THE DESIGN APPROACH TO SOCIO-ECONOMIC MODELLING

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The exploration of alternative futures is an important part of socio-economic analysis. This paper describes one approach to socio-economic modelling that is intended to support this exploration by scenario analysis. The approach involves the repre:;entation of a socio-economic system by a simulation framework which has no imposed optimization. Alternative futures are explored by changing the control variables governing the simulation framework which is a loosely coupled set of physical transformation processes, each using existing design information to represent a segment of the economy. The variables that control the processes are set by the user or, alternatively, by the user in conjunction with a model of decision processes. In this way, the user is an integral part of the system and a source of novelty. A prototype representation of the Canadian socio-economic system serves to illustrate this approach and its use.

Keywords: socio-economic modelling; scenario analysis; design approach simulation

THE 'DESIGN' APPROACH to socio-economic modelling has two meanings in this paper: the act of designing alternative futures through repeated simulation; and the use of design information, like engineering studies, to construct the models which form part of the simulation framework used in support of designing futures. The models, the simulation framework and the user combine to produce a way of exploring the future rather than predicting it. This differs from conventional modelling and projection in the social sciences.

The approach incorporates principles of general systems theory and control

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theory. Models of the physical transformation processes of the socio-economic system, such as demographics, consumption, production and resource extraction, are linked together, but with the main control variables accessible to the user of the framework. The user, who may be an individual, or an individual combined with a model of decision processes, is an integral part of the system, providing novelty and change through scenarios, which are specifications of the control settings over the time period of the simulation.

The separation of the user from the physical representation of the socioeconomic system facilitates the making and assessment of policy decisions. For this to work, however, there must be no global optimization built into the simulation framework. This does not preclude optimization as part of the control of a physical process, represented by a model in the framework, but it does exclude optimization to achieve economic equilibrium, or to maximize social welfare. The policy decisions necessary to achieving equilibrium and maximizing welfare are concerned with the allocation of resources and the resolving of social issues, such as unemployment and health care. In the design approach, these decisions, and their consequences, are explicit.

With no optimization, simulations can produce physically inconsistent or socially unacceptable futures. For example, a scenario to study technological change might be deemed inconsistent because of a projected shortage of systems design engineers at a particular time in the simulation; as well, there might be growing unemployment of other occupational categories throughout the simulation. In the language of the design approach these inconsistencies are called 'tensions', and it is central to the approach that tensions be reported to the user and resolved through changed scenarios and repeated simulations. It is through this process that understanding of the socio-economic system grows, and only when a scenario produces a simulation which satisfies both physical constraints and the social constraints imposed by the user is it considered consistent, or balanced. A balanced scenario forms the basis for variations which establish bounds on policy options and the sensitivity of the system to policy changes.

A socio-economic system has a geographical location, so the spatial extent of the representation is defined from the outset. The problems to be studied, using the simulation framework, define the time scale or length of the simulation, the spatial resolution and the time step. Once the time scale and the time step are defined, stocks and flows are distinguishable, and the remaining pieces of information required are the age structure of the stocks and the probability of survival of the components.

A model of a socio-economic system implemented using the design approach can deal with compositional effects (such as an aging population) and substitutional effects (nuclear power supplanting non-nuclear power, for example) as well as externalities (pollution). These effects are crucial in the understanding of physical and social constraints and their associated tensions, as well as the robustness of structural problems in the socio-economic system under examination.

In what follows, the design approach to socio-economic modelling is eXplained in greater detail, after which the problems of using the design approach in representing a socio-economic system are considered. Next, the Canadian Socio- Economic Resource Framework (SERF) is presented as an application of the design approach and finally, this work is put into historical perspective and some conclusions are drawn about where it is leading.

The design approach

The 'design' approach applies to what a user does in designing alternative futures through repeated simulation, and also to the use of design information to construct models which form part of the simulation framework. These two applications of the design approach are related through the user.

The user explores alternative futures, learns from resolving tensions through repeated simulations and introduces change and novelty through new scenarios. In so doing, the user is an integral part of the model of the socio-economic system. To make the user so central requires a separation between the processes that control the system and the physical transformation processes that underlie it. It further requires certain restrictions on the simulation framework, and on the constituent models of physical processes.

To give the user control, the simulation framework must impose no optimization or equilibrium conditions and it must also make explicit the tcmsions between supply and demand which the user may choose to resolve. The making of tensions explicit is facilitated by requiring the information flow between the models of physical processes to proceed in one direction only. As for the models themselves, the user should find as many control variables as exist in the real world and models that represent the complexity of the real world in a plausible way. This leads to models that can be overdetermined and that depend only on their present state.

Models that depend only on their present state are called Markovian and the physical stocks they use are required to be vintaged, or to carry information about the past in their age structure. The representation of complexity in a plausible way and the use of vintaged stocks is made easier by the use of design information. This approach results in a representation of physical transformation processes which the user can accept as realistic and as providing support for the design of the future.

