THE ROLE OF SIMULATION IN SOLVING COMPLEX OPERATIONS MANAGEMENT PROBLEMS: A REVIEW

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Introduction

This paper begins with an explanation of what is meant by modelling and shows simulation to be a sub-set of modelling. It then discusses the nature of simulation and how it may be used to solve particular types of management problems. The development, and continuing evolution, of simulation as a management tool is explored. The impact of this evolution on the interdependence of manager and management scientist is examined. The paper concludes with a look at likely future developments in simulation.

Modelling

Naert and Leeflang (1978) succinctly define a model as "a representation of the most important elements of a perceived real world system".

In certain circumstances it is practice to build physical models of systems to increase understanding and appreciation, e.g. Sir Christopher Wren built a scale model of St. Paul's cathedral. Wind tunnels are used to test the aerodynamics of prototype cars and aircraft. Engineers build model dams to experiment with water flows. These examples of iconic models, while of immense benefit to the professionals who use them, are of minimal relevance to managers.

In the early days of simulation, before computers were available, analogue models were sometimes used. These are models which imitate the process or system being studied. One such model is described by Jones (1992). Scaffolding 50 feet high was the framework on which the model was built and the vertical drop of lead shot through hoses, biscuit tins and the like was used to imitate the horizontal flow of a proposed steel plant. Three tons of lead shot (which had to be manually hauled in buckets to the top of the scaffolding) were used in the model. The approach was certainly original and the model worked, but such methods have become redundant with the advent of computers.

Conceptual models, rather than the foregoing physical models, are more likely to be of relevance to managers. Let us examine a hierarchy of such models. At the first level we have a verbal description of a system. This is a model of that system in that it attempts to capture the essence of the reality and should ignore irrelevancies. A written

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description is better than having no model as it helps to refine, communicate and make explicit a common understanding of a system. The second level in the hierarchy is some form of system diagram. One objective means of recording the processes in a system is to produce a flow diagram which represents, for example, the progress of work or documents through a system. More sophisticated system diagrams show cause and effect relationships. These latter models are of benefit, for example, in developing an understanding of a complex economic system. Quantification, applied to a system diagram, takes us to a higher level again. To know how many items are produced per week, what was the profit made last financial year, when did the new machine start on the production line, or, how many full time equivalent staff are in post, gives a more powerful model than one which is not quantified. Measurement enables us to gauge the performance of a system and hence to compare similar systems or examine one system over time.

Even more powerful is the establishment of mathematical relationships. In forecasting, for example, if sales can be approximated by a mathematical expression then this model may be used to predict future sales. There are many well established mathematical modelling techniques applied to management problems. For example, break-even analysis enables a manufacturer to identify at what level of production, revenue starts to exceed expenditure. Linear programming can identify a unique product mix which will maximize profit within the stated constraints of a business.

Simulation

There are occasions, however, where it is difficult to establish mathematical models for complex systems and it is here that simulation is the technique which may be of use.

Systems are prone to having queues or bottlenecks caused by an imbalance of resources, either in terms of quantity or in performance when compared with demand. We find queues in the cafeteria, at the bank or at traffic lights but stocks of work in process, documents in an in-tray, telephone calls in a system or aircraft stacking at a busy airport are also examples of queues. An analysis and understanding of queues will provide managers with information which will enable them to decide where on the spectrum of quality of service they wish to position the system being studied. At one extreme, a high quality service with a large number of servers may be provided: at the other extreme, a low quality, low cost, service with few servers would be typical. Queuing theory can deal with the analysis of relatively simple queues but once the system which is to be analyzed becomes at all complex then simulation has to be used as the mathematics becomes too unwieldy.

Simulation allows us to capture the dynamic nature of the interactions within and between systems. It may be defined as a modelling technique for the study of complex systems (existing or proposed) with a view to reordering them for more efficient performance. The following quotation from Ackoff and Sasieni (1968) encapsulates the main difference between modelling and simulation – "Models represent reality, simulation imitates it. Simulation always involves the manipulation of a model; it is, in effect, a way of manipulating a model so that it yields a motion picture of reality."

Why simulate?

Simulation enables us to represent systems in a dynamic manner which reflects reality. We can capture the essence of a system in a computerised format and then analyze its performance and explore changes. Simulation gives the manager the opportunity to experiment and to experiment safely and cost effectively. Having been convinced of the worth of the changes in the model, managers may then with reasonable optimism of success, make similar changes in the real system. Simulation is frequently used when considering a substantial capital investment in equipment or processes. The technique enables a full and rigorous evaluation by means of the simulation model before any commitment is made to spending capital. Simulation is probably the only opportunity that managers have to experiment, in the scientific sense, with systems. It is possible to vary one parameter at a time, while holding other parameters constant, and thus learn more about how the system operates in practice.

