Discrete Simulation and Related Fields

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DISCRETE SIMULATION AND RELATED FIELDS

Proceedings of the IMACS European Simulation Meeting on Discrete Simulation and Related Fields held in Keszthely, Hungary, 10-12 September, 1980

edited by

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PREFACE

It was an honour to have been asked by European Coordinator of IMACS, Professor Vansteenkiste, to organize and chair the European Simulation Meeting on Discrete Simulation and Related Fields.

Judging from the comments expressed by the participants, Keszthely, at Lake Balaton, Hungary, provided a very pleasant venue for the meeting.

In accordance with the general rules of IMACS European Simulation Meetings, participation was held low. Scientists from eleven European countries, viz. Belgium, Bulgaria, France, FRG, GDR, Greece, Hungary, Poland, The Netherlands, UK, USSR, were present thereby demonstrating that participation was international. A pleasant opportunity was provided for the fruitful exchange of fertilizing thoughts on the subject matter. The addition of "Related Fields" was a consequence of the fact that in modelling real complex systems with a considerable degree of fidelity, in some cases no strict border can be kept and artifical restrictions should be avoided.

Apart from the sessions on Methodology, System Modelling, and Applications a very lively Round Table Discussion took place under the title "Future Tools of Simulation versus the Future of Simulation Tools". This proved to be a highly stimulating part of the Meeting enabling the different thoughts and ideas on future trends including both software and hardware aspects to be aired; the informal give and take was highly interesting.

The discussion was recorded and is presented in this volume. Only a limited amount of editing was done to correct trivial errors and to remove some of redundancies due to the colloquial form. A few omissions were due to the quality of the recording at certain parts. Similarly, the papers of this volume are presented as the authors submitted them apart from the correction of minor typing or translation errors.

The present monograph is based on the Preprints Volume of the papers submitted prior to the Meeting. There are here: extended versions of papers presented at the Meeting; the edited version of the Round Table Discussion; and additional invited papers. This last category deserves further mention. We have the valuable invited papers presented by Professor Ameling and Professor Vansteenkiste that could not be included in the Preprints Volume. We also have papers invited from authors who were not present. Of these, I should like to draw particular attention to the paper of Professor Greenspan whose views and proofs by practical examples on the extended usage of discrete simulation in fields employing classically continuous methods are highly stimulating; and the contribution of Professor Shub representing a valuable survey paper.

The papers in this volume thus tackle discrete simulation and its related fields from various angles: methodology and principles of simulation, simulation system and language design principles, various fields of application, digital logic simulation and testing to be used as CAD tool, and the emerging possibilities provided by the boom of microelectronic technology in the application of new - parallel processing - multiprocessor based computing systems. Accordingly, the book is divided into four parts, viz. "Philosophy, Methodology, General Questions"; "Simulation Systems"; "Applications"; "Round Table Discussion".

The realization of this book owes much to the initiative of Professor Vichnevetsky, president of IMACS. Acknowledgements are due to the Central Research Institute for Physics, Budapest, and to the Hungarian Academy of Sciences for their support in organizing the meeting.

András Jávor

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TRENDS IN THE ROLE OF MODELLING AND SIMULATION

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The role of the digital machine in man's scientific and engineering endeavour has grown steadily. Formerly many problems could not be solved because the analytical skills were insufficient to properly utilize abstract and formal methods. The computer, however, has opened a new road to solutions. The approach has been called simulation. There has been a steady development of hardware and software tools so that the impact of the computer on the overall problem solving process has increased. This has caused shifts in the relative roles of modelling and simulation and even in their meaning. The paper gives a picture of the issues involved when formal and abstract models are used to solve real world problems. Based on the analysis, the concepts of modelling and simulation are developed and the trends in their roles are identified.