The exercise of control is a task for the user, or for the user along with models of decision processes. The user, with or without the support of models of decision processes, has access to information about the past, and is able to form expectations about the future. If models of decision processes are present, they must be able to react to the actions of one another and to the user.

The representation of decision making in the simulation framework is quite different from the representation of physical transformation processes. This point will be made again, but first the basis for separating the control process from the physical transformation process is discussed.

The process aradigm

Central to the design approach is the concept of process: the dynamic transformation of information, energy and material from one state to another. The structure of a system is a manifestation of the underlying process, a point which is emphasized in systems theory by Capra! and in decision-related sciences by Miller.2 Inherent in process is hierarchy which provides a basis for dividing the system into a control space, concerned with information, and a machine space, concerned with energy and materials.

The hierarchy in a design process is in the order and the relationships of the flows of information, energy and material. The transformation of material requires both energy and information, the transformation of energy requires information, while the transformation of information can take place on its own. To illustrate this hierarchy, consider the following: a legislature, a hydroelectric power station, and the manufacture of ploughshares from swords. The legislature takes note of socio-economic indicators and acts to change tax policy, for example. In doing this the legislature uses information and produces information. The conversion of the mechanical energy of falling water to electrical energy requires more than just energy. It needs the information embodied in the turbine and the information necessary to its control. At the bottom of the hierarchy, the material transformation of the beating of a sword into a ploughshare requires mechanical and thermal energy, as well as information about the process and its control and the design of the final product.

In the design approach, processes are separated into two classes: those that transform information and those that transform energy and material. Models of processes dealing only with information-and these include decision processes -occupy the control space of systems theory, while models of processes dealing with energy and material occupy machine space, but with their control function linked to control space.

The models of physical transformation processes are Markovian, which means that, within machine space, the present human fertility, for example, cannot depend directly on the industrial production of five years ago. Such a link can be made through control space where the user and the models of decision processes do have access to the past. The lack of direct use of the past means that whatever history is available when the model is made can only be projected onto the starting year of the simulation in the form of vintaged stocks.

In the design approach, the modelling of physical transformation processes, using design and engineering information when it is available, makes it easier to use the data on vintaged stocks required by the Markovian condition on the models. Models of a physical process can also be used to reconstruct unobserved input or output data from available data on other inputs and outputs. The same technique can be used to enhance data of poor quality. This is a direct benefit of using the design approach at the level of models of physical processes.

The models of physical processes tend to be overdetermined, which means that more than one setting of the control variables can lead to the same output from the model. This contributes to the user's problem of tension resolution. However, the fact that the models are overdetermined, combined with their physical design, means that they are capable of activity never recorded in historical time. This is an important feature of the models in machine space and it derives from the fact that the models are (simplified) representations of physical processes rather than statistical models.

The simulation framework and coordination

Once the models of physical transformation processes are built, it remains only to link the models and their data bases to each other and to control space, in blocks which represent common activities such as demography or consumption. The blocks are linked together to form the simulation framework and, once the blocks and links are in place, consideration can be given to representing social institutions by models of decision processes in control space.

Deciding upon the number of control variables available to the user, the number of links between blocks and the direction of information flow between blocks is a modelling problem. The problem relates to how the activities represented by the various blocks are to be coordinated, and to the amount of feedback permitted between the blocks. The choice for coordination lies between doing all of it in control space, or none of it. If all of it is done in control space, there are no links among blocks. Each machine is monitored from control space and coordinated settings of control variables for all machines are supplied from control space. If there is no coordination in control space, all of the behavioural decisions are embedded in the models and the links between them, and there is no connection to control space.

In the design approach control space must be involved, and there is a balance struck between the number of control variables and the number oflinks between the blocks. Further, no feedback is permitted between the blocks as information is- allowed to flow in one direction only from block to block in a predetermined sequence. The direct result of preventing feedback from downstream to upstream blocks is that the inconsistencies or tensions that arise can only be resolved by the user through repeated simulations. This lack of feedback in machine space extends over time, as the models do not use information about past settings of the control variables. Also, calculational advantages follow from having information flowing between the blocks in just one direction.

The framework simulates alternative futures by following scenarios which are the settings over time of the control variables that link control space to the models in machine space. The simulation framework is open and able to evolve. It is open to new ideas from the user, to new resources through exploration, and to new energy, so long as the sun shines and plants grow. The evolution can take the form of changing decision rules or, in extreme cases, altering the models of decision processes and the way in which they interact. The key to evolution and to the design of alternative futures is the user, who designs scenarios, resolves tensions and decides when the simulation framework no longer provides a valid representation of the socio-economic system being studied.

The user

The user in the design approach forms part of the model of the socio-economic system and acts, in part, as a surrogate for the society. In doing this the user is able to introduce both the policies that are being studied over the time period of the simulation, and the expectations of the society in response to those policies. The learning, which results from repeated simulation, provides the source of novelty which allows the system to change and evolve. The user navigates from the present through the future while avoiding physical boundaries and selfimposed social constraints. The end product is a balanced scenario, stable under perturbation.

