LINGUISTIC DYNAMIC MODELLING USING LOGIC PROGRAMMING

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Abstract. A new dynamic modelling methodology, SLIN, allowing for the analysis of systems defined in qualitative or quantitative terms is presented. Simulation of qualitative characteristics is performed by applying a set of logical rules which include base, tactical, strategic and structural change rules. Quantitative simulation applies traditional system dynamics concepts. To make the transition from qualitative into quantitative modes, logical rules are also used. SLIN is advantageously implemented on a very high level language such as PROLOG, as shown in this paper. To illustrate its potential applications, simple water quality models are included.

INTRODUCTION

The qualitative component of reality has been traditionally neglected by modellers. As a result models have widen the gap between qualitative and quantitative worlds. They usually are incomplete and of no practical application whenever quantitative information is missing.

In the field of dynamic modelling, Wenstop (1976) among others proposed fuzzy set theoretic based concepts to model qualitative systems. Ten years have past however without significant applications of Wenstop method, maybe due to the little appeal fuzzy set theory has for practitioners.

Camara et al. (1985) presented a new linguistic dynamic simulation methodology, named SLIN (after Simulação LINguistica), which attempts to model qualitative phenomena using simple logical rules. In this paper, a new improved version of SLIN is presented. Its implementation on a very high level language such as PROLOG is also discussed. Simple water quality models are included to illustrate its potential applications.

SLIN THEORETICAL PRINCIPLES

SLIN is a fuzzy simulation methodology which is not patterned after fuzzy set theory but applies instead simple logic concepts. SLIN has two modules: an operational module and a support module. The operational module consists of a modelling methodology that allows for qualitative and quantitative simulation. The support module is a knowledge base.

Operational Module

The quantitative dynamic modelling in SLIN is made using traditional system dynamics. Herein, attention will be focused on SLIN's linguistic modelling capabilities. SLIN allows for qualitative modelling through semantics and a particular syntax. The model semantics consists of defining the meaning of the system characteristics and their degrees. The syntax relies upon a set of logical rules.

Characteristics can be either qualitative or quantitative. They are grouped in layers with degrees evolving through time. A characteristic belongs to the base layer if its degree at time t does not depend on the degree of any other base characteristic at t. A characteristic belongs to a higher order layer if its degree at a given instant may be inferred from the degree or degrees assumed by lower order characteristics at that instant. A higher order characteristic is defined always using a higher level of aggregation.

Degrees are associated with qualitative scales (i.e., high, medium, low) or quantitative metrics, depending on the nature of the characteristics.

The main objective of SLIN is to determine the degrees associated with the system base characteristics at time t+dt, where dt is the simulation step, knowing the degrees assumed by those characteristics at time t. This process is called the "horizontal" simulation step. The "vertical" step consists of defining the degrees of characteristics belonging to higher order layers, knowing the degrees of base characteristics and occurs at a precise point in time: the end of each simulation step.

SLIN allows for simulation when all the characteristics are qualitative or quantitative but also accomodates information flows between qualitative and quantitative characteristics.

Simulation of Qualitative Characteristics

The key element in the dynamic simulation of qualitative characteristics is a set of rules which include: base, tactical, strategic and structural change rules. Another important component is the consideration of uncertainty.

Base rules. Base rules are lower level rules that allow one to obtain the degrees of the system characteristics at time t+dt given their degrees at t (horizontal simulation), and the degrees of characteristics of layer i+1 given the degrees of characteristics belonging to layer i (vertical simulation).

