FUNDAMENTALS OF SIMULATION FOR COMPLEX SYSTEMS

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Summary

Simulation in general pretends to deal with a real thing, while really working with an imitation. In Operations Research the simulation is a computer model of the imitated reality. Computer simulation is a fundamental discipline for studying complex systems. One of the great values of simulation is its ability to effect time and space decomposition of the system, which allows comprehending the system behavior in minutes or hours, while normally, that would take a very long time. Like any other discipline, simulation must grow and be fine-tuned so that it maintains its position as the base methodology underlying computational science and construction of virtual worlds.
Simulation is intimately connected to mathematical modeling. These two activities have the same purposes - forecasting of behavior of an actual object and obtain guidelines towards the choice of controls. In both cases the mathematical models of actual objects are used.

The difference is in the modes of work with outer states of the model, controlled and uncontrolled. In mathematical modeling the forecast of uncontrolled outer states and the selection of controls implements formal methods of statistical processing and

optimization.

But the capabilities of formal methods are limited, therefore dealing with complex problems the expert ways of construction of the scripts for the outer states and designing of the different control circuits are used, whereas a computer in accordance with the mathematical model calculates the inner states. Such types of the man-machine procedures are called as computer simulation.

1. Simulating Complex Systems

To play SimCity on a computer is safer and cheaper than build and manage a real city. For precisely this reason computer models are used in industry, businesses and military: it is very costly, dangerous or even impossible to make experiments with real systems. Provided that models are valid descriptions of reality, experimenting with them can save time, money and efforts.

Simulation embodies the principle of “learning by doing” – to learn about the system one is first to build a model and then work with it. So, simulation is an activity that is as natural as role-playing by children. Computer simulation is the adult equivalent of children’s toys and imagination in the understanding of reality in all of its complexity. To recapture the lost imagination of children, one builds the virtual world, using computer simulation and acts out roles with its interacting dynamic artificial objects.
Within the overall simulation technology, there are five primary sub-fields:

- Model building,
- Identification,
- Execution,
- Verification, and
- Exploitation.

(see *Modeling and Simulation Techniques,* and *Life Cycle Processes for Model Definition and Deployment*).

The concept of a “complex system” is rather relative: today a system is complex i.e. its prognosis is on the edge of the mathematical modeling technology, but tomorrow after some technology development, the same system may become simple. Nevertheless, there are some features of “complexity”:

- Complex model structure, i.e. great number of components (groups, objects) and complicated relations among the components;
- Complex model dynamics, i.e., big information flows among the components, and dependence of the components behavior on this information;
- Great number of inner and outer state variables;
- Presence of stochastic outer states in model equations;
- Impossibility to obtain certain results without computer;
- Presence of human controls (i.e. presence of outer states which are chosen by experts in such a way, that the properties of system acquire the “desired”

character);
- Elements of virtual reality.

The examples of such complex systems may be R. Reagan's Strategic Defense Initiative project, or the project of Global Ecological Monitoring System (see *Global Environment Models*, and *Socioeconomic Models*).

2. Concepts of Simulation for Complex Systems

Historically the first attempt at simulation of a complex system, which got worldwide attention, was Jay W. Forrester's System Dynamics in 1971 (see *System Dynamics Models*).

The concept of System Dynamics, in a nutshell, is to define state variables involved in a model, and then study the relations among them using the principles of feedback, so the system behavior is treated as a result of feedbacks among the state variables. To describe quantitatively the feedbacks among the state variables, the "Dynamo" language was introduced. The System Dynamics approach is most fruitful when there is rather a small number of state variables and events, which may change the system stage, occurring not very often. The System Dynamics approach is often applied for improving the quality of models by using methods and insights from feedback control engineering.

> **The disadvantage of this approach is that it can hardly deal with systems, where the events, which may strongly change the system stage, occur very often. Further, when the number of the states increases as n, the number of possible feedbacks grows as n^2, and even the task to find out the actual feedbacks becomes rather complicated. Finally, there is no clear way to decompose such a complex model into a set of more simple components, and this will cause difficulties in the process of model building and debugging.**

The next step in the simulation concepts development was the appearance of the Object Approach in the mid 1980s. It is well known that the roots, from which the object-oriented programming grew, were in the field of simulation.

The heart of the Object Approach is the idea of decomposition. Nobody can clearly comprehend how such a complex system as the Strategic Defense Initiative works entirely. But one can describe how it works as an observation station, or a command center, or a missile. The idea is to decompose the whole system into a set of objects and simulate each object separately, then link the simulated objects into the whole model, run it, and see what happens. The problem is to find rules of synthesis, which would permit linking the separately simulated objects into the entire model. But the reality itself encourages solving this problem: most complex systems consist of their components, which will be the objects in our approach, and interrelations among them are what they are (i.e. are known as a part of arrangement of the system). So such decomposition is to conserve the system arrangement, for the future synthesis.

Multimodeling Approach: Modeling complex systems requires a "model of models", or a hierarchy of models where each model represents the systems at a given level of abstraction. The need for this kind of model was first brought out when blending discrete event methods with continuous methods. As the essence of the multimodeling is decomposition again, it may be combined with an object-oriented approach: a model is supposed to be a group, and each group may consist of groups and/or objects. So there is a hierarchy of object-oriented models. The multimodel is computationally more attractive than the single level model because the analyst may weave through the abstraction network while focusing the computation of dynamics only on those areas that require additional computation. To design more effective models, one needs to have models containing more than one level of abstraction. Such a model may be more complex, but it can answer a larger class of questions than a single-layer model. It gives an ability to choose the lowest level of detail on those parts of a model which are of special interest.

A further step in simulation concepts development was the Event Approach. The idea to serve an event whenever it occurs is known in programming from the time of the first Interrupt Service Routines (ISR). A computer processes its routine job, and when an inquiry from some external device occurs, the computer interrupts its job and an ISR serves the inquiry, then the computer resumes its interrupted job, though it may be now influenced by the results of the ISR call. But this idea became very popular in programming of the 1990s, when event-oriented languages appeared. In simulation of complex systems the Event Approach was used from the end of the 1980s. From the simulation point of view, the main idea of the Event Approach is decomposition again, but here it is the decomposition of time. This decomposition conserves the set of system events. If there are no events, all elements of all the processes do their routine jobs, but it is known about every element what kind of system events it may cause, and before the element begins its routine job, it schedules the nearest system event it will cause in future. A system event may change the order of elements execution, and then the routine jobs of all the elements repeat, till the next system event occurs.

This scheme of alternation of the routine job and the system events is the basis of the synthesis, discussed in the section devoted to the Object Approach. Taking it along with the Object Approach and Multimodeling, one can get the Multimodel Object/Event Approach − the most powerful of contemporary methods for the Simulation of Complex Systems. The main advantage of this approach is that all the interrelations of the elements become carried over the system events – the points of synchronization of all the processes – while all the elements, while running their routine jobs, are independent of each other. The power of this decomposition allows the members of the team working the simulation to elaborate the routines of elements concurrently and independently, knowing almost nothing about the neighbor’s work and the entire project, but being sure that the entire model would start to work properly, just after the programming and debugging of all the elements was completed. So this approach is profitable from the point of view of the team programming technology, and the last fact is a sufficient advantage of the method, as the Simulation of Complex Systems is always a task for a team. Further, as between the two adjacent system events the elements run independently, so they may run concurrently, on parallel processors or on several workstations in a computer network. So the Multimodel Object/Event Approach leads to the idea of Parallel, Distributed and Web-based Simulation.

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Biographical Sketches

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