The user, as an integral part of the system, is the controller of the simulation framework, and this control can be exercised in two ways: directly through the specification of the scenario or indirectly through the control of a model of decision processes. The presence of the user in the control loop distinguishes the design approach from most socio-economic models where the user remains outside of the system, which is closed. The design approach is closer to the system dynamics of Forrester, 3 where the system to be studied is divided into levels and rates or, in economic terms, stocks and flows, and these are linked through positive and negative feedback loops. Once the system is represented by such a model, the model can be run to simulate the behaviour of the system with the control exercised by the feedback loops built into it. In the design approach, however, the user forms part of the loop, either directly or indirectly if the user controls a model of decision processes.

A distinction should be made between a control mechanism which receives input and acts on the system at each time step in the simulation and the role of the user in the design approach. In the absence of a model of decision processes in control space, the user specifies all of the system parameters. The resulting time series constitute a scenario (ways of simplifying scenario building are discussed later). The scenario is run by feeding all of this information to the simulation framework and at the end of the run the physical and social tensions are displayed. The user then acts to resolve the tensions, and in so doing creates a new scenario, and so on, until a satisfactory scenario is arrived at. The resolution of tensions by the user is an important characteristic of the design approach.

Tension and debate

A characteristic of the design approach is that the structure of the simulation framework is designed to highlight certain tensions or inconsistencies. The user then imposes a value structure on top of the simulation framework and establishes an order of priority in which tensions are to be resolved. Certain tensions must be resolved for the scenario to be feasible and shortages of labour, material and energy are examples of these, but others need not be resolved and their resolution is a subjective choice made by the user.

In the implementation of the design approach, emphasis is given to the documentation of scenarios as they are developed by the user. This has a number of benefits when it comes to tension resolution, as a complete record is provided which describes each scenario and the progress towards a balanced scenario. The record of the path followed is useful as there are bound to be a number of ways of resolving a set of tensions, ranging from the opposite extremes of a continuum of resolutions, to discrete resolutions which cannot be turned into others by smooth variation of the variables of the system.

Well-documented scenarios provide a means of exploring alternative futures, and they support informed debate of the policy decisions built into the scenarios and the resolution of their tensions. The simulation framework becomes, in this context, a debating arena where the merits of alternative futures and policies can be discussed, as can the relative merits of arriving at an agreed end point by different means. It is a small step from debate to gaming, as a single scenario can be developed with different groups responsible for separate parts of the scenario -the private and public sectors, for example-with tensions resolution resulting from negotiation between the groups. Both methods allow alternative futures to be studied, debated and approached with greater understanding.

In both debating and gaming it is essential, of course, that the participants agree from the outset that the models and the simulation framework are plausible, and also that the data used by the models are acceptable. Plausibility is an important consideration in the design approach and is, in fact, one of the validity criteria. Some examples of computer models used in support of negotiations are given by Sebenius.[4]

What happens when tensions cannot be resolved? If the tensions are physical, insufficient energy or water, for example, the scenario is attempting to describe the impossible. It is then the task of the user to search for an alternative, as the simulation framework imposes neither feasibility conditions nor optimality. If the tensions are social, such as high unemployment, the same procedure can be followed, or the user can choose to accept high unemployment as part of an alternative future. In this case, unemployment ceases to be a tension.

If no tension-free scenario can be found, the simulation framework may be indicating that the socio-economic system it represents has, in the course of the scenario, reached a critical point, a point at which the society and its institutions undergo a transformation. Indeed, some would argue that such a point is soon coming[5] and the advantages to be gained from foreseeing it constitute a case for an approach to socio-economic modelling which does not preclude such a phenomenon. The question does arise, however, as to the ability of the simulation framework to represent the socio-economic system as it goes through such a transition. This raises the further question of the validity of the simulation framework, and of the models and links which constitute it.

Validation

The criteria of model validation in the design approach are the same for the individual models and for the simulation framework. There are two criteria. The first requires that there be a setting of the control variables of a model, or of the simulation framework, which reproduces any set of observed data. The second requires that the model be a plausible representation of the system being studied.

The first criterion is a necessary, but by no means sufficient, condition of validity. It simply states that one of an infinity of control settings must reproduce a set of observed data. Failure to do this shows the model to be invalid, but success does not guarantee validity. In applying this criterion, account must be taken of the time step used in representing the system. If, for example, a time step of a year is used, fluctuations in quarterly data will not be reproduced, but the yearly data should be. If the purpose of the model is to study long-term effects, then it should not be expected to reproduce business cycles in the data, but it should reproduce their trend.

The second criterion is that the model should be a plausible representation of the system being studied. This means that the representation of the system should be sufficiently disaggregated for an informed person to follow the structure of the representation-the stocks, flows and control variables-and decide that the representation and the values of the parameters are plausible. In the example of the Canadian residential energy model[6] which follows in the SERF discussion, the thermal efficiency of space heaters and the thermal characteristics of houses are model parameters taken, in the spirit of the design approach, from engineering studies. Their use and their values are expected to be plausible to a person familiar with residential energy systems.

