Linguistic Simulation in Planning
Theory and Application

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ABSTRACT

This paper introduces a new linguistic dynamic simulation methodology, SLIN which deals with systems defined in either qualitative or quantitative terms. The simulation mechanisms proposed in SLIN include a set of logical rules and fuzzy set theory. An application of SLIN to Sado estuary showed its promise but also some of its present limitations. Future developments including an appropriate diagrammatic representation, a new linguistic simulation computer language, implementation in parallel computers and subsequent real-time multi-expert based simulation are also discussed.

INTRODUCTION

Good communication is essential in any transdisciplinary activity such as planning. Most planning experiences demonstrate that there is, in fact, poor communication among the different disciplines involved. In a planning model including three dominant steps: (1) generation, (2) simulation and (3) evaluation of alternative strategies, the communication gap in particularly acute in phase 2.

The several disciplines intervening in planning may be divided into two main groups concerning the language type they use: (1) the "fuzzy" disciplines (i.e., social sciences) which use a language similar to natural language, where variables are expressed qualitatively; and (2) the "tech" disciplines (i.e., physical sciences) operating in quantitative terms. For disciplines to interact in a simulation exercise there is a need for a common language, which implies the adoption of one of two alternatives: (1) to convert "fuzzy" variables into quantitative terms (the traditional approach); and (2) operate in a language close to natural language. The second alternative is preferable, as natural language is easily utilized by all the participants in the planning process and because one can translate quantitative into "fuzzy" variables without significant information losses.

The goal of this paper is to introduce a new simulation methodology, linguistic simulation (SLIN from Simulação LINguistica), based on "fuzzy" departures from traditional system dynamics concepts, which may be used as a tool to overcome the communication barrier between social and physical disciplines. Linguistic simulation may also be applied to model physical phenomena if quantitative data is insufficient.

The methodology consists basically of the specification of logic operations in a dynamic environment, where numerical variables are replaced by verbal characteristics. In addition, it allows one to make the transition from qualitative into quantitative modes, if needed, adapting fuzzy set theoretical principles.

A simple water quality planning model for Sado estuary in Portugal was used to illustrate the proposed approach. The simulation was performed manually. Future developments including an appropriate diagramatic representation,a new linguistic simulation computer language, implementation in parallel computers and real-time linguistic simulation are also discussed.

LINGUISTIC SIMULATION--THEORY

SLIN is a methodology where one is modeling a system defined by "characteristics", grouped in "layers", with "degrees" evolving through time. It is inspired on ideas collected from the works of Buchanan and Shortliffe,(1984) Bundy, (1983), King, (1983), Laikoff, (1976), McCawley, (1981), among others. others.

Characteristics can be either qualitative (i.e., "polluted") or quantitative (i.e. x mg/l BOD). A "characteristic" belongs to the "base layer" if its value at time t does not depend on the value of any other "base characteristic" at t. A "characteristic" belongs to a "higher order layer", if its value at a given instant may be inferred from the value or values assumed by lower order characteristic(s) at that instant. A "higher order" characteristic is defined always using a higher level of aggregation.

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

The main objective of linguistic simulation 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" linguistic 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.

One may consider four types of information flows between base characteristics: quantitative-quantitative; qualitative-qualitative; quantitative--qualitative and qualitative-quantitative. The first kind is adressed in traditional system dynamics modeling. SLIN attempts to model the latter three types.

Qualitative-qualitative flows

First of all, let us consider the qualitative-qualitative type of information flow. "Characteristics" are now verbal statements. It is necessary then to determine suitable operations that enable the determination of the "degrees" of these verbal "characteristics" through time. These operations are a set of rules, which include: base, tactical, strategic, acceptance and structural change rules.