Not only can one experiment with new or rearranged systems to ensure that the systems are likely to produce the expected outcome but one can then introduce and manage the change more effectively because one should have the confidence that a good decision has been taken and minimal unplanned changes will occur. A further benefit of simulation is its capability to compress time. Depending on the complexity of the model, one could simulate the next twelve months operation of a system in minutes, at worst, in hours. Often in real life it is easy to be distracted by the irrelevant aspects of a problem. A well designed simulation model which concentrates on the essential elements and interactions in a system helps managers to focus on the relevant issues in solving problems. In circumstances where safety is of key concern, it is essential to simulate before changing system elements. Simulation provides a framework for future evaluation since not only are assumptions made explicit but expected performance has been documented.

Typical applications of simulation to management problems

In general, simulation is used in problems to do with the balancing of resources in existing systems through the removal of bottlenecks and queues. It may be used for proposed systems such as the setting up of a new production facility. It can provide answers to "what if?" type questions. An investigation of worst case scenarios or the management of disasters provide further opportunities for simulation. Having built a sound model of a system there may well be training opportunities with the model.

Simulation may be used at the strategic, tactical and operational levels of an organization. Probably most models have been of operational level systems but the decisions which have emanated have had implications at strategic and tactical levels. A multi-national company which has a simulation model of its manufacturing capacity world wide has a tool of great relevance to its strategic decision making. Some examples of applications of simulation in management problems are:

- utilisation of hospital theatres and associated resources
- models of health care systems
- efficient, cost-effective transport of coal across Canada
- balancing maintenance cost and plant reliability
- determining storage requirements in a warehouse
- analyzing shipping operations
- job shop scheduling
- developing flexible manufacturing systems
- estimating the impact of just-in-time
- capacity planning
- order picking
- streamlining complex supply chains

Paul (1991) suggests that surveys of practitioners, the number of simulation packages on offer and the amount of research related to simulation are indicators that simulation is a widely used and increasingly popular technique. He also points out that simulation is frequently used where more than one manager has an interest in the problem as the technique can provide a useful medium for resolving conflicting views about the nature of the problem. In some cases, the building of the model provides sufficient useful information that any subsequent model testing and experimentation become irrelevant.

The process of simulation

Although the technology – hardware and software – is available to managers, few of them will actually build a simulation model. The prime reason for this is that modelling is time intensive in terms of system analysis, data collection, model building, debugging of the model and designing and running experiments. Not only is there a great requirement for time but specialist knowledge in statistics, model building and computer hardware and software is needed to be able to successfully build a simulation model.

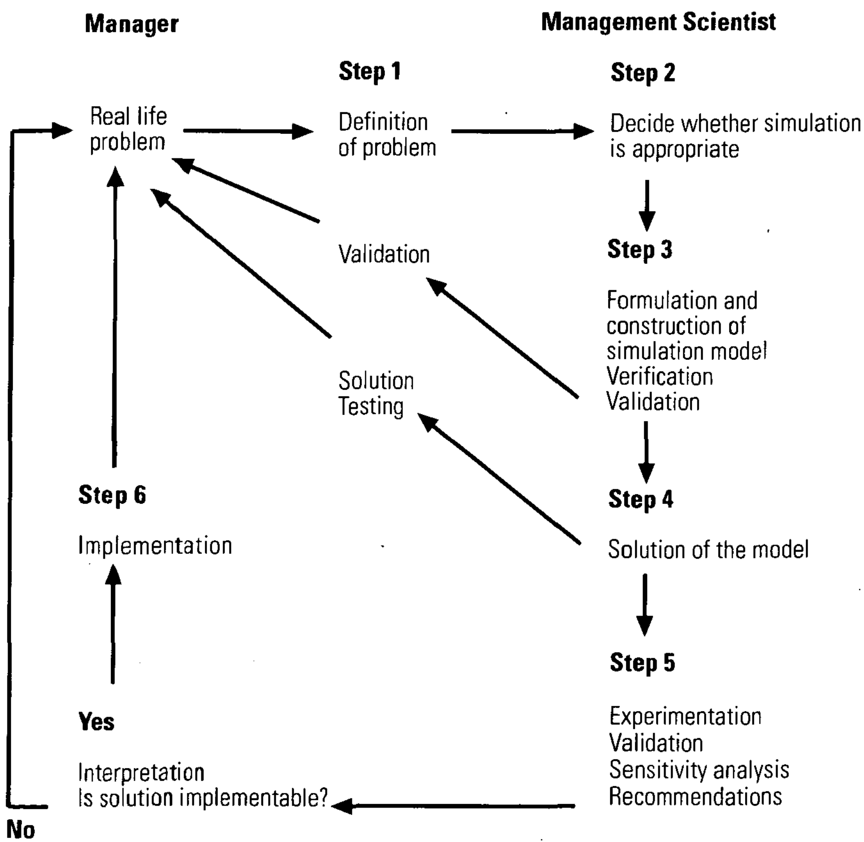
It is normal practice for a manager wishing to use simulation to work with someone who has expertise in modelling. This person may be an employee in a management services or operational research role, or an external consultant who has skills in modelling. We will use the term 'management scientist' to refer to the modeller. His/her role will be to bring a scientific approach to the solution of the complex problem and to provide the necessary skills and knowledge which the manager may not possess. Furthermore the management scientist is likely to have experience from earlier model building which will be of relevance to the current problem.