These validity criteria distinguish this approach from that of macroeconometrics where the reproduction of historical data follows directly, if those data were used in the estimation of the model, and the plausibility criterion cannot be applied because of the degree of aggregation of the models. The validity criteria are closer to those applied by Forrester in his system dynamics, 7 although they differ in detail and emphasis. For example, he says that: "Much of the information from the real system is used for a 'plausibility' check", and that: "A model which shows no significant inconsistency with the full range of information available from the real system has passed a powerful composite test, even if each individual test is weak". These points would fall under the first condition of validity presented above. He also expects his models to "predict modes of behaviour which could occur but which have perhaps never been encountered in the past of a particular system", and this would fall under the plausibility criterion. It is important to remember, when comparing the design approach to system dynamics, that the control loops in the Forrester models are closed, while in the design approach, they begin and end in the user.

A final point which bears on validity is the presence of counter-intuitive behaviour in a simulation and whether this means that a 'plausible' model is no longer so. In the design approach, counter-intuitive behaviour can rise because of the change with time ofthe structure of vintaged stocks. The use of vintaged stocks is imposed by the requirement that models in machine space be Markovian and the compositional effects which can result from their use are not always obvious to the user. Vintaged stocks also lend themselves to the study of substitutional effects and these too can be unexpected. The presence of counterintuitive behaviour resulting from compositional and substitutional effects is entirely consistent with the design approach. There is also, however, the question of counter-intuitive behaviour resulting from feedback mechanisms.

In system dynamics, counter-intuitive behaviour appears as a result of nonlinearity and feedback, and it is regarded as a normal outcome of the modelling process. In the design approach, such counter-intuitive behaviour is also possible when the user controls the physical transformation models in machine space, either independently or with a model of decision processes. However, in the hierarchical, loosely coupled, multilevel systems method of Mesarovic,8 counter-intuitive behaviour is a symptom of disorder which leads to a loss of intuitive understanding and a requirement that the representation of the system be restructured to restore the loose coupling between the strata in the hierarchy. 9 In the design approach, the work of Mesarovic would be most appropriate for the modelling of decision processes in control space, and were such a model to exhibit counter-intuitive behaviour, it would signal a breakdown of the social structure. Both the counter-intuitive behaviour of Forrester's system dynamics and Mesarovic's hierarchical systems theory can coexist in the design approach.

Representing a socio-economic system

Before the design approach can be used to design alternative futures through repeated simulation, the simulation framework has to be built, and it has to satisfy the validity criteria. Building and validating the simulation framework, however, are both constrained and influenced by the types of problems to be simulated. The problems carry with them a time scale and an indication of the spatial and temporal resolution necessary to their study. They also exhibit a degree of complexity which has to be represented in a plausible way.

The first step, then, in representing a socio-economic system is to decide upon the common requirements of the problems to be studied. In the SERF example that follows, the principal requirements are the study of compositional and substitutional changes in physical stocks and their consequences in the medium to long term. This is data-intensive as it requires a very disaggregated representation of physical transformation processes, and it sets a timescale of the order of fifty years. The models of physical transformation processes are required to be Markovian and consequently all stocks (people, machines, houses) are vintaged so that changes in their age structure and composition can be studied in yearly time steps. These models are formulated in discrete time and they have a finite state space. Transition probabilities, such as fertility and survival, can be changed, exogenously, over time.

. The timescale of a simulation is an important constraint as it influences the distinction between physical parameters and control variables. In the long term, the physical parameters available from engineering studies, such as engine efficiencies, thermal properties of insulating materials and availability of su perconducting alloys, change in response to combinations of consumer demand and government policies. The effect is that short- to medium-term physical parameters can become control variables in the long term.

Once the constraints imposed by the problems to be simulated are established, account must be taken of the goods, services and capital crossing the geographical boundary of the system. In the SERF prototype this is done by maintaining complete current and capital accounts with provision for changing relative prices, the terms of trade, debt accumulation and interest payment on the debt. This could be augmented by the accounting of embodied energy, material and labour, and this is a decision for the implementer of the trade model, taking into account the problems to be simulated.

Complexity within the system is made manageable by grouping together similar models, such as population, household formation and labour force participation, into blocks and then linking the blocks together in a causal chain with no feedback. The simplification resulting from grouping the models into blocks makes it easier to apply the second validity criterion to the design of the simulation framework: that it be plausible.

Within the blocks, the related models have to be designed, built, populated with data and validated. As part of the model design process, control variables are identified and divided into two types: those which act directly on the model and those which act in conjunction with information from an earlier calculation in the causal chain. The data for the models include physical data such as the efficiency of types of space-heating equipment and survey (or census) data which, to continue the example, would be the age-structured stock of spaceheating equipment in domestic housing.