To perform the horizontal simulation operations, one considers the following generic representation for each equation:

$$[\text{Action Op1 Memory Op2}]\ x_{t+dt}$$

The component "Action" is similar to the rate terms in the level equations of traditional system dynamics. This component provides a "preliminary" degree for x_{t+dt}, taking into acount the degrees of x and other independent variables at time t, that is:

$$\text{Action}= \{ a_t \wedge b_t \wedge ... \wedge z_t \}$$

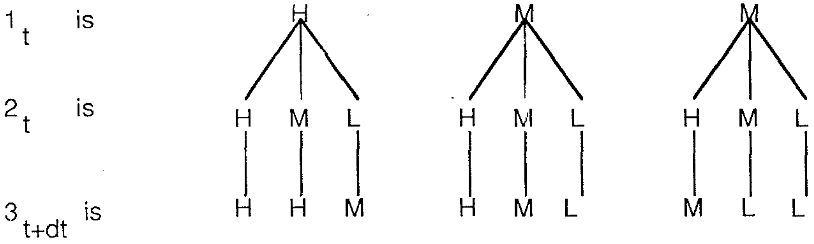
To determine this contribution, one may define trees enumerating all possible combinations of degrees for the independent characteristics and the resulting degrees for the dependent characteristic such as in Fig. 1. Feasibility considerations should be used to eliminate branches in trees to improve computational efficiency.

Another alternative, which is less explicit but much more efficient consists of a set of built in operators that allow one to automatically simulate. These operators are defined as follows:

$$a_t \wedge b_t \wedge c_t \wedge \ldots \wedge z_t \ \text{Op1} \ (x_{t+dt})\text{prelim}$$

If characteristics a, b, c, ..., z have a similar influence on the degree of x, typical operators Op1 are the majority rule operator, the average rule

$$\text{charact } 1_t \wedge \text{charact } 2_t \ \text{Op1} \ \text{charact } 3_{t+dt}$$



H—High; M—Medium; L—Low

Figure 1. Example of a tree defining the action contribution

operator and the additive rule operator, depending on the type of operation on the degrees of the independent characteristics.

If a, b, c, ..., z have a different influence on x, then one selects the most influent characteristic of the set {a, b, c, ..., z} as the dominant characteristic "dom". The degree of x will be equal to the degree of "dom" more or less a number of degrees which depends on the relative dominance of "dom" over the other independent characteristics. Operators Op1 are in this case, named after the degree of dominance, i.e., superdominance, overdominance or dominance rule operators.

The final degree for x_{t+dt} depends however on another term which may called the "memory" of the equation. This component attempts to reproduce the accumulation process present in typical finite difference calculus and neglected in previous qualitative dynamic simulation methods (Wenstop (1976), Camara et al. (1985)). The memory includes:

$$\text{Memory} = \{ x_{to-t}, \text{Action}_{to-t}, \text{Threshold rate} \}$$

where:

x_{to-t}= set of degrees of the dependent variable x from intial time to up to t

Action $_{to-t}$= set of degrees representing the action component contributions from to up to t

Threshold rate= a term that taking into account the degree of x_t, previous action contributions Action $_{to-t}$ and the current action contribution (x_{t+dt}) prelim, determines the final degree of x_{t+dt}

This threshold rate term enables x_{t+dt} to assume a different (or similar) degree from x_t, by considering that the accumulation of the contributions of a certain action during a number of integration steps is higher (or lower) than a given threshold limit.

Note that: in typical upward or downward x trajectories, the influence of the action and the memory are identical (Fig. 2 (a) (b)); in oscillating modes, every saddle point, represents the superiority of the action over the memory (Fig.2 (c)); and in stable trajectories, memory prevails over net action contributions (Fig. 2 (d)).

To perform vertical simulation operations similar processes to the ones used to determine the action component contribution are applied.

