Strategic Microworlds and System Dynamics Modelling [1]

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ABSTRACT

In the past ten years, system dynamics has become more accessible to managers and more applicable to strategic issues. The paper reviews developments in software, theory, gaming and methods of simulation analysis that have brought about this change. Together these developments allow modellers to create computer-based learning environments (or microworlds) for managers to "play-with" their knowledge of business and social systems and to debate strategic change.

INTRODUCTION

In the past ten years there have been several important developments in system dynamics which make the subject more accessible to managers, more applicable to strategic issues and more challenging for research. There have been improvements in the symbols and software used to map and model system structure. New ideas have been adopted from behavioural decision theory, which help to capture managers' knowledge in computer models. There have been improvements in methods of simulation analysis that enable model users to gain better insight into dynamic behaviour. Greater emphasis has been placed on small models incorporating managers' knowledge and on dialogue between "mental models" and computer models.

As a result of these developments, system dynamics can now be used, with a management team, to structure informed debate about strategic change. In this process, models and computer simulations are an integral part of management discussion. The paper explores each of the major developments in more depth in order to show the range of ideas and concepts that system dynamics now encompasses. The paper concludes with some thoughts on future research.

SYSTEM DYNAMICS - A MICROWORLD FOR DEBATING STRATEGY

What is a "microworld"[2] for strategy debate? Figure 1 shows the many elements in the microworld provided by system dynamics. At the top left is a problem or issue facing managers which leads to debate and dialogue. The dialogue results in clarification of the problem or issue and eventually to recommendations for action. The microworld contains all the elements included in the discussion. A most important factor is the managers' own knowledge (or mental model) of the business or social system. This knowledge provides the raw material for discussion. In conventional policy-making (by means of argument) it is the interplay between the knowledge base and the discussion that produces a consensus for action.