Blocks and links

Dividing the representation of the socio-economic system into separate blocks with causal links facilitates the understanding of the simulation framework. It also gives the additional advantage of being able to change the time step, spatial resolution and complexity of the models from block to block. The only constraint on this is that each block be able to receive input and to produce output according to a global standard for space and time reporting, used throughout the simulation framework for the scenario and the information in the links between blocks.

Control variables, which are links to control space, act directly on a model in a block or in conjunction with an input link from a previously calculated block. In SERF, where blocks are called components, a consumption component, which represents the desire to consume goods and services, follows directly after the demography component. In the consumption component are models of freight service and telephone service which are not tied to the human population and there are control variables which govern the amount of these services available directly. There is also a dwellings model and a household appliance model. The appropriate control variable for these is not the desired number of refrigerators or houses, but refrigerators or houses per household. This means that the control variable must be taken with the information on households produced by the demography component before the desired number of houses or refrigerators is obtained.

The number of control variables, input links and combinations of the two is a design problem in which the designer must strike a balance between doing all of the coordination between blocks in control space, or some of it. In SERF, for example, each component has both links and control variables.

Models

The models which make up the blocks are intended to satisfy the validity criteria, and this includes using, where possible, existing design and engineering information as well as representing the system to be modelled in a way which is plausible to an informed user.

When sufficient information is not available to build a model, some estimation procedure must be used. An example is an age-structured stock/flow problem which recurs throughout this work. The missing information is frequently the life expectancy of the components of the stock. While this information is available for people and some domestic livestock, it is not readily available for lathes, computers and furniture, and estimates have to be made from available data on total stocks and flows. The results are unlikely to be unique, but in the spirit of the validity criterion, they are expected to be plausible.

The physical nature of the models and the pervasiveness of stock/flow accounting means that material and energy accounting[10] could be applied, where appropriate, and linked throughout the simulation framework. To do this, however, requires a great deal of data and it is not done in the SERF prototype.

Tensions and decisions

Tensions and their resolution depend, in part, on how the simulation framework is constructed and on the degree of coordination of the blocks done in control space. In the SERF example, the simulation framework consists of four causally linked blocks of models. The actual simulation results from a scenario, which is the exogenous setting of all control variables. The causal linkage means that the first block takes the settings of its control variables from the scenario and the models in the block are executed. The outputs from this block, in the form of time series, are used along with the relevant control settings from the scenario as inputs for the next block, and so on down the chain. There is no feedback among blocks in the simulation framework and, as the models make no direct use of the past, there is no lagged feedback except implicitly, through the vintaged stocks. This leads to tensions.

As mentioned earlier, tensions arise for physical or social reasons. Insufficient labour, new materials and energy are physical tensions, while an excess of labour, insufficient housing, health care and education are social tensions. There are strategies for resolving tensions which lead to progressively more complex structures in control space.

The strategy used in SERF, where there are no explicit models of decision processes in control space, is a repeated simulation approach. That is, if tensions arise as a result of the first scenario, modifications are made and another simulation is done. This is repeated until a balanced scenario results, or until the user decides that the remaining social tensions are acceptable. This places a considerable burden on the user, which can be reduced by automation once the goals are identified, but there are other approaches to this problem. Sets of decision rules can be represented in control space which transform outputs from one simulation into inputs for a subsequent simulation.

An example is a decision rule which relates participation rates, labour productivity and immigration to the tension between labour availability and labour requirement. While this can proceed iteratively, there is no guarantee of convergence as each tension can relate to many others. A simple example is resolving a shortage of system design engineers at one time in the simulation by choosing to increase the production of such people by the universities. This might lead to tensions relating to the university infrastructure at an earlier time in the scenario.

Another strategy is to populate control space with models of decision-making institutions in much the same way as machine space is populated by models concerned with material and energy transformation. Models in control space must have access to the information on past events and be able to incorporate feedback mechanisms. The hierarchical, multilevel systems method of Mesarovic[11] offers an appropriate framework for such models as, with weak feedback between layers in the hierarchy, it provides a way of representing the complexity of decision processes in a socio-economic system.

Adaptive learning could be introduced at this stage by representing the formation of expectations and using the comparison between expectations and realization to modify the setting of the control variables. Some work has been done on modelling the change of decision rules of firms in the context of a model without equilibrium[12] and there is considerable interest in adaptive learning in other fields. 13 The work of Burns14 on actor-system dynamics is relevant to this approach, but there is much research to be done before it could be incorporated into a simulation framework of the type described in this paper.

Even with models of decision processes, however, the role of the user remains central. It is most unlikely that these models can resolve all tensions and, with a hierarchy of models of decision processes in control space, counter-intuitive behaviour might arisels which would require the user to restructure control space or to intervene to change the rules for decision making.

An example of structural change that could arise from attempted tension resolution is illustrated by Hardin's "tragedy of the commons" .16 Here, the tension is between the desire of individual herdsmen to add additional grazing animals to land held in common, and the capacity of the land to support more grazing. When capacity is reached the system is not stable, as each herdsman, in considering adding one more animal to the commons, anticipates receiving all the benefits of the sale of the animal while sharing the cost of overgrazing with the other herdsmen. Rational herdsmen add more ani~als and the commons is destroyed. Hardin17 asserts that there is no technical solution to the problem as posed. However, solutions involving change in the structure of decision-making can be explored: dividing the common land into private holdings, or establishing a commons council with power to allocate and police its use, are starting points.