1. INTRODUCTION

In recent years one has witnessed a steady growth in the field of simulation. Especially the digital machine has become pervasive in scientific work as well as in engineering and industrial activities. The computer has changed man's scientific and engineering approach towards reality. A brief historical perspective will illustrate the point. Modelling in the physical sciences, whether it is approached physically by analogy or mathematically, has a long history. Newton was one of the first to construct formal, mathematical representations of a vast class of physical phenomena. During several decades abstract models have extensively been used to build complex physical theories or to develop formal descriptions. Unfortunately, the approach was not always succesful or it yielded results that could not be utilized due to a lack of analytical capability. Indeed one may have a faithful mathematical description for a given process, but in many cases one must have the analytical ability to manipulate the describing equations in order to be able to take profit of them. The advent of the electronic computer in the 1940's has brought a decisive change in the utility of the formalization process mentioned before. Initially it was mainly used for complex calculations that were formerly too tedious to perform. Quite rapidly it was realized that thanks to numerical schemes the machine was able to solve and manipulate equations that were analytically untractable. At first, around 1955, it was the aerospace industry which accepted the computer as a major tool in reaching its goals. Soon, the machine was accepted by other industries and since the early sixties it was also used for military and industrial operations scheduling. At the end of the sixties, it was realized that electronic machines could be assigned more complex tasks. Research in pattern recognition and artificial intelligence provided a basis for new developments. In the last decade, there has been a steady growth of the computer's performance for almost all its applications : one could mention advances in numerical techniques for solving partial differential equations and stiff equations, computed-aided design, computer-aided education, advances in artificial intelligence and robotics, developments in data storage and manipulation, etc... .

It is certainly beyond the authors capabilities to give a detailed picture or analysis of the issues that are involved when digital or discrete computing power is introduced in the many fields where the machine can be of use. In the paper here, we focus on the role the computer can play when a specific problem or a real world process is approached with formal and abstract means, like mathematical models and descriptions. In order to be able to refer to this approach, it is called here the scientific-engineering approach.

The text is organized as follows. Section 2 analyzes the scientific-engineering approach in order to show how and where the digital machine can be of help. An analysis of the process is given before the digital machine was introduced and a second present day overview is given. The reasons for the developments are given. Then the concept of simulation is presented in section 3, followed by the concept of modelling in section 4. Section 5 gives a sharper description of man and machine cooperating to solve a problem. Section 6 finally discusses the trends that has occurred in the role of modelling and simulation. It is the hope that in that manner, the reader will have obtained a better insight into the manner the electronic machine did and will modify human scientific-engineering endeavour.

2. RELATIONSHIPS AND ACTIVITIES IN THE SCIENTIFIC-ENGINEERING APPROACH

2.1. An example for illustration

Before giving a more general discussion on the relationships and activities that characterize the scientific-engineering approach to reality, an example is provided. It may serve as an illustration for the general discussions that will follow.

A bioengineer is working in a fermentation plant where micro-organisms are cultivated to obtain a useful product, for instance an antibiotic. Suppose that there is evidence that the temperature of cultivation is a crucial factor of the overall process. The engineer's objective may be to look for a temperature profile during the actual fermentation process, which optimizes the product yield. Clearly the brute-force approach consisting of trying out all temperature profiles is unfeasible. An approach to the problem may be the following : first a deterministic dynamic state space model is looked after. The model describes growth and product formation and it incorporates the influence of temperature on those variables. Then a suitable cost is defined and a mathematical optimization technique is applied. The scheme makes use of the dynamic model and its result is a temperature profile which optimizes the cost. Having the example in mind it is quite easy to recognize and define the major interactions between man and reality in more general terms. In the next section the case is considered when no explicit reference is made to computers or advanced computational power. The discussion is appropriate in case the model builder has no computer at his disposition ; or in other words the discussion was the only valid one before the advent of the digital machine.

2.2. Interactions between man and reality

Before the widespread use of the digital machines relationships and activities in the scientific-engineering approach were largely determined by the human mind and its formalization and analytical powers. A description of the process can most easily be given with the help of a diagram shown on Figure 1.

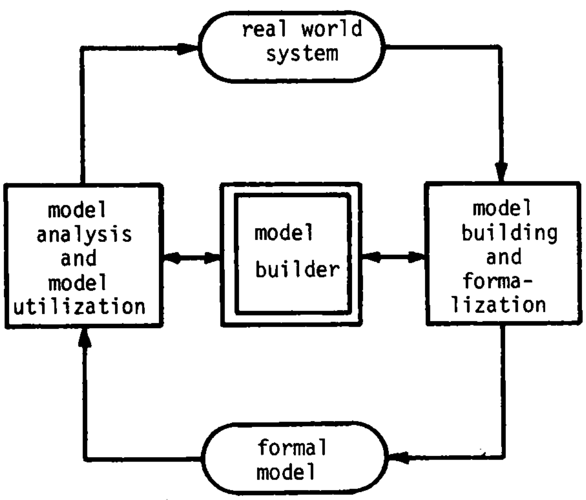

Fig. 1. Interactions between man and reality

At first the scientist or engineer who approaches a real world process or system tries to gain insight or an understanding of the phenomena or the processes under study. One of the very powerful methods consists in trying to obtain an abstract or formal model or representation of the process. The activity is defined here as model building and formalization. In essence the procedure requires abstraction and simplification. A typical example of the abstraction process is the representation of a property of the real world system by a quantitative or numerical quantity. Simplification is necessary to restrict the complexity of the representation. One only chooses those properties within given boundaries of space or time which are believed to be connected with each other but unconnected with other properties or other parts of the world. Basically the model builder proceeds by hypothesis, induction and deduction. However, the procedures for model building are seldom straightforward especially when the model is not overly trivial. The complete body of methods is called modelling methodology.