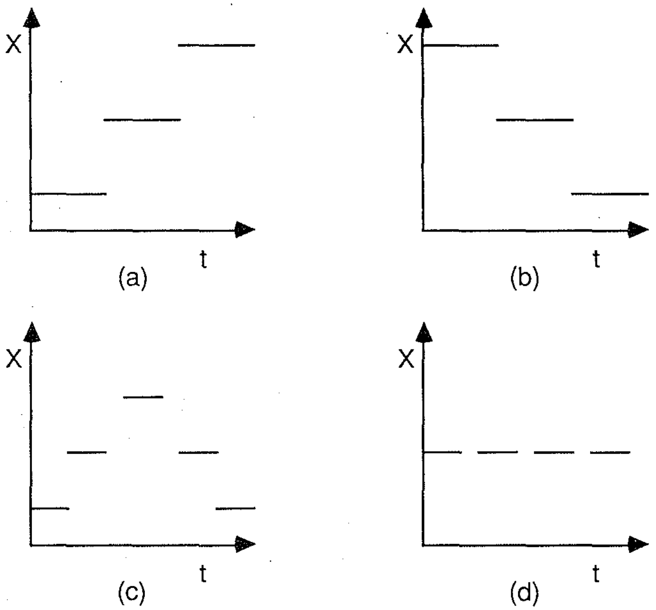


Fig. 2 Trajectories for dependent characteristics x: (a) upward; (b) downward); (c) oscillating; (d) stable

Tactical rules. Tactical rules are divided into "tic-tactical" and "metatactical" rules. The latter direct the simulation, by assigning the characteristics for which one wants to obtain degrees at the end of each simulation step ("destinies"). The former define for each equation the simulation step dt to be used which varies with the nature of the dependent characteristics. Resulting synchronization problems are identified by using a timed Petri net construct and solved subsequently using PERT.

Strategic rules. While base and tactical rules apply within the simulation step, strategic rules intend to coordinate the simulation process during the whole simulation period. Strategic rules may be applied to connect simulation objectives set by the modeller to the "destinies" to be defined at the tactical level.

Strategic rules can also be used to guide backtrack searches to explain the degrees of characteristics of high order layers in terms of base characteristics.

Structural change rules. Structural change rules are designed to accomodate the possibility of eliminating or incoprporating characteristics and changing rules at a given time t during the simulation process, taking into account the trajectories defined by the same characteristics up to that time.

The adoption of PROLOG to implement SLIN will greatly facilitate the creation of learning capabilities in the simulation models, following the AI tradition (Carbonnel (1983)). The implementation of these capabilities will provide the methodology with automatic structural change mechanisms.

Uncertainty considerations. Uncertainty may also be incorporated in the simulation of qualitative characteristics. Uncertainty can be due to randomness (hard uncertainty) or lack of knowledge (soft uncertainty).

The consideration of hard uncertainty applies to each simulation step dt and may be dealt with Monte Carlo methods. Soft uncertainty conditions are more relevant if one considers several simulation steps n.dt. The method proposed, in this case, consists of an analysis of the model output. If discrepancies between obtained and expected results are considered to be significant, then the model is restructured; otherwise, the information produced should be incorporated into the support base. Note that this approach is intimately connected to the model verification and structural change.

Quantitative- Qualitative Information Flows

Quantitative-qualitative information flows in any layer may be considered by a number of methods.

In the first case, one can easily transform a quantitative into a qualitative characteristic by applying a value function. From then on, one may proceed as described for the simulation of qualitative characteristics.

The transformation of qualitative into quantitative flows may also use the value function method. Other aproaches include the definition of logical rules and the application of fuzzy set theoretic concepts. The most promising of these is the adoption of logical rules. Suppose that one wants to perform an operation of the type:

$$\text{qual. charact i}_t \wedge \text{quant. charact. j}_t \text{ Op quant. charact. k}_{t+dt}$$

This means that qualitative characteristic i has a quantitative influence on the quantitative characteristic j in terms of quantitative characteristic k. For instance if:

$$\text{citizen information}_t \wedge \text{pollution load}_t \text{ Op pollution load}_{t+dt}$$

where "pollution load" and "citizen information" are quantitative and qualitative characteristics, respectively, one may perform operation Op by establishing rules of the type:

if citizen information is [high medium low] then pollution load at t+dt will be a X% of pollution load at t.

Support Module

The support module consists of a knowledge base which includes a dictionary with the characteristics, qualitative scale and quantitative metrics, the built in operators, the tree rules, and the "memory" terms for each equation-- all the valid information produced by each simulation step in terms of dependent characteristics and action contributions and the threshold rates.