This example illustrates tension resolution as a creative process in which the user exercises choice and introduces novelty. In this respect the design approach differs from models which provide forecasts from inputs and a predetermined set of assumptions. The future, as Prigogine18 emphasizes, is not given: it is a consequence of choice.

SERF the prototype

SERF is a computer simulation framework consisting of 44 separate models which combine to represent the Canadian socio-economic system.19 The models have access to 400000 time series of data for the period 1961 to 1981 and there are 100000 time series of input variables which can be used as control variables in the repeated simulations which lead to a scenario free of tensions. The simulation framework is supported by interactive graphics and data base facilities, as well as a simulation language.

SERF is designed to address a particular set of problems relevant to public policy. They include the provision of social infrastructure such as health care, education and transportation; the use of non-renewable and renewable resources including energy sources, minerals, agriculture, forestry and fisheries; the treatment of waste and pollution; and the impact of technology on the need for human resources. These problems are all medium to long term and they have a number of other characteristics in common.

The problems on which SERF is focused are concerned with composition, substitution, the effect of the socio-economic system on non-market areas and the interconnectedness of all of these problems. Examples of compositional effects arise from the age structure of the population, of manufacturing plant or of consumer durables, while the effects of substitution arise when one technology-fuel, material, etc.-replaces another. Another common characteristic is that these problems are best described in physical rather than financial terms, especially in areas external to the economy where there is no market mechanism.[20]

SERF evolved at Statistics Canada in a group concerned with the development of input-output models[21] and it can be regarded as a new generation of this type of model, rooted in the work of Leontief[22] and applying the activity analysis of Koopmans[23]. SERF evolved in response to a series of issues which influenced the Canadian economy in the 1970s.

The 'baby boom', resulting from high birth rates between 1950 and 1965, entered the labour market in the 1970s in increasingly large numbers, at a time when female participation in the labour market was rising. Unemployment and the effect of technological change became important issues, and the Canadian industrial strategy debate looked for a resolution of the unemployment problem through increased export of manufactured goods, in place of the traditional export of raw materials. At the same time, concern was developing about industrial pollution and the diminishing of non-renewable resources. .

Macroeconomic data was not adequate for the description of these problems. "SERF was developed, in part, to integrate the data necessary to their description and to act in a manner complementary to the system of national accounts. The exploration of alternative futures, from the point of view of a statistical agency, was seen as a way of anticipating areas in which data collection programmes could be established in order to provide a coherent picture of the evolving Canadian socio-economic system.

In developing SERF and its precursors, the design approach to socioeconomic modelling emerged, with the emphasis on physical stocks and flows, and on using the simulation framework to compare alternative futures. It was recognized very early on that the solution to economic and social problems, in the context of the simulations, had to be the result of explicit policy decisions taken by the user of the framework and not the result of implicit behavioural assumptions. Consequently, no market forces were represented which produced equilibrium. Equilibrium could only be achieved by the user of the simulation framework. The design approach and SERF are still evolving.

As it has developed, SERF has been applied to a variety of Canadian socio-economic problems. The nature of this work, for industry associations and other government departments, has meant that case studies could not be published. However, in 1984, the University of Waterloo established the Waterloo Simulation and Research Facility (W A TSRF) which places SERF and its application in the public domain. So far two studies have been published, one on long-term employment projections[24] and the other an application of the approach to regional modelling.[25] The version of SERF at Waterloo is the same as the Statistics Canada version which is now described.

Components and models

Representing the complexity of the Canadian socio-economic system is simplified by viewing it as four blocks or components: demography, consumption, fabrication and assembly, and material resources. The various supply and demand tensions are made explicit by ensuring that information