The formal model, though a simplified representation of reality, always summarizes a vast amount of information, comprising facts, axioms and hypotheses. If its validity is high or in other words if its descriptive quality good, then it can be used to obtain useful knowledge on the system under study. This knowledge is not directly available in the sense that the model has to be analyzed, manipulated or incorporated in other mathematical procedures in order to provide the answers required. The latter step is called model analysis or model utilization. In giving the picture of the approach we have glossed over many difficulties and sensitive points. Those will be discussed next.

2.3. Difficulties inherent in the scientific-engineering approach

The scientific-engineering approach discussed up to here certainly does not guarantee success. All formal descriptions whether they are complex theories of a vast class of phenomena or they are more simple mathematical equations describing a more restricted process are subject to error. Indeed, one single experiment that is in clear contradiction with the derivations of a theory or model topples that theory or model or at least sets their limits. Because theory or model building always encompasses inter- and extrapolation, its validity is a direct function of the precision of the measurements and the number of validity checks performed. Those are facts of life and they are well-known and accepted as the limits and dangers involved when utilizing the scientific-engineering approach.

Unfortunately, the approach may fail for much more down to earth reasons. It may happen that methodology is lacking or that carrying it through by hand is inconceivable, so that the formal model cannot be obtained. It also happens that a model is available but that manipulation is not possible because man's analytical skills are much too limited. As an example, consider the Schrödinger equations ; they are a useful model but in many circumstances, they cannot be solved. Such problems are frustrating and it is here that the advent of the digital machine has opened new vistas and revolutionized the field. Here lies the birth of simulation.

2.4. Interactions between man, machine and reality

As long as calculating devices are used as simple and straightforward computational support, it is not necessary to modify the basic picture on Figure 1. In fact the most dominant and important interactions are present. Clever computation on a digital machine, however, adds a new methodological dimension. It is agreed upon that in certain cases the computer's availability may be the crucial factor in reaching the goal. More recently however, it has been realized that a digital machine endowed with vast amounts of software may be of tremendous help in the whole approach. From this point, it is useful to consider the machine as a crucial part of the scheme and a more complex picture follows - see Figure 2.

The basic scheme can directly be recognized. Besides the computer as an active agent, which cooperates directly with the model builder, there is a new entity termed programs. The programs may take different forms. This will be discussed later on. Very often the main part of the program follows from the formal model or is related to methodology for building or using those models. There are basically two new activities. The first consists in preparing the digital machine for useful work. It is called programming, taken in a broad sense. It may actually comprise writing program code for the computer but it also means preparing the machine through data input, through conversational interaction, through program set-up, through library search, etc... . The second activity is for a large part the job of the digital machine and consists in actually doing the computations and calculations. It is important