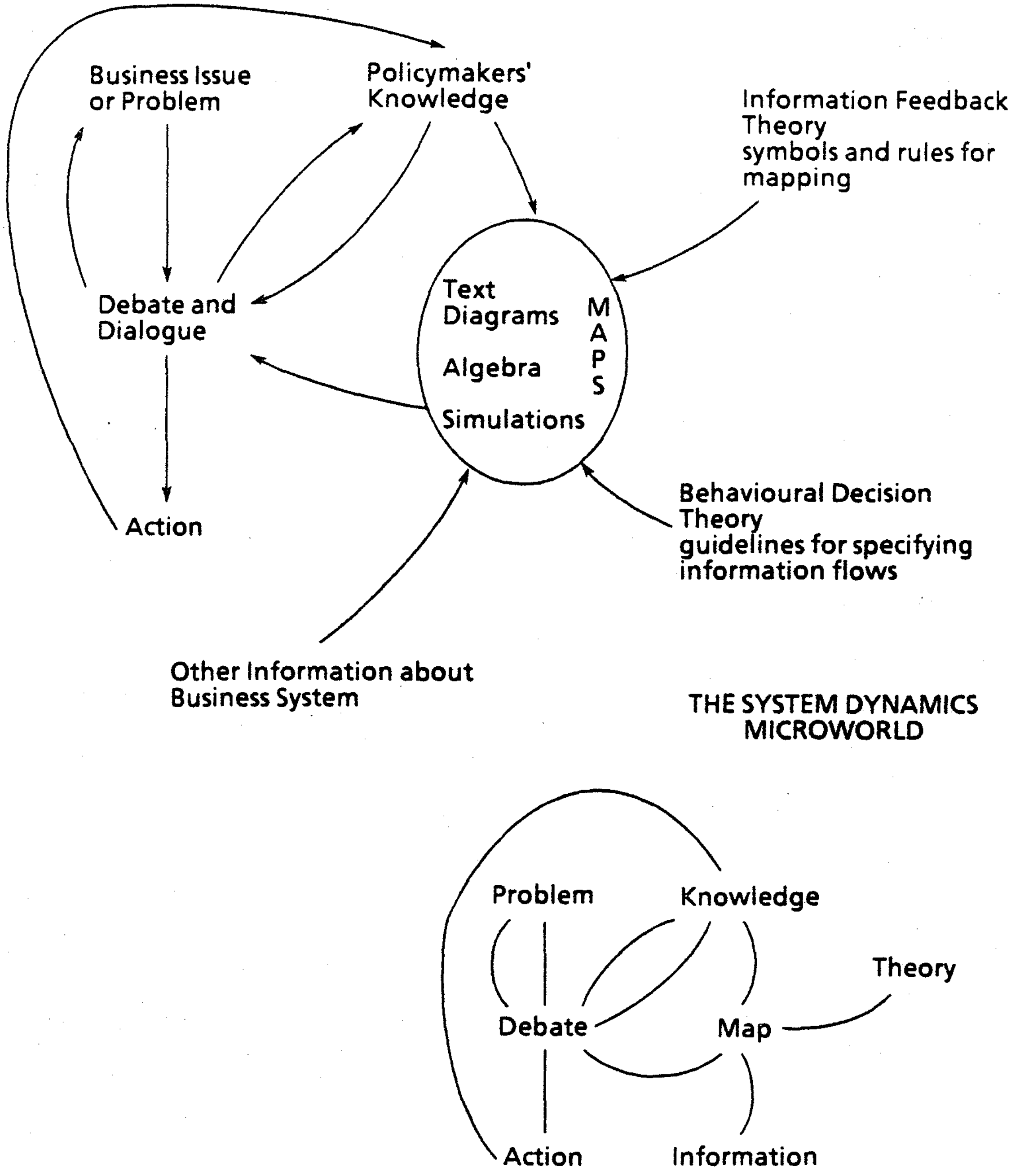


Figure 1 The Microworld for Policy Debate Provided by System Dynamics

When modeling and simulation enter the debate, the picture becomes more complex and the interplay of knowledge, information and discussion becomes more productive. Managers' knowledge, and other information about the business (staff reports, financial documents etc) are converted into text, diagrams, algebra, and simulations. This process of mapping knowledge and information is guided by the theory and concepts of system dynamics. The figure shows two main inputs from theory. The first input, from information feedback theory, provides symbols for diagramming a system and rules for mapping. As readers know well, these symbols include "levels", "flows", "flow regulators" and "converters" to represent physical, financial and decisionmaking processes. The rules for mapping include rules for connecting the symbols, guidelines for equation formulation and guidelines for simulation and analysis. The second input, from behavioural decision theory provides the modeller with guidelines for specifying a model's information flows. It helps modellers to ask the "right" questions of managers and so capture in diagrams the managers' knowledge of the system's operating structure. The microworld includes knowledge (K), information (I), theory (T), maps (M), debate (D) and the interplay of these factors as summarised in the inset of figure 1.

The scope of policy discussion is potentially greater than can be achieved by conventional argument. The maps, (text, diagrams, algebra and simulations) provide managers with a variety of perspectives on their pooled knowledge. The maps also draw information from reports and staff. So the interplay of discussion and knowledge is enhanced through increased variety of representation, more information, and additional paths of interaction. Moreover, the content of the maps themselves is guided by information feedback theory and behavioural decision theory.

Now let us turn to the developments in system dynamics which have made possible this microworld for debating strategy.

REVIEW OF MAPPING METHODS

One of Forrester's (1961) major contributions to modelling was to adapt abstract analytical methods from classical control theory into a flexible form suited to modelling and discussion in the business and social arena. He created symbols for mapping systems together with rules for connecting the symbols and converting them to algebra.

The main symbols for mapping are shown in figure 2. I will assume that all readers are familiar with the symbols, so I will not explain them further. My point here is simply to note that using these few symbols one can create a visual representation of an organization which provides a basis for discussion with a management team. Moreover, after converting the map or diagram into algebra, one can use simulation to obtain a visual representation of dynamic behaviour. System dynamics is a highly graphical subject, whose diagrams and graphs provide a focal point for discussion and learning in a management team.