Base rules are lower level rules and are extracted from experts that will define adjacency matrices establishing the relationships between characteristics at time t and the characteristics at time t+dt and between characteristics layer i and characteristics layer i+1. Applying reachibility matrices (Cristofides, 1975) one can now derive for each"characteristic j", which are the "characteristics i_t" that influence its degree at t+dt, and similarly, for each "characteristics t/layer i+1", which are the "characteristics j t/layer i" it depends on. One thus has:
.horizontal simulation

$$\{\text{charact.}_t 1 \oplus \ldots\ldots\ldots \oplus \text{charact.}_t N\} \Rightarrow \text{charact.}_{t+dt} i, \ \forall i \qquad (1)$$

.vertical simulation

$$\{\text{charact.}_t 1/\text{layer } i \oplus \ldots\ldots\ldots \circledast \text{charact.}_t N/\text{layer } i\} \Rightarrow$$
$$\Rightarrow \text{charact. } j/\text{layer } i+1,\ \forall j \qquad (2)$$

where $\oplus$ and $\circledast$ are logical operators of the conjunction or disjunction type

Based on representations (1) and (2), experts define then trees allowing for the enumeration of all the possible combinations of degrees for the characteristics in the left hand side and the determination of the degree of the characteristics in the right hand side, corresponding to each combination using non-boolean logics, as illustrated in figure 1. Feasibilty considerations are used to eliminate branches in the trees (i.e. non--probable degrees for certain characteristics) to improve computational efficiency. In some cases uncertainty may lead to more than one possible degree for characteristics t+dt or characteristics/layer i+1 (i.e. characteristic t+dt=highly polluted or =medium polluted).

Ex: $\text{charact.}_t 1 \wedge \text{charact.}_t 2 \Rightarrow \text{characteristic}_{t+dt} 3$

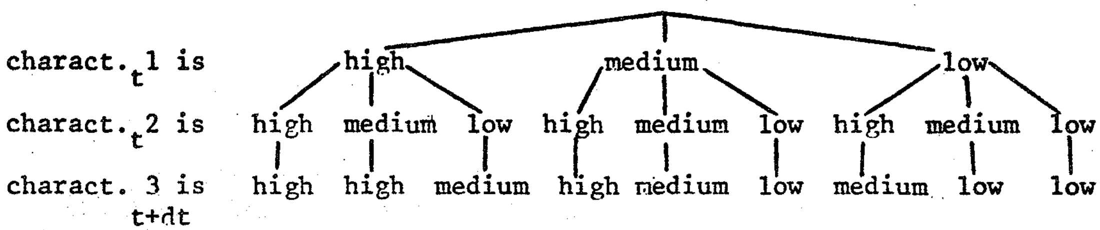


Figure 1. Example of a tree defining a base rule

The set of trees defined in this manner, which are necessary to perform horizontal and vertical simulations are SLIN's base rules. Another alternative to define the degree of a characteristic at t+dt, being studied at present time, consists of applying the associative property in succession to the left hand side of equations 1 and 2. This approach seems to have the potential to be more rapid from a computational standpoint.

Tactical rules are defined by a three-tupple:

destinies <set of equations 1 and 2> time interval of solution (3)

They are divided into "tic-tactical rules" and "meta-tactical rules". Tic-tactical rules define for each equation type 1, the simulation step to be used. These vary with the nature of the sub-system which the equation attempts to model, (i.e. a meteorological equation may be processed at a hourly basis, while an economics type equation may produce output in monthly intervals). Meta-tactical rules define the characteristics (in equations 1 and 2) for which one wants to obtain degrees at the end of each simulation step--they represent the destinies in 3. This is because one may only want to perform directed instead of global evolutive simulation.

While base and tactical rules apply within the simulation step, strategic rules intend to coordinate the simulation process during the whole simulation period. They are of an essential importance in the uncertain cases (a characteristic having more than two possible degrees). To avoid combinatorial problems (one would have trees with an increasing number of paths) that would augment through time, strategic rules specify which degree should be selected in those situations, depending on the type of uncertainty (these types are defined by Wick, 1973). If one is dealing with ignorance (things which we do not know but could), a strategic rule consists of using a safety criteria. If the type of uncertainty is randomness (things we do not know with exactitude until they happen) and indeterminism (things we can not know), the rule is just to choose an arbitrary value. In this cases, the model may be run several times, each one reflecting a certain combination of choices for the uncertain characteristics. The resulting output could then be analyzed using simple statistics.