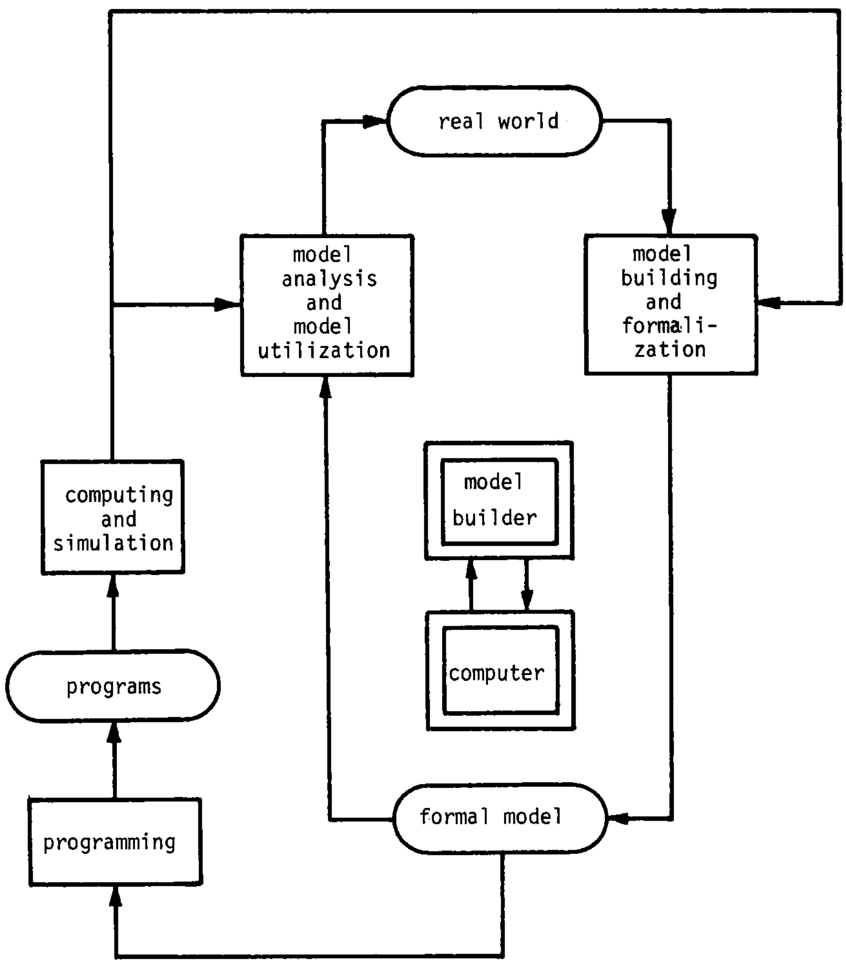

Fig. 2. Interactions between man, machine and reality

to note that the work may be in support of the model building and formalization step as well as in support of the model analysis and model utilization step.

In order to see the relevance of the new activities and interactions, the example presented in section 2.1. can be considered again. Due to the nature of the process under study, it will happen that the impact of the temperature on the growth and product formation equations can only be introduced with the help of experimental outcomes. The model equations will contain parameters and the numerical values of those parameters will have to be inferred from the data points. Though approximate procedures may exist a statistically appropriate approach will require a numerical parameter estimation scheme which is computationally much too demanding in order to be executed by hand. Programming may be required to prepare the parameter estimation session and computation will be needed to obtain the actual values.

Once the model is obtained, Pontryagin's principle can be applied on a suitable cost. Unfortunately the formal model is likely to be nonlinear and there is very little chance that an analytical solution can be found. Here again the computer has to be used and again the programming and computation steps are required to find a solution. The changes in the scheme representing the major steps in the problem solving process indicate the growing role of simulation. This trend will be discussed in the next section.

3. SIMULATION

It is fair to say that before the advent of electronic devices simulation activity, though it existed, was of limited importance. The ability of the computer in solving equations and models has quickly been recognized and out of it the field of simulation has originated. During the years, shifts in meaning have occurred. Therefore the concept is developed in the light of the discussion of the previous paragraph.

3.1. Simulation in the small

The original idea and the 'core-meaning' behind simulation is the 'running' of a model on a machine. Herewith it is meant that on the computer a program is executed that represents a given physical process. As a consequence experimentation can be done on the machine in a hopefully much faster way and much more flexible manner than on the actual real world system. From a mathematical point of view, simulation is equivalent to solving equations computationally. The tremendous impact that simulation has had is a clear indication that in many practical problems the methodological tools for solving models analytically were lacking. This corroborates the statement made before that very often technical issues have hampered the scientific-engineering approach.

It is now possible to evaluate the role of simulation in the context of this paper. It is quite obvious that simulation will be useful in the model analysis and model utilization stage. In order to put the formal model to use, it is very often required to solve the equations under a number of conditions that are specific to the problem at hand. Some further thought however reveals that very often simulation will also be useful in the model building and formalization stage. Indeed, many modeling techniques require the solution of 'candidate' models because a comparison has to be made between measurements and model equations.

Having established those facts, it is now interesting to turn back to the scheme on Figure 2. Clearly simulation belongs to activities summarized under the heading computing and simulation. The program consists in a numerical solution technique for the formal model together with a programmed specification for the equations. The programming task consists in designing those programs or in providing the specifications for a suitable simulation language. It is the thesis of the paper that simulation with the meaning given here is only a part of the computational solutions that are available to the model builder. Therefore, it has been called here simulation in the small.

3.2. Simulation in the large

Based on the scheme in Figure 2, it is possible to give a more general meaning to the concept of simulation. One could define simulation or more adequately simulation in the large as the global set of computational activities that are involved as support during the problem solving process. There are many useful numerical and computational procedures that are not directly related to simulation in the small, but which may be of real help in building a formal model of utilizing such a model. To be mentioned are structure characterization methods, direct or recursive parameter estimation schemes, optimization procedures, dynamic non linear and linear programming techniques, experiment design methods, statistical analysis procedures, etc... in as far as those methods are of direct help for the study at hand. One could even go further and include activities like table look-up, model base search, etc... . Those issues and the trend from simulation in the small to simulation in the large will be discussed in section 6.