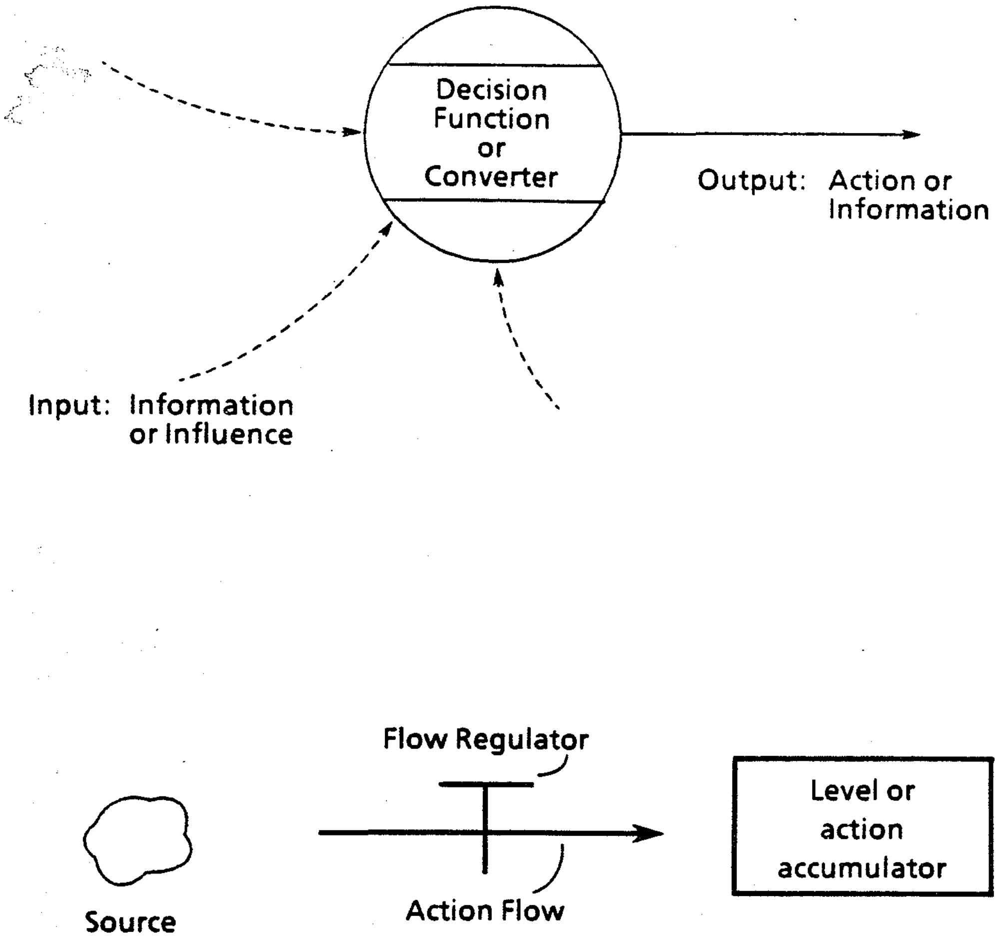


Figure 2 Symbols for Mapping

IMPROVEMENTS IN SOFTWARE

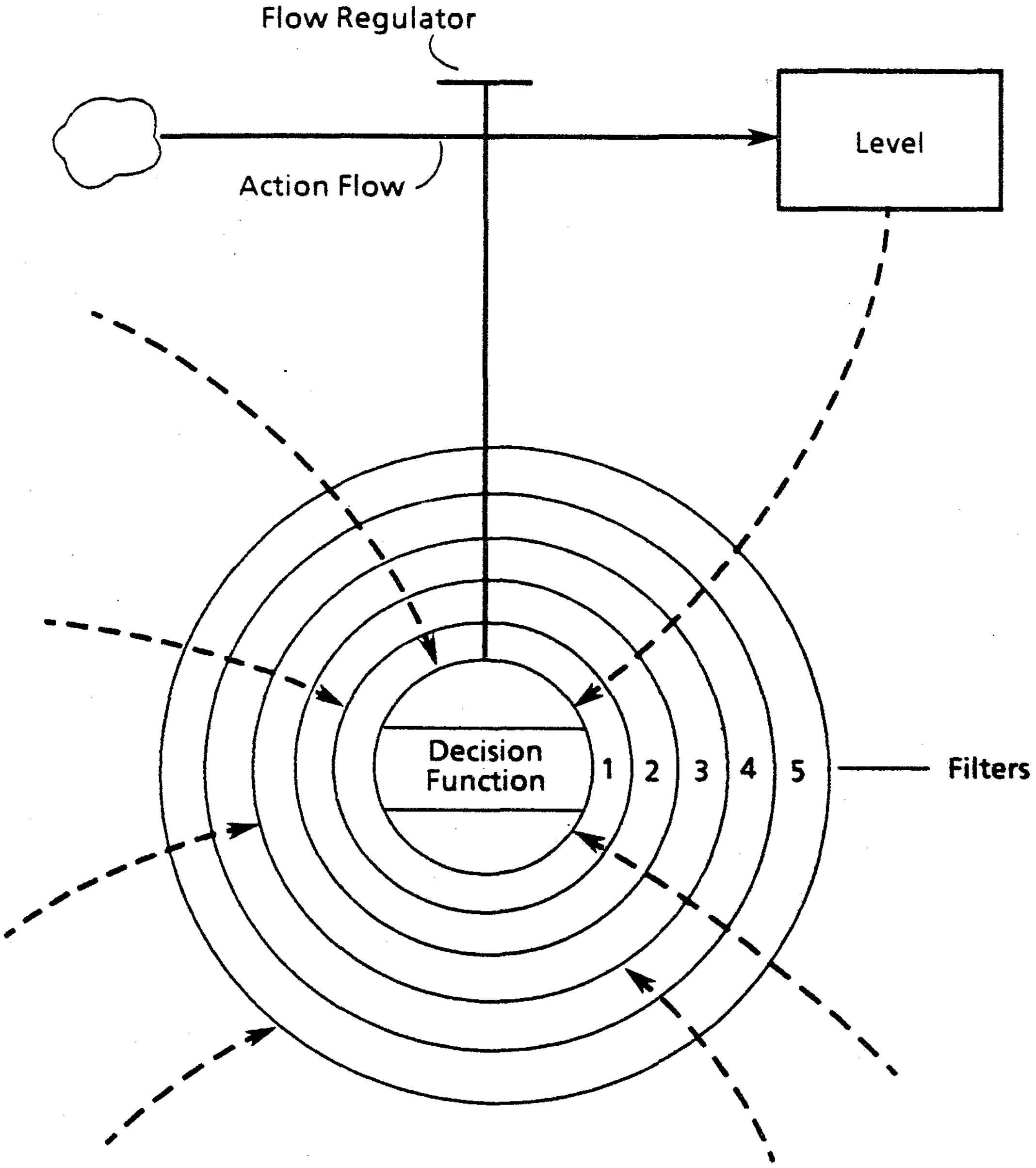
Until recently it has been cumbersome and time-consuming to create diagrams and graphs, so the visual power of the subject has been underutilized. However, the arrival of graphic computers like the MacIntosh has now made it possible to draw symbols directly onto a computer screen and to edit diagrams interactively. The modelling and simulation package STELLA (Richmond et al 1987) provides the modeller with a menu of symbols for creating a diagram on an electronic worksheet. The symbols include those shown in figure 2 and several others that help in organizing and connecting the elements of the diagram. One can select symbols from the menu, move them onto the computer screen (a small part of the available electronic worksheet), connect them and edit them. The software provides a very effective (and entertaining) medium for capturing managers' knowledge. Better computer graphics have also made it possible to create visually clear simulation runs that are much easier to read and quicker to prepare than the old character plots that were common only five years ago.

NEW CONCEPTS FROM BEHAVIOURAL DECISION THEORY

With the symbols and mapping rules of system dynamics it is possible to create quite complex networks of decisionmaking processes. But there are innumerable ways to link the symbols which all obey the connection rules of feedback systems. However, only some symbol configurations correspond to realistic decisionmaking structures. There is a need for modellers to be discriminating in their choice of information links and influences if they are to produce plausible and insightful strategy models.

Recently, system dynamics has adopted concepts from behavioural decision theory that are useful for specifying information links among decision functions. (Hall 1984, Morecroft 1985, Sterman 1985). Behavioural decision theory focuses on the information and heuristics used in real-life decision making. What information receives attention in organizational decisions? What information is ignored, and why? What factors condition the quantity and quality of this information? Behavioural decision theory concludes (with plenty of empirical evidence) that people make choices using only a few sources of information processed with simple rules of thumb. So the network of information flows in a realistic organization is quite sparse relative to the network that would exist if each decisionmaker used information from every source in the system.

Figure 3 shows how behavioural decision theory guides the mapping of decisionmaking processes. One can see in the figure the standard feedback representation: decision function - action flow - level - information - decision function. In addition there are many other information flows and influences (originating from other levels in the system) which are shown on the outer boundaries of the decision function. Only a few of the information flows actually penetrate to the heart of the decision function where they influence the choices and actions of the players' (individuals, groups, subunits). The concentric circles surrounding the decision function represent organizational and cognitive filters which select or limit the information made available to decisionmakers at different points in



1. People's cognitive limitations
2. Operating goals, rewards and incentives
3. Information, measurement and communication systems
4. Organisational and geographical structure
5. Tradition, culture, folklore, leadership.