The interaction between manager and management scientist is key to the successful implementation of simulation. This relationship has changed dramatically as advancement in simulation has occurred over the years. As we shall see, the manager can now play a much more significant part in simulation, thanks to the changes in technology.

Turban and Meredith (1991) portray the process of management science and the roles of the manager and management scientist in diagrammatic form. A slight adaptation will allow us to explore the relationships between these two roles with reference to simulation.

From the structure of the diagram it may be seen that control of the process is often out of the hands of the manager. There is an initial involvement in problem definition where the manager has an important role in helping determine the boundaries of the problem and its constituent parts. The process of communication with the management scientist is vital at this stage to ensure the success of the project. The agreed communication should be a written specification of the problem, supported by some form of logic diagram to capture the essence of the model. To a large extent, control of the problem subsequently passes to the management scientist who builds the simulation model.

FIGURE 1



In Step 3, after the model has been built, the management scientist must be convinced that the model reflects reality. Performance measures of the system being modelled and the simulation model would be compared to provide that reassurance to the management scientist. Since it is of importance to both parties that the model is valid, there would then be communication with the manager to further validate the model. A solution of the model is only of relevance if it reflects the reality of the manager's situation. Accordingly, there is further communication at Step 4 between the management scientist and the manager to test the appropriateness of particular solutions. Step 6 is clearly the responsibility of the manager, supported by the recommendations from Step 5.

There are three phases of the communication process in Figure 1 between manager and management scientist where the information to be communicated is a product of the computer model. These phases are validation, solution testing and interpretation. To consider how the interaction between manager and management scientist has changed over the years, let us look first at the batch processing environment of mainframe computing in the 1960s. How did the management scientist communicate with the manager once the computer modelling began? In general, the manager was reduced to viewing the process as a black box one. That is, the manager did not know or fully understand the process and had to trust the expert. The manager would have had great difficulty in validating the model. There would be a heavy dependence on the management scientist's interpretation of the output from the computer model which could then be compared against reality. As for solution testing and interpretation of the recommendations the manager would be reliant on the expertise of the model builder in conjunction with personal experience of the system being studied.

Today, the steps of the process are the same as outlined in Figure 1. What has changed is that the manager has a much greater opportunity to understand what is happening. Thanks to developments in computing power, the reduction in physical size of hardware and the capabilities of computer graphics, the manager can "see" what is happening on the screen. He will not have the intimate knowledge of the management scientist but the black box analogy is no longer so appropriate when considering validation, solution testing and interpretation.

Early computerised simulation

In the 1960s when commercially oriented computing was yet in its infancy, managers depended heavily on computer specialists as well as management scientists if they wished to use simulation. The first simulation models were run on mainframe computers which by today's standards had limited memory – RAM of 64k was typical and programs and files were held off line on punched cards. Electromechanical input devices such as card readers were slow. The computers could only operate in a protected environment where the dust free air had to be maintained within specified temperature and humidity ranges. In addition to these factors, the size and cost of computers led to computing being centralised in organisations. Furthermore, the jargon associated with the world of computers created further barriers of access and impeded communication with managers.