4. MATHEMATICAL OR FORMAL MODELLING

The act of modelling and more specifically modelling methodology is basically more oriented towards human intervention. One can distinguish different levels of such intervention.

4.1. Modelling in the small

The basic meaning of mathematical modelling - referred to here by modelling in the small, consists in applying inductive and deductive techniques in order to obtain a formal representation of a real world process. Modelling itself is for a part still considered as an art. There are a large number of factors that come into play.

As mentioned before, the representation process involves almost always 'inter- or extrapolation'. Certainly, a large body of methodology is objective and mathematically sound. Many tools are well-defined and clearly stated. Statistical techniques, parameter estimation procedures, etc... have a firm logical basis. Standard techniques cannot solve all problems. The final product is the result of careful trade-off's between existing facts, decisions on the choice of representative details, careful experimental work and its interpretation. Examples of such issues relate to the choice of formalisms, the evaluation of the validity of a priori facts, the required level of descriptive details, etc.

It is to be noted that modelling and its methodology only refer to one of the branches on Figure 1. In general one will have to draw on analysis and model utilization techniques in order to reach one's goal. Those procedures are by no means always straightforward, but by tradition they have not been included in the concept of modelling.

4.2. Modelling in the large

Modelling in the large has yet been given different meanings. Zeigler for instance, refers to modelling in the large when model integration is performed. Herewith it is meant, that different descriptions of the same real world process are compared, screened for consistency and integrated into a whole. Notice that the activity is a basic step in scientific work, especially in the process of developing a theory and working out general principles. Because modelling in the large, in the sense mentioned, is nothing else but a modelling activity at a higher abstract level, we simple consider it here as modelling.

With modelling in the large we mean here the act of model building and model utilization and its methodology refers to the techniques that can be utilized to execute that act. In that sense, modelling in the large refers to both branches on Figure 1 as well as on Figure 2 and it is a more complete concept when we refer to the scientific-engineering approach in general.

5.INTERACTION BETWEEN MODELLING AND SIMULATION

According to the Figure 2 simulation activities support model building and model utilization. Before discussing the trends in their role, it is useful to have an idea concerning the way the activities are supported. Modelling and simulation are performed by man in cooperation with the computer. A better understanding is obtained if one considers a more complete diagram of the levels involved - Figure 3. Modelling and Simulation activities are in fact highly sophisticated processes that require the availability of a number of hierarchically organized levels.
In case of the model builder, the lowest level refers to the body which supports the human mind. The mind itself allows man to think. In case of the processes involved, logic and mathematics are the basic substrate for more complex processes. At the highest level one finds human modelling methodology, know-how concerning the real world system under study and model building