Figure 3 The Behavioural Decision Function - Decision making and Information Filters the system.

There are five filters surrounding a decision function. The first filter represents people's cognitive limits. People are unable to process all the information that a business or social system may present to them. They make their judgements on the basis of a few dominant sources of information processed according to quite simple rules of thumb.

The outer filters (2,3,4 and 5) in figure 3 represent the ways in which an organization conditions the information made available to decisionmakers. This part of the figure draws particularly on Simon's Administrative Behavior (1976) which explains how organizations may display effective decisionmaking despite the cognitive limits of managers and an over-abundance of information. Simon identifies organizational processes which are designed to simplify decisionmaking tasks. All employees make their judgements and decisions in a "psychological environment" provided by the organization. The psychological environment limits the range of factors considered and, in principle, supplies only the relevant information (a tiny subset of the total information available in the system) for making the correct decision. The filters show the components of the "psychological environment" and they also provide a convenient basis for questioning managers.

Filter number 2 represents the influence of operating goals, rewards and incentives on information flow. Decisions and actions in business and social systems depend on the operating goals and rewards faced by the key players in the system. One can only understand organizational choice and action relative to these goals and rewards. So, for example, it is well-known that factory managers who are held accountable for a specific end-of-year inventory target will drastically curtail or boost production to meet the target, in defiance of "rational" cost-minimising scheduling criteria. For these factory managers, information about the status of inventory easily penetrates filter number 2. The filter excludes other information on future expected demand, cost structure and capacity constraints, which together with information on inventory would be required to set a rational production schedule.

Filter number 3 represents the influence of information, measurement and communication systems on information flow. To take another production example, a "good" production schedule for a microcomputer manufacturer might require information of the status of inventory in all retail outlets. If there is no information system capable of monitoring and reporting retail inventory, then the production schedule must make do with factory information on the size of the order backlog, the amount of finished inventory and the recent shipping rate.

Filter 4 represents the influence of organizational and geographical structure on information flow. As a decisionmaker, one's position in an organization (both geographical location and position on the organizational chart) has a profound influence on the information sources one is exposed to.
Filter 5 represents the influence of tradition, culture, and

leadership on information flow. Filter 5 is intangible yet very important in determining the factors that get the attention of decisionmakers For example, suppose one is modelling the service division of a computer company and wants to understand the quality of service provided to customers. Quality of service depends on the speed with which servicemen fix customer problems. The division can respond quickly if its servicemen receive information promptly from customers. But the company also needs a "service culture". A customer problem which is known to serviceman will get attention (i.e. bring about some action) if the company's "culture" encourages good service. A culture for good service may derive from stories which circulate the company. Such stories underpin the attitudes of individuals in the service division, and condition the attention they pay to customer problems (in other words, the weight they give to information from customers requiring service).

What guidance do these filters provide the modeller? Principally they help modellers to map the structure of organizational decisionmaking by forcing them to pay close attention to the information sources that are actually used by decisionmakers (as opposed to the information sources that are available or that seem, at a distance, to be the most "sensible") and to be aware that information deficiencies, bias and error are commonplace. Also, the filters focus attention on the modelling of decision processes, not just casual links or influences.

By being aware of the filters, modellers can ask more precise questions to draw-out managers' knowledge, and to better specify decision functions. The result is plausible feedback structure that comes from linking well-specified decision functions.

EMPHASIS ON LEARNING AND DIALOGUE

Increasingly models are viewed as tools for learning-by-simulating, where learning can involve the use of scenarios and many "what-ifs". The challenge is to generate a useful dialogue between managers' mental models of the system and simulation models which embody some of the critical variables and interactions identified by a management team. Workshops and role playing simulation games have proved to be useful in creating such dialogue.

An effective dialogue comes from a combination of obvious and "surprise" simulations. The obvious simulations (usually partial model simulations) build confidence in the model and clarify how it works. Surprise simulations show unexpected or counterintuitive dynamic behaviour, and often suggest new interpretations of facts about the system. In order to use surprise simulations effectively, model users need to establish in advance the results which they expect from a model simulation (Mass 1981). Discrepancies can then be recognised as such when they occur and examined closely to explain whether they arise from errors in the computer model or errors in people's mental models.