Strategic rules may be applied to connect simulation objectives set by the modeller to the destinies to be defined at the tactical level. They can also be used to guide backtrack searches, much like in dynamic programing (Bellman and Kalaba, 1965), to explain the degrees of characteristics of higher order layers in terms of "base characteristics".

Acceptance rules attempt to verify if the model is operating correctly. This is defined by comparing simulated and expected degrees for the system characteristics. A rule of this kind would say, for instance, that if there is a difference of just one degree between simulated and expected values, the model is acceptable. They are always used as a complement to strategic rules. To facilitate the process, acceptance rules may be defined just for higher order layer characteristics which are in a smaller number.

Finally, structural change rules are designed to accomodate the possibility of eliminating or incorporating characteristics and changing rules at a given time t during the simulation process, taking into account the trajectories defined by the system characteristics up to that time. They are basically a set of "trees", much like base rules.

Quantitative-qualitative flows

In this case, one can easily transform a quantitative into a qualitative characteristic by applying a value function (figure 2). From then on, one may proceed as described for the qualitative-qualitative flow case.

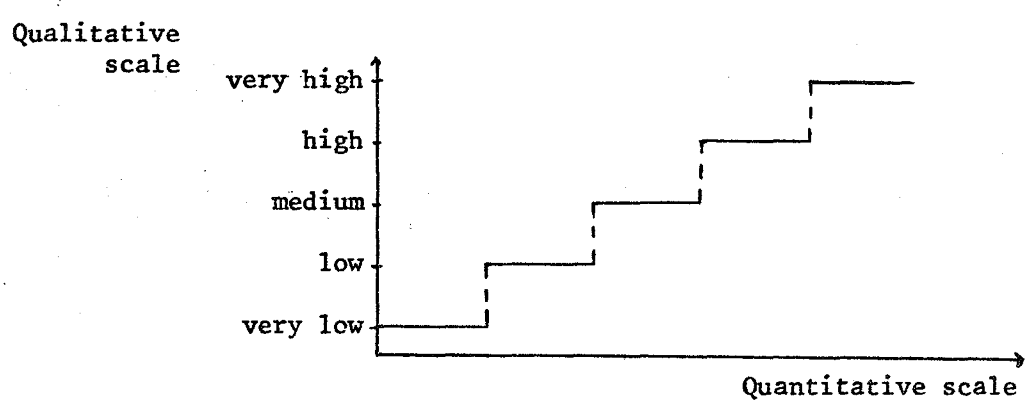


Figure 2. Value function transforming a quantitative into a qualitative characteristic

Qualitative-quantitative flows

Information flows between qualitative and quantitative characteristics may be addressed applying fuzzy set theoretical concepts (interfaces of system dynamics and fuzzy set theory have been proposed by Wenstop, 1976 and Adamo and Karsky, 1977 among others).

Let us consider that to each characteristic corresponds a discourse universe U which includes all the possible degrees associated to that characteristic. Each degree is a fuzzy subset A of U. Subset A is defined by a membership function $u_A:U \rightarrow [0,1]$ assigning to each element x of U a number $u_A(x)$ in the interval $[0,1]$, representing the "membership degree" of x in A. Thus one may express the discourse universe of a given characteristic (either qualitative or quantitative) by a set, for instance:

$$U=\{a,b,c,d\}$$

The degree associated to that characteristic may be then represented by a fuzzy subset:

$$A=\{0.5/a,0.3/b,0.4/c\}$$

Having the qualitative and quantitative characteristics defined in fuzzy set terms, the value of a quantitative characteristic may be given in a certain instant, applying traditional system dynamics by:

$$L_t=L_{t-dt}+dt(RI-RO)$$

where L, RI and RO are fuzzy subsets.

The operations between fuzzy subsets may be done using "function operations" which are mappings intervening in the fuzzy subsets support elements (the support of a fuzzy subset A includes the elements of U for which $u_A(x)>0$). If A1,...,An are fuzzy subsets of U1,...,Un, respectively, and g a function mapping U1,...,Un into U, then g(A1,...,An) is a fuzzy subset of U given by (Chang, 1975):

$$g(A1,\ldots,An)=\{u(x)/x : x=g(x1,\ldots,xn),\ u(x)=u_{A1}(x1)\wedge\ldots\wedge u_{An}(xn) \text{ and } u_{Ai}(xi)/xi\ \Sigma Ai,\ i=1,\ldots,n\}$$

where $\wedge$ is a minimizing operator.