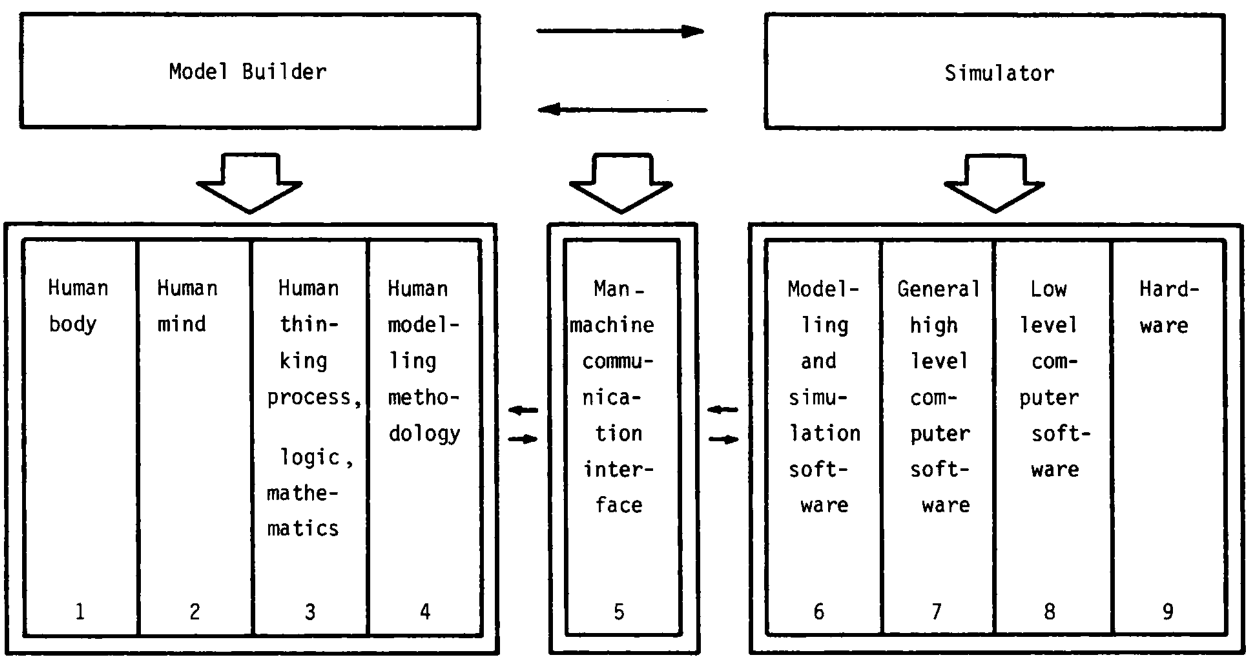

Fig. 3. Build-up of the model builder and the simulator

experience. For simulation activities one first has a hardware level. The hardware has to be provided with low level computer software : machine language and other elementary software tools. Then one has a higher level of general computer software : higher level languages, data storage facilities, etc... . Finally there is the specific advanced modelling and simulation software. As the processes at both sides are rather complicated, smooth cooperation is only possible if there are provisions for suitable man-machine communication.

It is important to note that levels 4, 5 and 6 on Figure 3 have not reached complete maturity. Furthermore though the human side is rather stable, new developments in computer hardware still continue and so the simulator is in continuous development. This fact will been of interest in the next section.

6. TRENDS IN MODELLING AND SIMULATION

Having in mind the build-up of the principal agents during objective problem solving, it is clear that nowadays modelling and simulation have to go hand in hand. It is now more easily to describe the trends that we have witnessed in the few last decades.

Before the fifties modelling and especially modelling in the small was dominating the overall approach, simulation activity was very limited. The advent of the digital machine has dramatically changed the picture. Simulation in the small supported first the model building and model utilization process. The availability of computing power has however also had its impact on modelling methodology. Indeed formerly methodology was developed for its user : the model builder. Man is especially apt in reasoning and in recognizing patterns. His computational powers however are limited. The digital machine however is extremely fast in calculatory operations. Such computational powers can be exploited in methodology. Consequently in the last decades a vast amount of techniques have been developed, which assume implicitly the existence of the machine. At the same time higher levels of computer software were implemented. Modelling in the large and simulation in the large developed concurrently. As mentioned before, nowadays there still are few cases were simulation software is developed to its very limit, while human modelling methodology is utilized at its highest level, partly for cost reasons, partly because the simulator is still in development.

It is difficult to say where the future leads to. There has been arguments that with time, modelling methodology could be incorporated for its major part in 'intelligent', 'self-organizing' machines, so that human intervention could be brought to a bare small level. In such cases, simulation would in a sense supplant modelling. Whether this is possible remains to be proved. In any case rules for 'intelligence' and 'self-organization' would be required which as a human activity would result in a new trend in the meaning of modelling. Much more likely is that developments in modelling and simulation will go hand in hand, maximizing the particular aptitudes of both man and machine.

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PROPOSALS ON THE STRUCTURE OF SIMULATION SYSTEMS

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The problem of building efficient discrete simulation systems is treated in a general way, taking into consideration the amount of work needed for system design and utilization of the system. The application is proposed of a single invariant internal structure with several different user oriented outer layers, i.e. languages. The suggested solutions for the structuring, state representation as well as the executive of the internal structure are presented.

1. INTRODUCTION

The need to investigate and penetrate into the different aspects of the complex world around us has led to the rapidly increasing use of simulation. This has had two consequences:

a/ A great deal of knowledge about simulation tools has been accumulated from practice.

b/ The contradictory demands for efficient "high fidelity" and simultaneously low cost simulation have to be met.

More than a decade earlier, the question "Do we need all these languages?" arose [1], initiating a debate on whether a single general purpose tool or specialized tools are necessary. In recent years an enormous number of simulation tools (languages, packages, systems) have emerged indicating that this problem has still not been settled [2][3].

Simulation now seems to be sufficiently mature for us to attempt a unified approach to the problem because clear theoretical concepts have been distilled from practice on outlining the concepts allowing simulation tools to be used [4][5][6][7][8]. Activities on standardization in the framework of IMACS have also begun. This paper sets out to add some ideas to these efforts based on the more than ten years of research and development in the field of discrete simulation.