Partial model simulations are particularly effective for building understanding of counterintuitive dynamic behaviour (Morecroft 1985, Sterman 1985). The simulations are designed by cutting feedback loops in the full model (or by building a deliberately simple, incomplete model) in order to isolate a subset of the system's interacting decision functions. The simplification is carried out in such a way that simulations correspond to scenarios that managers can easily identify with. Partial models are then combined and simulated in logical stages to show how counterintuitive behaviour of the whole model arises from the coupling of understandable pieces.

Partial model simulations expose the "intended rationality" of decisionmaking in complex systems. They show that decisions and actions of players in a system are "sensible" (intendedly rational) when the feedback setting of the players' decisions is simple. Dynamic behaviour which arises from "sensible" decisions and actions is usually intuitively clear, and therefore conducive to dialogue.

USING WORKSHOPS AND ROLE-PLAYING SIMULATION GAMES

It used to be common in policy modelling to develop models containing several hundred or even several thousand equations. These large models accurately replicate historical time series and provide good short-term predictions. Now, smaller models of thirty, forty or fifty equations are commonly presented to management teams. The purpose of these models is to prepare people for debate. Much less emphasis is given to replicating time series.

In order to stimulate debate a model should be presented in a way that dramatises assumptions and relates them to managers' experience. The idea of "dramatising" a model has led to the development of "policy workshops" and has brought renewed interest in role-playing simulation games. In both cases the modeller (perhaps best thought of as a facilitator/modeller) creates a "learning environment" for managers that makes them feel part of the model situation. In principle, participants come to relate their own experience more closely to the model than they would in a conventional model presentation. They also learn more readily the "lessons" about dynamic behaviour that the model contains.

For example, Kreutzer (1985) has developed a workshop to explore the dynamics of an arms-race. The workshop builds on a small, 20 equation, dynamic model (Forrester 1985). The model represents in outline the decisionmaking processes used by two countries, X and Y, for estimating their opponent's stock of arms, for judging the adequacy of their own stock of arms and for procuring arms from industrial military suppliers. The model also includes levels that represent the stock of existing arms and new arms under development. The decisionmaking network of the model captures in very interesting ways the lags, distortions and biases that occur in the transmission and processing of sensitive military and political information. The dynamic properties of the model (exponential growth in the stock of arms of both countries X and Y) arise from the imperfections assumed in the system's decisionmaking processes.

The workshop immerses participants in the realities of military and political decisionmaking. They are provided with articles on the arms-race from magazines like Newsweek and the Economist. They are presented with charts showing the history of the Soviet - US arms race. They are given cartoon illustrations from magazines like Punch or the New Yorker which portray (in amusing but memorable and usually realistic ways) the imperfections of military intelligence (for example, an illustration showing large crates being shipped to Cuba on anonymous freighters, and two military officers debating the likely contents of the still-closed crates). All this material activates participants' mental models of the arms-race and highlights the role of information processing and information feedback in arms control. With this preparation, participants are able to relate their knowledge and experience of arms races to the model and to appreciate the assumptions that underlie the model's feedback structure and dynamic behaviour.

The arms-race workshop also uses partial model simulations to show how the decisionmaking processes that generate an arms-race are quite "sensible and benign" when the imperfections and biases in information processing are eliminated. For example, simulations which assume that decisionmakers in countries X and Y have perfect knowledge of their opponent's stock of arms (both installed and in development) exhibit much slower exponential growth, or in some cases, no growth at all.

Role-playing games fulfil a very similar function to workshops by providing a context of realism and drama to relate managers' knowledge to simulation models. In the case of games the drama is provided by making participants play the role of selected decisionmakers in the model system.

The production-distribution "hand simulation" game Sterman (1984) is a good example of a game that promotes learning and policy debate. It is a board game played by teams of four players. Each player takes a role as either retailer, wholesaler, distributor or manufacturer in a vertically integrated manufacturing and supply system (a beer production and distribution system is usually selected). A player is responsible for managing inventories and backlogs at one point in the system (e.g. wholesaler) and for placing orders with the adjacent player downstream (e.g. distributor) in the supply chain. The objective of the players is to minimise the team's inventory and backlog costs in the face of exogenous customer orders. The volume of orders is not known in advance by any player, and is revealed week-by-week to only the retailer. The game shows the difficulty of co-ordinating decisionmaking in a system with imperfect information processing. Almost all teams that play the game incur inventory and backlog costs which are much greater than the "theoretical" cost minimum.