For instance, if A and B were fuzzy subsets given by (example taken from Chang, 1975):

$$A=\{0.2/1,\ 0.8/5\}$$
$$B=\{0.4/2,\ 0.6/3\}$$

then

$$A+B=\{0.2/1,\ 0.8/5\ +\ 0.4/2,\ 0.6/3\} =$$
$$= \{(0.2\wedge 0.4)/(1+2),\ (0.2\wedge 0.6)/(1+3),\ (0.8\wedge 0.4)/(5+2),\ (0.8\wedge 0.6)/(5+3)\} =$$
$$= \{0.2/3,\ 0.2/4,\ 0.4/7,\ 0.6/8\}$$

The vector obtained with these operations can be compressed into a scalar value, considering the average of the vector components or selecting from these the one with the higher membership.

LINGUISTIC SIMULATION--APPLICATION

The Sado estuary

The goal of this application is the simulation of the Sado estuary ecossystem from two standpoints: (1) the inputs of pollution and (2) the use of beaches. To achieve this goal, four main components were chosen: Sado beaches, Setúbal city, factories and a shipyard.

To construct the base layer three groups of characteristics were considered:

- .Natural estuary characteristics
  - .Degradation Capacity--DEGC
  - .Dilution Capacity--DILC
  - .Colour in the estuary--COLOUR
  - .Oil in the estuary--OIL
  - .Organic Pollution in the estuary--ORGPOL
  - .Biotic Activity--BIOT

.Tides--TIDE
.River Flow--FLOW
.Input characteristics
From the city
.Discharge of Organic Pollution--DORGPOL
From the factories and shipyard
.Discharge of Colour--DCOLOUR
.Discharge of Oil--DOIL
.User characteristics
.A social system including potential users of the Sado estuary beaches was considered. "BEACH USE" was selected as the most representative characteristic of this system, in the context of this simulation exercise.

Horizontal simulation step: layer 1

In this layer, the ecossystem behaviour is evaluated for each simulation period through a classical causal diagram (figure 3).

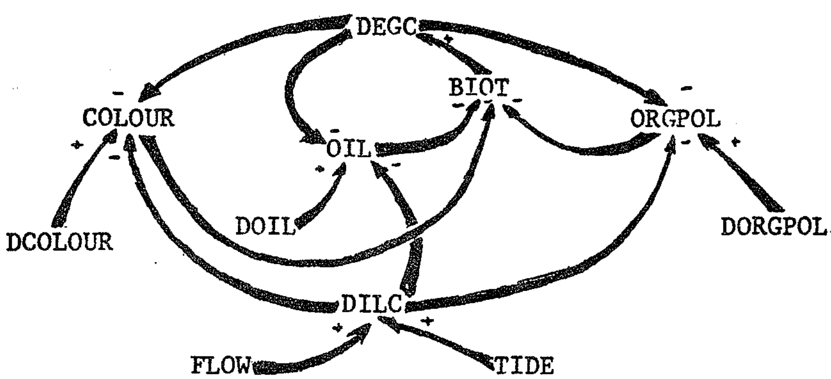


Figure 3. Causal diagram--Sado estuary model

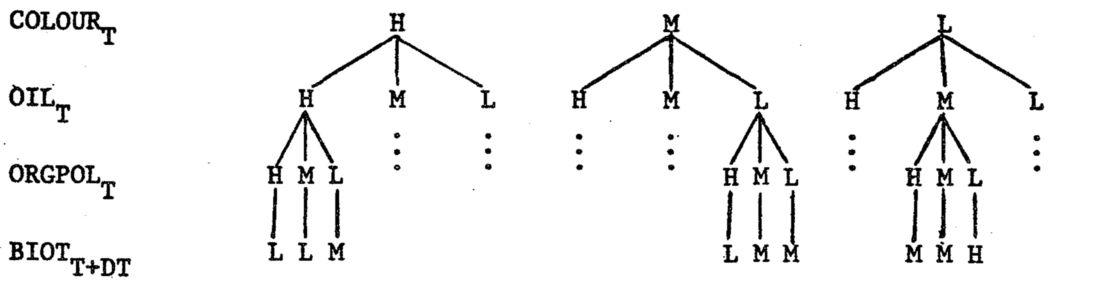
From this diagram the linguistic equations were developed (Table 1)