2. THE PROBLEM

It seems that a very definite controversy does exist between those having a highly specialized approach and the wide community of people who require their well-defined practical problem to be solved by simulation. The latter group are from different disciplines, they have problems to be solved and they are concerned solely with their own problem. To the simulation expert a well structured highly sophisticated language that enables model building in practically every field looks attractive whereas the latter category requires a highly specialized tool directed to a specific field of interest, enabling model-building to be performed as conveniently as possible in what tends to be a narrow field, with its special terminology and which deals with as few general simulation concepts as possible. The problem is somewhat similar to that of ALGOL 68 in general purpose high level languages. A theoretically well structured very powerful language has been developed but just this high complexity poses a problem for the average user who would be satisfied with a far simpler structure with less possibilities but with a language more closely fitted to his specialized demands.

This aspect is even more important in the field of simulation because modelling is of interest mainly to people who are experts in the subject matter of the field to which the model belongs (i.e. chemistry, biology, microelectronics, economy, agriculture, etc.) and *not* in programming languages, computer science or simulation as a discipline on its own. This is a matter for serious consideration since it is a fact that simulation is already used practically everywhere.

A useful analogy might be that of railways which are used by everyone everywhere but we have to keep in mind that the great impact of railways on transportation results from the fact that it is not only railway personnel that use the trains. It can thus be seen that contradictory requirements for universality and specialization exist.

3. ONE INNER STRUCTURE - SEVERAL LANGUAGES

Let us try to resolve the problem. Laski's concept [9] of the simulation system consisting of a simulation language and an executive can be extended further. Let us divide the simulation system into an inner structure and an outer layer. The invariant inner structure has to be such as to be able to handle effectively model structures in general; it needs also to provide an effective time advancement method that adapts itself well to the different event distributions of different models [10]. The outer layer means that the languages can be fitted to each field of application. This concept may lead to considerable savings in time (i.e. money) spent on simulation.

In the conventional way, the amount of work needed for simulation can be expressed as

$$M = \frac{M_D}{N_M} + M_M \qquad (1)$$

M being the amount of work needed to solve a single simulation task

M_D the amount of work needed to develop the simulation tool used

N_M the number of models simulated using the above tool

M_M the amount of work needed to simulate a single model

(the above values are, of course, mean values).

M_M decreases if the simulation tool used is more specialized for the given field, but at the same time N_M decreases if the field of application is more restricted.

By using our proposed construction the overall amount of work can be expressed as

$$M' = \frac{M_{DL}}{N_L} + \frac{M_{DS}}{N_S} + M_M \qquad (2)$$

M_{DL} being the work needed to develop the language (and its compiler) used

M_{DS} the work needed to develop the inner structure (executive)

N_L the number of simulations using the same language

N_S the number of simulations using the inner structure,

where

$$M_{DL} + M_{DS} = M_D \qquad (3)$$

If we use the level of specialization usual in specialized packages, the values M_M in formulae (1) and (2) are equal, $N_M = N_L$; and because $N_S \gg N_L$,

$$M' < M \qquad (4)$$

Q.E.D.

This concept does not contradict the need for an advanced general purpose simulation language for two reasons

a/ In cases when the field of application (i.e. N_L) is very limited the development of a specialized language cannot be justified and it is better to let M_M grow thereby making $M_{DL}=0$.

b/ A universal language attached to the inner structure can serve as an intermediate language into which the other languages are mapped (see Figure 1).

4. SOME CONCEPTS FOR THE INNER STRUCTURE

In order to have a universally applicable inner structure it is necessary to design it in such a way that models from a wide range of applications could be mapped conveniently into it. Simultaneously, the inner core has to provide for an effective model representation both statically (i.e. storage space used) and dynamically (i.e. run time required).

In order to achieve this end a number of measures have to be taken in designing the inner structure. In the following we outline some principles whose application would seem to be advantageous.