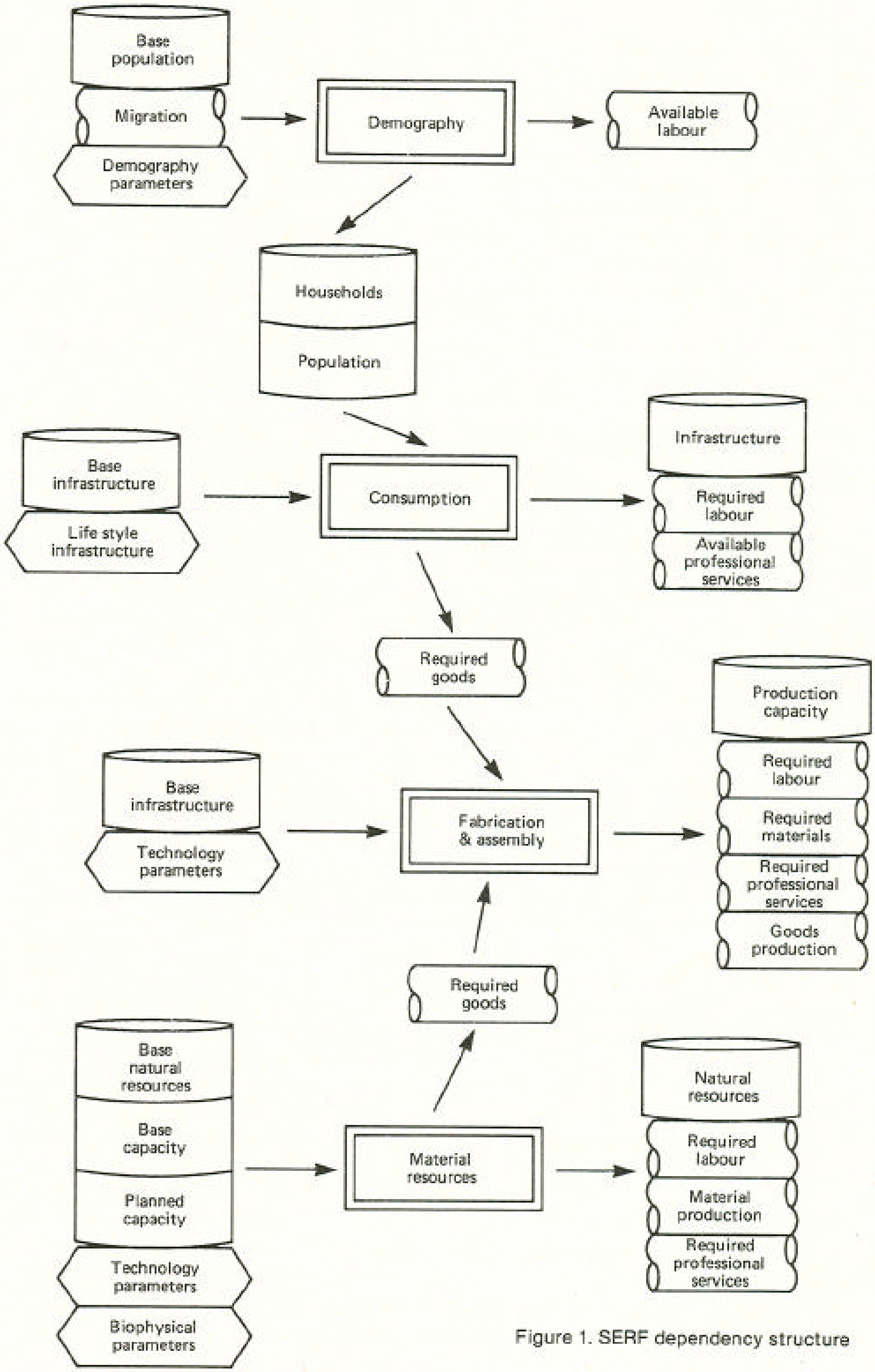

Figure 1. SERF dependency structure

flows from one component to another in one direction only. The components and their links are illustrated in Figure 1. The historical and other inputs appear on the left-hand side of Figure 1 while the stocks and flows, which the user may wish to balance, appear on the right-hand side.

While SERF is constructed as shown in Figure 1, the user sees it as presented in Figure 2, as a hierarchy which allows the user to navigate from the top, or SERF, level down to the components and then to the models. At each level it is possible to examine variables and to set new values, and this is how a scenario is actually constructed. The viewing of tensions can only be done from the highest level, in what has been described earlier as control space, and it is here that models of information processes can reside. In fact, there are only two models in the control space of SERF, and they are concerned with resolving tensions between international payments and receipts, and between productive capacity and its utilization.

The four components of SERF are described in detail elsewhere[26] and briefly here. The first component is demography which consists of three models: population, household formation and labour force participation. The cohort population model keeps track of population by single year of age, and by sex, by adding births and immigrants to a base population, aging it, and subtracting deaths and emigrants. The number of households is calculated by applying age and sex-specific headship ratios to the population, using the Canadian census definitions of household and headship. The available labour force is evaluated in