SLIN-IMPLEMENTATION

A simplified version of the SLIN methodology was implemented in PROLOG on a VAX 11/780 system. Table 1 shows a portion of a PROLOG program illustrating the main procedures of SLIN and also the definition of the majority rule operator (named "freq" in the program).

The major problem with the application of this version lies on its user "unfriendliness". In order to make query, the user has to introduce N (the number of desired iterations); a list containing the initial degrees of the characteristics; and another list indicating, for each characteristic, which are the characteristic it depends on and also which is the operator to be used. Some of the operators (like the majority rule in the sample program) are already "pre-defined", but the user can introduce his own operators as clauses added to the program.

PROLOG is highly suitable to implement a logical rule based methodology such as SLIN. "Friendly" interfaces will have to be developed however to use it in practical applications.

SLIN--APPLICATION

To illustrate SLIN applications, let us consider a simple estuarine water quality management case. The estuary has a bivalve zone which suffers impacts from agriculture runoff and domestic effluents discharged upstream.

The system is described by the following characteristics: precipitation; runoff (measured by its inorganic suspended solids content), domestic effluents (measured by its organic suspended solids content), habitat substrate (measured by both organic and inorganic solids content), bivalve diversity, productivity and quality. These characteristics may be assessed in quantitative or qualitative scales depending on their nature.

A model using SLIN can be developed for this system with design objectives such as: determine the most appropriate time of the year to catch bivalves, under a fuzzy information state; define domestic effluent discharge patterns to minimize impacts upon the bivalve populations; to

TABLE 1 Sample Listing of a PROLOG Program for SLIN

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sim (O, O, V)  :- escreve(V).
sim (N, O, V) :- N1 is N - 1, iterar(O, V, NV), escreve(V), n1, sim(N1, O, NV).

iterar ([], _, []).
iterar ([Op|Pos]|B], V, [Variavel|NV1]) :- corresp(1, Pos, V, Lista),
                                             oper (Op, Lista, Variavel),
                                            iterar (B,V, NV1).

corresp (_, [], _, []).
corresp (N, [N|R], [A1|R1], [A1|R2]) :- N1 is N+1, corresp(N1, R, R1, R2).
corresp (N, [K|R], [A1|R1], R2)        :- N1 is N +1, corresp(N1,[K|R], R1, R2).

oper(freq, Lista, Result) :- freq(Lista, AuxLista), maxfreq(AuxLista, Fq,
                                                      Result).

freq([], []).
freq([A|R],K)   :- freq(R,K1), ins(A,K1,K).

ins(A,  [],[[A,1]]).
ins(A,[[A,P]|X],[[A,Q]|X]) :- Q is P+1.
ins(A, [[B,P]|X],[[B,P]|Y]) :- ins(A,X,Y).

maxfreq([],O,_).
maxfreq([[A,P]|R],P,A) :- maxfreq(R,Q,V), P>= Q.
maxfreq([[A,P]|R],Q,V) :- maxfreq(R,Q,V), P<Q.

escreve([]).
escreve([A|R]) :- write(A), tab(2), escreve(R).
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maintain a sustainable ecosystem with high long term levels of bivalve productivity and quality.

To operate such a model a number of rules have to be formulated. At the base level, dependent characteristics of interest are the bivalve diversity, productivity and quality. Independent characteristics representing the action component of the model equations include precipitation, runoff and domestic effluents. The memory component of each equation consists of dependent characteristic and action component trajectories, and a threshold rate term. An example of a base rule for this system is:

Action Memory
{[runoff ^ domestic effluents] Op1 [bivalve quality $_{to-t}$, action $_{to-t}$, threshold rate term] Op2} bivalve quality $_{t+dt}$

In this equation, Op 1 could be a dominance rule type operator, and the threshold rate term could mean, for instance, that if the action contribution is medium twice in a row, the bivalve quality at t+dt is one degree higher than at t. The impacts upon bivalve quality over time could be divided into five categories depending upon the relative dominance of runoff and domestic effluents influence as shown in Fig. 3.