TABLE 1
Linguistic equations of Sado estuary model

DESTINY	RULES
DILC	$\square FLOW_T \oplus \square TIDE_T \rightarrow \square DILC_{T+DT}$
DEGC	$\square BIOT_T \rightarrow \square DEGC_{T+DT}$
BIOT	$\square COLOUR_T \oplus \square OIL_T \oplus \square ORGPOL_T \rightarrow \square BIOT_{T+DT}$
COLOUR	$\square DCOLOUR_T \oplus \square DILC_T \oplus \square DEGC_T \oplus \square COLOUR_T \rightarrow \square COLOUR_{T+DT}$
OIL	$\square DOIL_T \oplus \square DILC_T \oplus \square DEGC_T \oplus \square OIL_T \rightarrow \square OIL_{T+DT}$
ORGPOL	$\square DORGPOL_T \oplus \square DILC_T \oplus \square DEGC_T \oplus \square ORGPOL_T \rightarrow \square ORGPOL_{T+DT}$

The blanks in Table 1 represent the degrees associated to a characteristic in a given instant.

For this example a simple scale consisting only of three degrees: high, medium and low was selected. The operation of each rule is determined by a tree which combines the several degrees associated with the characteristics embedded in the rule. For instance, the operation of the rule which determines the behaviour of the characteristic BIOT may be expressed by a tree represented in figure 4.



H-high; M-medium; L-low
Figure 4. Example of a base rule "tree"--Sado estuary model

Vertical simulation step

The vertical model comprises four hierarchycal layers interacting as described in figure 5.

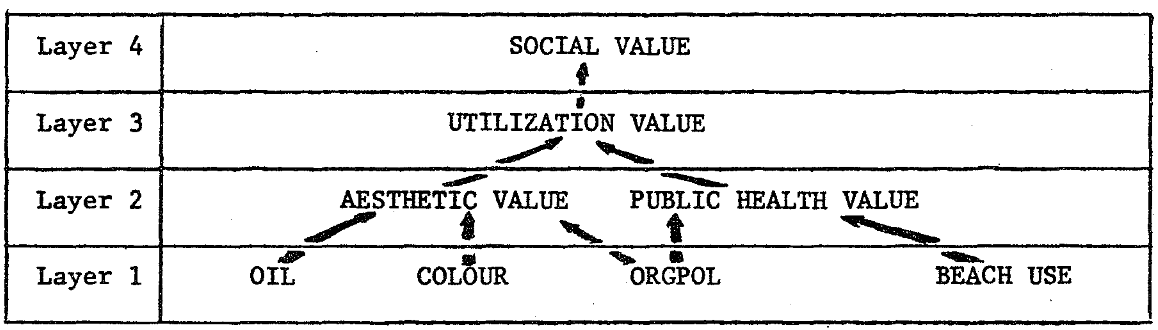


Figure 5. Hierarchycal layers--Sado estuary model

The rules applied in the transition between layers are presented in Table 2.

TABLE 2
Linguistic equations of Sado estuary model

LAYERS	RULES
1 → 2	[ ] $COLOUR_T$ ⊕ [ ] OIL_T ⊕ [ ] $ORGPOL_T$ → [ ] $AESTH.VALUE_T$ [ ] $ORGPOL_T$ → [ ] PUBLIC HEALTH $VALUE_T$
2 → 3	[ ] $AESTH.VALUE_T$ ⊕ [ ] PUBL.HEALTH $VALUE_T$ ⊕ [ ] BEACH USE → [ ] UTILIZATION $VALUE_T$

TABLE 2 (CONT.)

3→ 4	▭ UTILIZATION $VALUE_T$ → ▭ SOCIAL $VALUE_T$

These rules operate in the same way as those described in the horizontal simulation step.

Simulation results

The simulation inputs are presented in Table 3.