1. The structure of the model should be built up from - a generally large number of - interconnected "element modules" with inputs, outputs, states and algorithms describing their operation, i.e. next state and output functions analogously to the quintuples of automata [11][12]

$$A = \langle Q, X, Y, \Psi, \Phi \rangle \qquad (5)$$

where Q, X and Y represent the internal, input and output alphabet respectively; Ψ is the next state function and Φ the output function performing the mappings:

$$q(t+1) = \Psi[q(t), x(t)] \qquad (6)$$

and

$$y(t) = \Phi[q(t), x(t)] \qquad (7)$$

where

$$q(t), q(t+1) \in Q;\ x(t) \in X;\ y(t) \in Y.$$

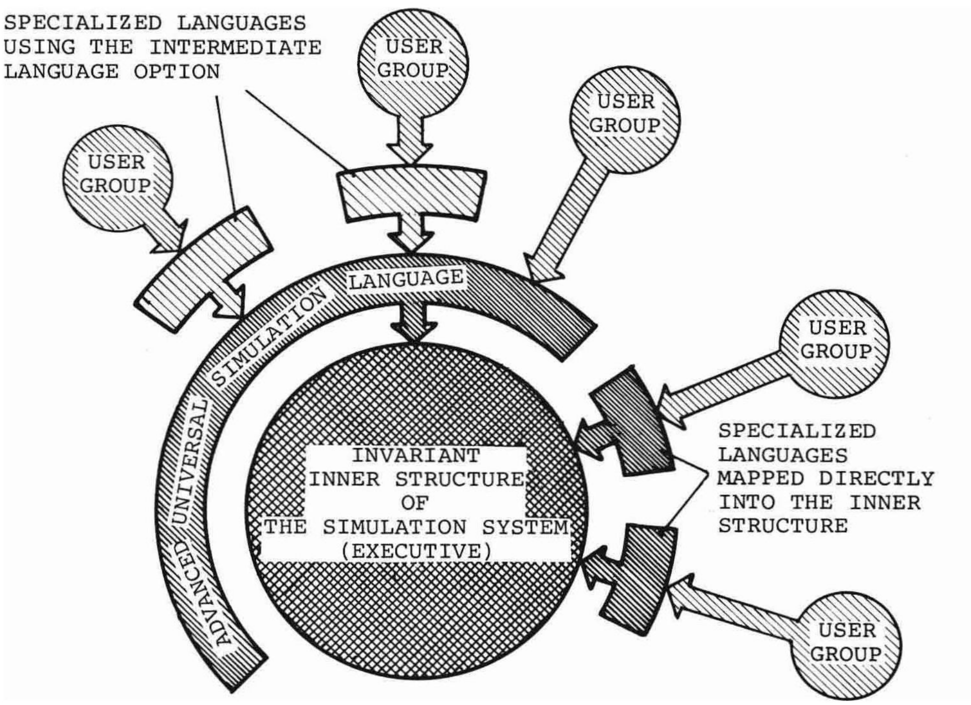

Figure 1 : Proposed simulation system structure

A generalization of the ordinary deterministic automata results in the probabilistic automata. Here an input letter $x \in X$ transfers the automaton from state $q_i \in Q$ into any state $q_j \in Q$ with constant, time independent probabilities $\Pi(x,q_i,q_j)$. As we do aim at the realistic description of systems in simulation, the description very often takes the form of a very important subclass: the automata with delay (i.e. Moore automaton). Here the only difference to the formulae above is that the function Φ takes the form $\lambda(q)$, i.e.

$$y(t) = \lambda[q(t)] \tag{8}$$

and the present value of y does not depend on the present value of x. This can be interpreted as the mapping of reality considering the fact that changes in physical systems never occur instantaneously although in a number of cases this time delay can be ignored.

The operation of the models in simulation however is controlled by mechanisms of time advancement different from those used in the classical description of finite automata, since in the former case some time advancement algorithms are based on unequally quantized time steps, by skipping those time increments where no change in the existing $\langle q_i, y_i \rangle$ takes place.

Thus the following problem may well arise.

At t_1 the letter $x_1 \in X$ schedules the next change to t_2 from $q_i \in Q$ to $q_j \in Q$ and analogously from $y_i \in Y$ to $y_j \in Y$. At time instant t_3 where $t_1 \le t_3 \le t_2$ (or in delayed automaton representation $t_1 \le t_3 < t_2$) another letter $x_2 \in X$ changes the anticipated next states $\langle q_j, y_j \rangle$ to $\langle q_j', y_j' \rangle$ and the anticipated time of the change to t_2'.

More precisely speaking: generally there are scheduled subsets $Q_2 \subset Q$ and $Y_2 \subset Y$ respectively to the set of future time instants T_2, i.e. for which the relation holds

$$(\forall t_{2i} \in T_2)\ (t_{2i} \ge t_1) \tag{9}$$

or

$$(\forall t_{2i} \in T_2)\ (t_{2i} > t_1) \tag{10}$$

for "delayed automata".

The letter x_3 may change the scheduled subsets to $Q_2' \subset Q$ and $Y_2' \subset Y$ and their re-