space (based on either individuals or habitat patches). The feature of cellular automata that their rules originate from local relations opens an opportunity to approach field situations since local colonization and extinction (mortality) can be more easily handled than global processes.

We used CA models to investigate habitat destruction [12] and plant competition in different spatial arrangements of the competing species [13, 14]



t=1 *t=20*



t=50 *t=150*

Fig. 7. Competition of two species in a 64x64 lattice. Evolution of the cellspace starting from a random distributed initial configuration. (The initial densities of species 1 and 2 are 20% and 80%). White, black and grey colours are coding cells being empty, occupied by species 1 and 2, respectively.

Simulations of one species cellular automata models show that colonization is the main determinative feature in suppressing of fast spreading alien species. The success of eradication depends on the possibility of reducing the colonization ability of the invasive species. The damage cased by the alien species to ecosystem can be decreased by eradication process initiated right time. If the native species are going to be displaced by the non-indigenous species is widely influenced by the spatial pattern formation and the level of habitat destruction.

Our experimental methods and tools can be applied for more general systems including inhomogen matrix, feedback from other environmental components (e. g. soil) and any number of species with different types of interactions.

Conclusions

(i) Characterization as well as prediction of the changes in the status of environment essential for realization of the sustainable development

(ii) Just then the environmental processes are complex, highly non-linear, secondary and subsequent reactions occur also consideration only of the causal physical –chemical – biological transmissions would even not be enough, if they could be exactly well known due to computational complexity of the task

(iii) Consequently/accordingly modelling is necessary where not only the results of changes but regulaties are generated by the model-algorithms themselves

(iv) In our opinion the soft computing methods, in this case the application of GRID based CNN as well as FUZZY RULES seem to be promiseable for modelling the environmental processes

(v) As a consequence the targeted aim of research would make by our is: building up a tool-kit for supporting the environmental decision making.

References

[1] Kerekes, S. Bulla, M. (1994): Environmental Management in Hungary. *Environmental Impact Assesment Review*, 14 (2-3):95-101.

[2] Bulla, M. (1992): State of the Environment in Hungary. Appendix I. in: *Environment and Development in Hungary*. A Blueprint for Transition. Ed. Z. Bochniarz., S. Kerekes. University of Minnesota, Minneapolis USA.

[3] Bulla, M. Széchy, L. (2003): Basic Theory of an Environmental Support System and Implementation Using GIS REGIONET III. Workshop University of Manchester. UK.

[4] L.O. Chua and L Young (1988): Cellular Neural Networks, Theory and Applications, *IEEE Trans. Circuits and Systems 35* pp. 1257-1290.

[5] L.O Chua and T.Roska (1993): The CNN Paradigm, *IEEE Trans. Circuits and System 40* pp. 147-156.

[6] L. A. Zadeh: Outline of a new approach to the analysis of complex systems and decision processes, *IEEE Trans. on Systems, Man and Cybernetics SMC-3*(1973) pp. 28-44.

[7] E. H. Mamdani, S. Assilian (1975): An Experiment in Linguistic Synthesis with a Fuzzy Logic Controller. *International Journal of Man-Machine Studies 7* pp. 1-13

[8] Kóczy, L. T. and Hirota, K. (1993): Interpolative reasoning with insufficient evidence in sparse fuzzy rule bases, *Information Sciences* 71 pp. 169-201.

[9] Kóczy, L. T. and Hirota, K. (1997): Interpolation in hierarchical fuzzy rule bases with sparse meta-levels, Tr. 9 7-3, Tokyo Institute of Technology, 12p.

[10] S. Wolfram (1986): Theory and Applications of Cellular Automata, World Scientific, Singapore.

[11] T. Czárán (1998): Spatiotemporal Models of Population and Community Dynamics, Chapman & Hall, London.

[12] É. V. P. Rácz, J. Karsai (2003): Computer simulations on cellular automata models of metapopulations in conservation biology. *Hungarian Electronic Journal.* ENV-011125-A

[13] É. V. P. Rácz and J. Karsai (2002): Computer simulation results for cellular automata models of some ecological systems, *Folia FSN Universitatis Masarykianae Brunensis*, Mathematica 13, pp. 213-221.

[14] É. V. P. Rácz, M. Bulla (2003): Cellular Automata Models of Environmental Processes. *Proceedings of International Conference in Memoriam John von Neumann.* pp. 109-119.