To use the computer, the management scientist would submit hand written input on 80-column coding sheets for punching by the data preparation department. The data would be keyed by one operator and normally verified by a second operator who re-keyed the same data to verify its accuracy on the principle that it would be unlikely for the two operators to make the same mistakes. The punched cards were then submitted as a batch to the queue of work to be run on the computer. Firstly the computer would compile the input to check that correct grammar and syntax had been used and where this was not the case a list of errors was produced. Only when the input was free of errors in syntax and grammar would the computer run the model. Output would take the form of tables with some limited graphical hard copy as an option – asterisks often being used to create simple histograms. On collection of the output, the management scientist had to analyze this, identify logic errors (if any) and submit the revised data for punching, thereby starting the process over again. When it appeared that the model was free of all errors, model testing and experimentation could begin. This would involve changing model parameters, running the revised model, analyzing the output data, performing statistical analyses, etc. Communication with the manager was based on the output (tables and elementary graphs) from the computer and, as may be gauged from the foregoing description, this could be a slow process.

Today the model is most likely to be built and run on a personal computer. The whole process is much more aligned to the needs of the manager as is explained in the following sections.

The impact of computer graphics

A major difference in the process today is the communication opportunity between manager and management scientist using the computer as the medium. The rapid growth in processing power and graphics capabilities facilitated the use of computers in a decision support role. An early example of such an application is described by Lembersky and Chi (1984) where a computer package was built to improve the decision making capabilities of loggers. The decision as to how many logs to cut from one tree trunk, or stem, and where to make the cuts had a profound impact on the market value of the resultant timber. Factors such as length, diameter, taper, curvature and the position of knots influenced the logger's decision. The challenge was to produce a model which was suitable for improving the skills of loggers in choosing where to make the most appropriate cuts in a felled tree. The model presented a randomly selected stem on screen and the logger, using a joystick, was asked to make his considered choice. He was able to rotate the stem on screen and to explore a variety of possible cuts. Instantaneous feedback identified the value of the logs but also showed the best way of cutting the trunk to maximise its worth. The improved decision making skills of the loggers led to an annual increase in company profits of several million dollars.

Bell (1985) classified graphic displays, as used in simulation, as representational or iconic. In the case of the former, bar or pie charts and line graphs would be examples. They give summary information on measures of system performance. Such graphical representations may be dynamically updated as the model runs, to show current or cumulative performance statistics. The use of colour adds to the impact of these screens. Iconic displays on the other hand, give a close picture of the system being modelled through use of factory floor layouts (including people, machines, parts, etc.), network diagrams or maps. The graphic displays of current simulation packages take full advantage of the capabilities of computing to provide working models of reality which are easily recognisable to the manager.

Dynamic displays may be improved by "flicker" (a change of colour to indicate changed state e.g. red to display that a predetermined action level has been breached) or animation (where an icon moves on the screen e.g. a product moves from machine to machine in a manufacturing facility). Both "flicker" and animation are features of modern simulation software. These features greatly enhance the manager's capability of understanding and validating the simulation model as, instead of receiving a summary or detailed output at the end of a simulation run, the manger can view the transient behaviour of the system throughout a run.

Interactivity

The second major change in current simulation modelling is the interactivity between computer and manager through the manager having access to a keyboard or mouse to stop or slow the model or input changes. None of this was possible in batch processing. The interactivity further reinforces the manager's understanding of the system because now he/she can change model parameters and see the impact immediately.

The evolution of simulation software

The first simulation models were written in high level, general purpose, computer languages such as FORTRAN. This proved to be a slow and expensive means of producing models as all the necessary code had to be written by a programmer. When it was recognised that many of the same functions were required in any simulation model, libraries of routines were written and produced as simulation packages. These provided routines written in a standard computer programming language which gave the user the basic functions necessary in simulation. The user could then write segments of program in the same language, to describe the logic of the system to be modelled, calling on the routines to handle the standard functions. According to Carrie (1988), typical functions to be found in a simulation package are:

- The timing control mechanism to monitor and display simulation time as the model runs.

- A data base to hold details of entities and their characteristics as these change through the model.
- Initialisation to reset counters and random number generators and to move entities to their chosen initial position.
- Random number generators for use in conjunction with observed distributions to imitate the reality of the problem being simulated.
- The recording of observations, analysis of results and printing of reports.
- The display of histograms and other charts.
- Error checks and diagnostics.
- Display of the state of the model at any point in time.

There has also been a growth of specialised simulation languages. Carrie (1988) defines such a language as "a programming language complete with its own vocabulary, grammar, syntax and so on, for performing the basic functions of a simulation program. The user will write this model using the vocabulary and syntax, and does not have to write any code in the underlying language in which the simulation language is written." Early examples of this type of language are GPSS (General Purpose Simulation Software) which was developed in the 1960s by IBM and HOCUS (Hand or Computer Universal Simulator) which was developed later in that decade by PE Consultants in Great Britain. GENETIK produced by Insight Logistics is a more recent example. It is written in FORTRAN but the FORTRAN code is not accessible to the user. These first three approaches give great flexibility to the modeller but have a high development cost due to the amount of time required to build models.