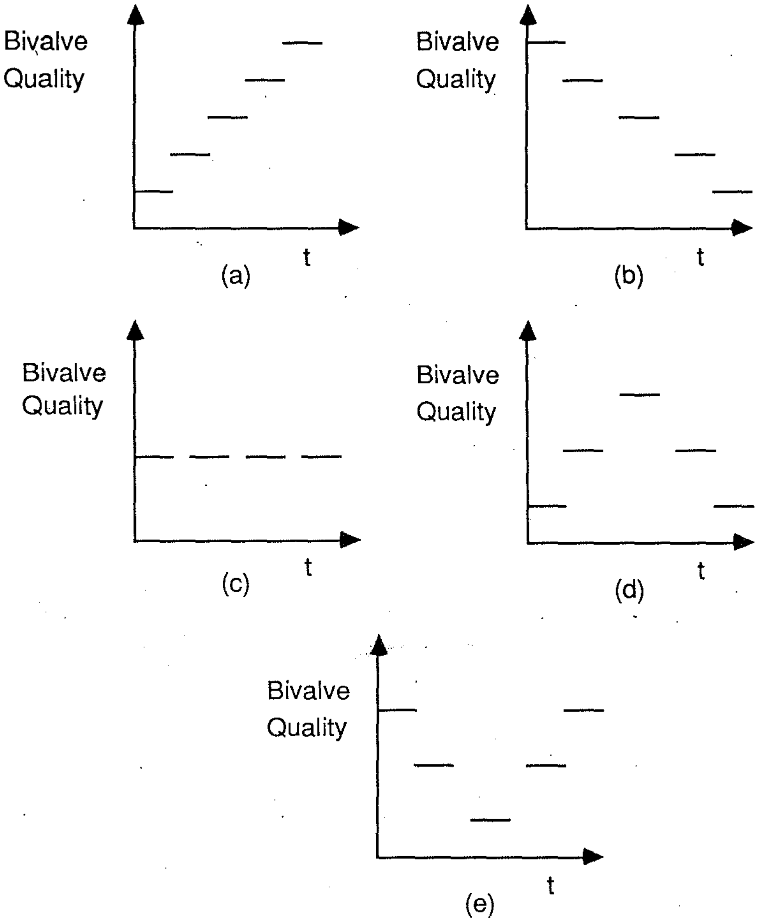

Figure 3 Evolution of bivalve quality: (a) maintained dominance of runoff; (b) maintained dominance of domestic effluents; (c) maintained balance; (d) dominance of runoff followed by domestic effluents dominance; (e) dominance of domestic effluents followed by runoff dominance

SUMMARY AND CONCLUSIONS

A new linguistic dynamic methodology using logic programing, SLIN, was introduced in this paper. SLIN models systems defined by characteristics, which may be qualitative or quantitative, grouped in layers, and with degrees evolving through time.

Simulation of qualitative characteristics is performed by applying a set of logical rules which include base, tactical, strategic and structural change rules. To make the transition from qualitative into quantitative modes, logical rules are also used. SLIN is the first qualitative modelling methodology to have "memory" in the model equations by applying simple threshold logic concepts.

SLIN is adequately implemented on PROLOG, although some problems remain to create a user-friendly environment.

Qualitative dynamic modelling has many applications in many areas. One of these, is certainly environmental engineering as shown herein with simple water quality management models.

REFERENCES

Camara, A., J. Seixas, M. Pinheiro and P. Antunes (1985). Linguistic Simulation--Theory and Practice. The 1985 International Conference of the System Dynamics Society, Keystone, Colorado.

Carbonell, J. et al. (1983). Machine Learning, Part I: A Historical and Methodological Analysis. Report CMU-CS-8B-135, Carnegie Mellon U., Pittsburgh, Penn.

Wenstop, F. (1976). How Can One Explicitly Represent the Fuzzy Nature of Social Causal Relations in Formal Models? Fuzzy Set Simulation Models. Proceedings of the 1976 International Conference of the 1976 International Conference on System Dynamics, Geilo, Norway.