The production-distribution game uses coins, paper and a plastic printed board. But many new electronic or semi-electronic role-playing games have been developed such as Meadows' (1985) STRATEGEM 1, Flint's (1986) multi-product salesforce game and Sterman and Meadows'(1985) STRATEGEM 2. The management consulting company Pugh-Roberts Associates (1986) has developed a role-playing game of project management.

FUTURE RESEARCH - IMPROVING MODEL SUPPORTED "DIALOGUE" AND THE MAPPING OF POLICYMAKERS' KNOWLEDGE

An important objective of future policy-related research in system dynamics is to improve the quality of dialogue and debate between managers and models. Better dialogue comes from capturing accurately in maps and models managers' knowledge of the system, and from strengthening the influence of model generated opinion in policy debate. Many research paths are open to improve model-supported dialogue. They include field experiments, behavioural decisionmaking, game design and mapping technology.

FIELD EXPERIMENTS

Fields experiments are already underway to explore the process for generating effective policy dialogue. The experiments are taking place in both large and small business organizations in the United States and Europe. Researchers and consultants are experimenting with the content and sequence of model development to better understand which modeling activities should be conducted during meetings and which beforehand; to better understand what balance to strike between qualitative mapping and simulation; and to better understand how to use partial model simulations and simple scenarios to challenge managers' intuition.

Researchers and consultants are also experimenting with the composition of the project team (the mix of managers, modelers and facilitators), the format of meetings (how frequent, how long, and what mix of discussants), and the "technology" for presenting and recording policy debate (flip-charts, blackboards, paper, overheads, video projectors and computers (with word-processing, diagramming and modeling software)).

Several recent papers describe the style and direction of the field work. Richmond (1987) and Senge (1987) describe a "Strategic Forum" which they view as a "process" to enable a cross-functional management team to improve the match between operating policies and stated strategic objectives. A forum involves several work steps for a management team: articulating current vision and strategy, developing simple "reality check" models, developing more complex models by closing feedback loops, conducting "what-if" policy testing and defining action steps. Morecroft (1984) describes "strategy support models" which are intended to "provide executives with insight into whether the policies and programs (of a business strategy) are properly coordinated and whether they are in fact capable of achieving the market and financial objectives called for by the strategy". He describes two phases of modeling, a first qualitative mapping phase to identify "players", policies, and feedback structure, and a second simulation modeling phase to develop equations and concepts and to debate the outcome of simple simulated scenarios.

It is interesting to note that research and consulting on the process of model-building with management teams is already well-established outside the system dynamics field. Well-known work has been carried out by Phillips (1986) and Eden (1985) and the topic is receiving increasing attention in the area of decision support systems (Land et al (1987). Some cross-fertilisation of research and methods would likely be fruitful.

BEHAVIOURAL DECISIONMAKING AND GAMING

The value of behavioural decision theory to system dynamics is clear enough: it can help modelers to ask better questions of managers, to specify decision processes more plausibly, and to capture more of managers' knowledge in maps and algebra. An important extension to this bridge-building is to embody the new ideas explicitly into symbols for mapping (say by including information filters in maps) and into protocols for questioning policymakers.

Another significant area for research is game design. Behavioural decision theory gives some guidance to game design by focussing the game-builders' attention on the design of the "decision shell" in which human subjects will role-play. Immediately one thinks of "designing a decision shell" then game-building takes on many interesting research dimensions (that go well beyond the purely technical issue of outfitting a simulation model with the capability for occasional human intervention). There is the question of how one "replicates" the organizational, cultural and administrative filters (of information) that condition choice and action. What information (from the vast matrix of simulated data available) should be presented to game-players? How should screens of information be organized? What balance of graphic, verbal and visual displays is appropriate? How much leakage of information between players should be allowed in multi-player games? What is an appropriate protocol for gaming-decisions? How should one gauge the adequacy and fidelity of the decision shell? The research questions are numerous. At a more technical level one might consider the merits of different programming environments and computers for developing behavioural decision shells.