TABLE 3
Inputs of the Sado estuary model

CHARACTERISTICS	DEGREE
BEACH USE	HIGH
FLOW	LOW
TIDE	HIGH
BIOT	MEDIUM
ORGPOL	LOW
COLOUR	LOW
OIL	LOW
DILC	MEDIUM
DEGC	MEDIUM
DCOLOUR	HIGH
DOIL	HIGH
DORGPOL	MEDIUM

In Table 4 sample calculations for the first simulation step are included to show how SLIN operates.

TABLE 4
SLIN operations--first simulation step

DESTINY	RULES
DILC	LOW $FLOW_0$ ⊕ HIGH $TIDE_0$ → MEDIUM $DILC_{0+DT}$
DEGC	MEDIUM $BIOT_0$ → MEDIUM $DEGC_{0+DT}$
BIOT	LOW $COLOUR_0$ ⊕ LOW OIL_0 ⊕ LOW $ORGPOL_0$ → HIGH $BIOT_{0+DT}$
COLOUR	HIGH $DCOLOUR_0$ ⊕ MEDIUM $DILC_0$ ⊕ MEDIUM $DEGC_0$ ⊕ LOW $COLOUR_0$ → MEDIUM $COLOUR_{0+DT}$
AESTH. VALUE	MEDIUM $COLOUR_{0+DT}$ ⊕ MEDIUM OIL_{0+DT} ⊕ MEDIUM $ORGPOL_{0+DT}$ → MEDIUM $AESTH.VALUE_{0+DT}$
PUBLIC HEALTH	MEDIUM $ORGPOL_{0+DT}$ → MEDIUM PUBLIC HEALTH $VALUE_{0+DT}$

TABLE 4 (CONT.)

UTIL. VALUE	MEDIUM AESTH.VALUE$_{0+DT}$ ⊕ HIGH BEACH USE$_{0+DT}$ ⊕ LOW PUBL.HEALTH$_{0+DT}$ → MEDIUM UTIL.VALUE$_{0+DT}$
SOCIAL VALUE	MEDIUM UTIL.VALUE$_{0+DT}$ → MEDIUM SOCIAL VALUE$_{0+DT}$

This application attempts to illustrate qualitative linguistic simulation concerning only base rules. However, other objectives can be achieved. For example, when our goal is to observe the effect in public health, strategic and tactical rules must be applied. To accomplish so, strategic rules select only meta-tactical rules which deal with organic pollution as a destiny.

A sample output of the model may be represented by simple sentences in which the evolution of the system is shown by the successive changes in the degrees as presented in Table 5.

TABLE 5
Sample outputs after three simulation steps
Sado estuary model

T=1	THE MEDIUM DILLUTION CAPACITY AND THE MEDIUM DEGRADATION CAPACITY OF THE ESTUARY TO THE HIGH COLOUR DISCHARGES, HIGH OIL DISCHARGES AND MEDIUM ORGANIC POLLUTION DISCHARGES DETERMINE A MEDIUM SOCIAL VALUE FOR THE ESTUARY.
T=2	THE MEDIUM DILLUTION CAPACITY AND THE LOW DEGRADATION CAPACITY OF THE ESTUARY TO THE HIGH COLOUR DISCHARGES, HIGH OIL DISCHARGES AND MEDIUM ORGANIC POLLUTION DISCHARGES DETERMINE A MEDIUM SOCIAL VALUE FOR THE ESTUARY.
T=3	THE MEDIUM DILLUTION CAPACITY AND THE LOW DEGRADATION CAPACITY OF THE ESTUARY TO THE HIGH COLOUR DISCHARGES, HIGH OIL DISCHARGES AND MEDIUM ORGANIC POLLUTION DISCHARGES DETERMINED A LOW SOCIAL VALUE FOR THE ESTUARY.

FUTURE DEVELOPMENTS

SLIN is obviously in its early stages. There are still some loose ends,that may be observed in the practical example provided,in the sensivity to the value scale chosen to express the "degrees" of "characteristics", setting tactical and strategic rules and new structures and processing information flows between qualitative and quantitative representations. The authors believe however that in all these areas, theoretical and practical robustness will be achieved by just consolidating the ideas advanced herein. More than incremental developments will be the creation of a new diagramatic representation, a new linguistic simulation computer language (why not SLIN?), implementation in parallel computers and subsequent real-time linguistic simulation.