The fourth approach to simulation modelling is through using generic simulation packages e.g. SIMFACTORY, WITNESS, XCELL. Such packages are suitable for classes of similar problems, such as modelling a manufacturing environment, and require minimal programming. Generic packages have less flexibility but their development costs are low because it is usually faster to implement a model produced in this manner. Initial software costs tend to be high because of the many man hours required to produce such a package. It is also as well to be aware that these packages may not be capable of modelling specific features in a particular case and may include unacceptable simplifications or assumptions.

Current software, whether a simulation language or a generic simulation package, tends to be written in the Windows environment. This facilitates the use of a mouse to select icons, to draw logic diagrams and choose the necessary logic from a menu of options. MicroSAINT and INSTRATA are examples of this type of software.

Visual interactive simulation (VIS)

Animation is a portrayal of what is going on in the model but it is usually added after the model has been built. Its main use is for illustration and communication. VIS is radically different as it encourages managers to interact with the model as it is being built and during runs. Interaction may be to stop, slow down, speed up, single step the model from event to event, change parameters or decision rules, zoom in or out on aspects of the model or change screens to view different parts or different representations of the model such as a dynamic graph of performance. Many of these facilities may exist on animated models but the capability to change parameters or decision rules in the middle of a run to manage crises is a facility unique to VIS. Whether the model is written in a high level language or in a generic simulation package, it is increasingly likely that it will be a visual interactive model. Hurrion is recognised as the instigator of the term "visual interactive simulation" from the work he did for his doctoral thesis in 1976.

VIS software enables full use to be made of the dynamic graphics of a personal computer to represent the simulation model. This means that the manager can see the model in operation and as Bell (1985) indicates, the manager can confirm "conceptual" and "experimental" validity of the model. According to Kirkpatrick and Bell (1989) "...as far as the user is concerned, the picture is the model." This, while mainly beneficial, may lead to a superficial validation by the manager since he has not ready access to the logic of the model. While seeing is believing, it may lead to a false sense of security in visual interactive simulation.

Bell (1987) identified that in using VIS there is a gradual process of ownership of the model passing to the manager. Compare this with what happened under batch processing where the manager had to take in trust what he was told by the management scientist and never really owned the model.

Pidd (1989) writing about visual interactivity in modelling proposes the following advantages. Firstly, the client can readily follow the model logic and this helps to establish trust in the model and facilitates development of the model. Secondly, it is an aid to effective experimentation on the model. Finally, earlier simulation systems provided statistical measures of the performance of the system whereas now it is possible to see what is happening as well as receiving statistical measures. Improved communication has led to greater confidence of the manager in the model.

We may believe intuitively that an iconic model is superior to a representational model which produces tables and graphs. It has been found by Smith and Platt (1987) that animation is useful to management scientists in debugging models and in improving communication with managers but that management scientists prefer to rely on numerical output for experimentation purposes. The Smith and Platt study did not, however, extend to the impact of dynamic pictures on management decision making, the prime reason for model building.

The future

Attempts are being made to automate parts of the process associated with simulation modelling. There are now packages which, to a large extent, generate the necessary computer code without the user being knowledgeable of the coding language. This is particularly true of the generic simulation packages, such as SIMFACTORY, referred to earlier, where models are designed by entering basic data about factory layout and production parameters.

A second area where automation appears to have much to contribute is in the speedy analysis of computer generated output. A single computer run of a simulation model can produce vast amounts of output data – cumulative and average figures, measures of dispersion, outliers, states of entities, lengths of queues, percentage utilization of resources, etc. The analysis of this data and the exploration of inter-relationships can be excessively time consuming and requires an understanding of statistical inference. Furthermore, a single computer run may not give adequate data on which to base statistical estimations of the population's parameters so that it may be necessary to run the model a number of times to obtain a sound basis for estimation purposes.

The situation is further compounded when the simulation is being used to compare several alternative policies and choose the optimal one. Where the model is being used to provide fast answers to problems e.g. in real time manufacturing systems, then it becomes desirable to use an expert system in goal seeking to automate the decision making process. Such a system as applied in Rolls Royce is described by Chaharbaghi et al (1988).

A model of how artificial intelligence might be harnessed to provide decision support for managers using simulation is to be found in the article by Dewhurst and Gwinnett (1990). This, however, is only a flavour of what might be available in the future. We will leave the final word to Paul (1991) who, despite all the advancements in simulation as a tool for aiding decision making, offers a word of caution: "It is not clear that simulation will ever advance to the point where a non-specialist can safely use it."

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