Finally, there is a challenging and potentially large research topic in the use of gaming to link experimentally the behavioural decisionmaking of individuals and groups to the dynamics of large organizations. In this kind of research a simulation game becomes a laboratory for "testing" cognitive limitations of individuals and groups in environments that "simulate" large organizations. Subjects make choices in an experimentally controlled setting (the decision shell) that provides operating information. The operating information is generated by a simulation model that "surrounds" the decision shell. Subjects are free to make any choice they consider appropriate, given the available operating information, their knowledge of operating goals and incentives, their "mental model" of how the rest of the organization operates, and also given their own cognitive limitations. The actions and reactions of the rest of the organization (comprising several behavioural decision functions, actions and levels) are represented by algebraic functions and simulated during the game. Since the situation is entirely experimental, one can replace the decision shell and human decisionmaker/s with an algebraic decision rule and discover (through analysis or simulation) an "optimal" decision rule. Knowing an optimal decision rule and the results of many game trials with many different players, one can discover if and when people use systematically poor decisionmaking heuristics. One can also model the players' heuristics and compare them with the optimal decision rule in order to probe the link between cognitive limits and observed dynamic behaviour.

Research along these lines is being carried out by Sterman (1986). It is a fascinating area that promises to yield better understanding of the reasons for (economically) inefficient dynamic behaviour in business and social systems; experimental methods for validating model assumptions; and new insights into the design of role-playing simulation games.

BETTER MAPPING TECHNOLOGY

There is a large potential for research which leads to better mapping technology and therefore to a richer flow of policymakers' knowledge into maps and models. The most direct research path leads straight to improvements in software. A more ambitious research path leads into aspects of modern computer science and artificial intelligence.

Software for mapping, modeling and simulation has improved over the past five years, as outlined earlier. However, there is room for still more improvement. Mapping (of the kind allowed by STELLA) should permit word-and-picture maps to be built at the level of policies (Morecroft 1982) rather than at the present level of algebraic converters. Such high level maps would allow better communication with policymakers (because the maps are readable, visually compact and easily changeable) and would guide equation formulation without constraining conversation (because they stand in a natural hierarchy above equation formulation). The needed software should combine the flexibility of drawing and writing packages (say like MacDraw and MacWrite) with the modeling capability of STELLA.

New software should also help modelers write good clear algebra that a policymaker can (almost literally) read! A simple step is to allow much longer labels so that equations look like sentences. Also needed, but more difficult to provide, is guidance for equation formulation - a computer environment for developing equations that weeds-out poor formulations. Here is an ambitious but clear research challenge: to capture in a software package (at least some of) the expert modelers' rules of formulations (for example, dimensional consistency checks and extreme-condition tests).

Finally, new software should give modelers more simulation power and flexibility. Given a credible model, one should be able to probe "policy parameter space" as quickly as one can envisage and articulate meaningful policy scenarios. The required flexibility here is not only for rapid re-simulation, but more important, for rapid reformating and reorganization of simulated graphs and charts.

The most ambitious research path leads into modern computer science and artificial intelligence. The challenge is to better understand how to elicit and reconstruct managers' broad operating knowledge into meaningful word-and-picture maps, algebraic "sentences", models and simulations. It seems to me that an important prerequisite is to discover more precisely what we mean by the phrase "managers' knowledge". Branches of Artificial Intelligence (AI) may provide some ideas (see for example Minsky's (1986) Society of Mind). However, there is a need for focus. The likely criterion for achieving focus is to select the work that is most informative on how symbols (words, charts, pictures, etc.) can be used to provide a "framework" on which to hang managers' knowledge.

I have outlined some promising paths for future research in system dynamics. A lot has been accomplished over the last ten years, but the remaining opportunities and challenges are enormous. Future research should provide the technology, theory and group processes for policy microworlds which will (in Richmond's words) "help organizations design their own future".

NOTES

1. This paper is an abridged version of "System Dynamics and Microworlds for Policymakers", forthcoming in the European Journal of Operational Research.

2. The term "microworld" comes from Seymour Papert (1980) in a fascinating book called Mindstorms. Papert is a mathematician and computer scientist at MIT who has devoted his energy to exploring how computers can help people to learn. A fundamental premise of his work is that people learn effectively when they have transitional objects to "play with" in order to develop their understanding of a particular subject or issue. The writer has pen, paper and word processor with which to hone his skill of composition. The very young child has building blocks to learn about sizes, sorting and simple construction. The combination of transitional objects, learner and learning process is what Papert calls a microworld or "incubator of knowledge". But what transitional objects can one provide for learning about "intangible" topics like motion, geometry, mathematics and (for our purpose) policymaking? Papert suggests the computer and simulations:

   > "The computer is the Proteus of machines. Its essence is its universality, its power to simulate. Because it can take on a thousand functions, it can appeal to a thousand tastes."

   The combination of computer, simulation language, learner and learning process is a computer-based microworld.

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