The development of a diagramatic language would greatly help in the formution of medium to large scale linguistic simulation models. The most simple representation could be, of course, a causal diagram as used in the example presented. A more precise diagram would include logical operators, which could be represented by traditional computer programming symbols, incorporated in event-graphs, to account for the system temporal evolution.

A new computer language to implement the methodology more efficiently then existing programming languages would have to be based on a very high level language such as PROLOG or LISP.

The implementation in parallel computers would represent though a more drastic development. For some time now, dynamic models have been programmed in parallel processors. Examples are the works of Huen et al (Huen, 1977) and Rzehak (Rzehak, 1977). This is because simulation models of dynamic systems consist generally of sets of ordinary differential equations, each one of these representing the evolution of a subsystem of the system being modeled. If one assumes,that for a time step, the integrations over each line are done independently, and this is the basis for all numerical methods, one has a set of parallel subsystems.

Huen and Rzehak have, basically, partioned common programs into clusters which are then executed in parallel, allowing for message passing between dependent clusters at some points in time (usually at the extremes of the time intervals of solution). The detection of parallel clusters and the organization of the parallel programs without deadlocks and inconsistencies applies timed Petri nets constructs (Ramchandani, 1973) or event-graph grammars (Goos and Hartmanis, 1979).

The main issue in this approach to continuous simulation modeling results from the trade-off betwenn the speed-up due to parallel execution of clusters and the the amount of message passing required to communicate between dependent clusters. On a purely intuitive basis, it seems that whenever the integration step is small (and in the solution of simultaneous differential equations, the smaller the better), the use of parallel computers may not lead to a significant gain. The application of parallel processing in dynamic modeling has however an advantage over sequential modeling from a conceptual standpoint--simultaneous equations should be modelled in parallel.

This conceptual advantage could be sufficient to investigate the feasibility of implementing this new kind of dynamic simulation--linguistic (dynamic) simulation--in parallel computers. But there are others.

One of the main objectives in the proposed methodology is to promote the communication between different disciplines intervening in planning, which occurs, in typical dynamic models, at the end of each integration step. It is at these points in time that messages are passed among dependent subsystems, each one of these representing one discipline. In reality, however, each discipline has its own time interval of solution as mentioned above. This implies that the intervals between the points in time when messages are exchanged among subsystems may not have constant size. The use of parallel processing could solve this problem through the use of multi-processors with different time-clocks (resulting programming problems were first addressed by Ramchandani, 1973).

Another advantage could well be the use of parallel processors in real time simulation. Each processor would be allocated to an expert representing a subsystem. A central controller would coordinate message passing. Simulations would then be made by each expert using rules such as the ones proposed in this paper. To facilitate his work, in a "window" of his processor, he could have a perspective on the evolution of the whole system --the trajectories of the system characteristics up to that time (the simulation of independent sub-systems could be even speed-up to augment his view).

The whole idea is to build a highly intelligent tool to simulate the future (like a modern time-machine). Using an analogy with the human brain, one has concurrently a primary line of thought and several secondary lines of thought, exchanging messages in some points in time. SLIN attempts to minimize the communication barriers usually occurring in message passing. Implementation of this methodology in parallel systems in real time would be much like building a physical model of a highly capable human brain, where each secondary line of thought belongs to an expert and the primary line to the central coordinator.

SUMMARY AND CONCLUSIONS

A new linguistic dynamic simulation methodology, 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, acceptance and structural change rules. To make the transition from qualitative into quantitative modes, fuzzy theoretic concepts are used.

SLIN was applied to build a simplified water quality model of Sado Estuary. This application showed the promise of linguistic simulation but also its present insufficiencies such as the sensitivity to the value scale chosen to express the degrees of characteristics and the difficulty in setting tactical and strategic rules and new structures.

Future developments including an appropriate diagrammatic representation, a new linguistic simulation computer language, implementation in parallel processing systems and subsequent real time multi-expert based simulation were also discussed.

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