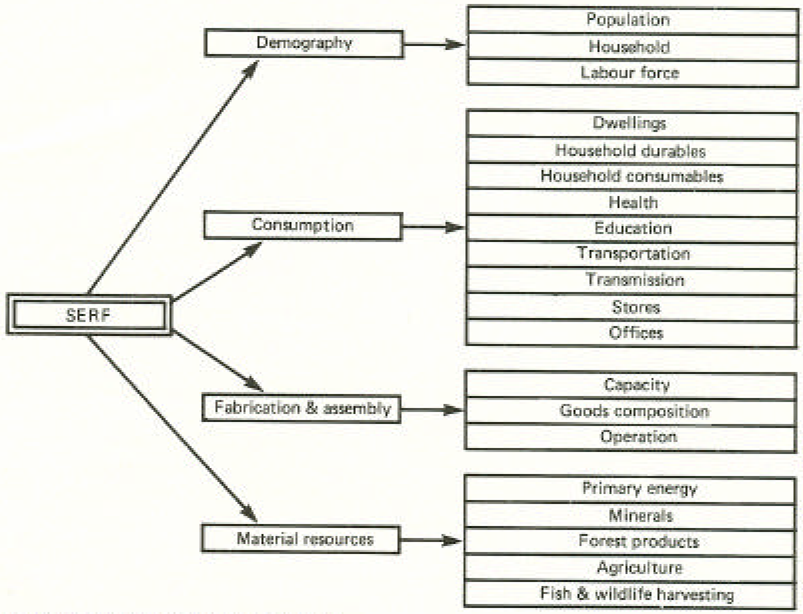

Figure 2. Conceptual hierarchy of SERF

two ways: the number of people willing to participate in the labour force and the quantity of labour service available. The former is a stock, measured in numbers of people, and calculated by applying age and sex-specific participation ratios to the population, while the latter is a flow, measured in person-hours per person-week and obtained by multiplying the labour force by the average number of work-hours per week.

The consumption component consists of models of dwellings, household durables, household consumables, health care, education, transportation, transmission, stores and offices. Each model relates vintaged stocks, or the services yielded from the stocks, to population or households and calculates the additions of stocks that are required to maintain them at a desired level, after allowing for retirements. Wherever appropriate, the goods, fuel and labour required to operate the stocks are calculated, as is the demand for professional services. Access to infrastructure stocks, and the services provided by them, constitute a measure of physical well-being or welfare. Welfare in this context is measured by the availability of stocks, rather than by the flow of production necessary to put the stocks in place which is the conventional measure used in the Gross National Product.

The fabrication and assembly component represents the processes that transform material and primary energy into the finished goods and fuel for both the consumption and the material resources blocks. The calculation of the activity levels of the processes that constitute fabrication and assembly is complicated by intermediate goods and the consequent interdependence of the processes, by the propensity to import or export intermediate and finished goods, and by lead times caused by the fact that the production of capital goods at a particular time is in response to a demand for finished goods at a later time. The representation of productive capacity and its utilization is also complicated as the utilization can adjust to absorb, to some degree, differences between the requirement for goods and the amount of production capacity in place. Strategies to deal with these problems have been implemented27 in the capacity formation, goods conversion and goods production models in the fabrication and assembly component.

The capacity formation model keeps track of the stock of productive capacity and the investment that is required to maintain the stock at an exogenous desired level. The model is able to represent any addition to capacity, and the necessary time stream of investment goods required to put it in place, from the desired level, the existing level and the life tables of the stock.

The goods conversion model does two things. It gathers goods requirements from the consumption and material resources components and the investment goods from the production capacity model and converts them to the classifications and units appropriate for the goods production model. It also calculates the share of these goods which will actually be produced in the goods production model by subtracting direct imports, and goods such as hydroelectricity, produced in the materials resources block.

The goods production model is an input-output model formulated in terms of approximately 500 goods and 200 processes. The demand for goods is allocated through market share coefficients to the processes that produce them. The production processes, in turn, may require goods and fuels from other production processes, as well as material resources, labour services and professional services., The market share coefficients, and their change with time, control the substitution of one process for another and it is in this way that technological change is represented. Technological change also depends on the rate at which substitution can take place, and this is influenced by the evolution of planned capacity, the existing pattern of installed capacity and the lifetime of the installed capacity. Rapid substitution can lead to the creation of excess capacity in 'old' processes.

The material resources component consists of five models: primary energy, minerals, forest products, agriculture, and fish and wildlife. At the time of writing, these models are in an early stage of development. All of the models are designed to be supply-driven, as planned production or capacity to produce are the main exogenous variables, and these are intended to reflect resource endowments. The difference between the available material resources and requirements for them in the fabrication and assembly component constitutes a tension. This tension, and its resolution, is complicated by the fact that material resources can also be exported, or imported.

That completes the brief description of the components of SERF and the introduction of some of its models. There are, however, two types of models in the design approach: those which deal only with information and those which also deal with energy and material. In SERF, most of the models are of the latter type, while an example of the former is the trade model.

The trade model in control space is an impact model of decision processes. It keeps track of all material resources, goods and services that are exported or imported. Each component, with the exception of demography, is able to export or import, and this information is available to the trade model along with exogenous information on prices, terms of trade, interest rates and trade-related debt. The SERF user is able to adjust the interest rates and terms of trade to achieve trade balance and this can be done automatically if required.

Of the models dealing with energy and material transformation, the residential heating model28 in the consumption component is a good example of an application of the design approach. The model is based on 1971 and 1981 Census data on the stock of houses and their characteristics which include location, the type of house and thermal properties. This information is combined with data on the difference in temperature between the inside and the outside of the house, taken from weather records, to derive the amount of energy required for space heating. Then, given the kind of heating equipment, the model calculates the quantities of fuel required to provide the energy for space heating. The parameters for the first calculation come from an engineering calculation of heat losses and gains at various temperature differentials. The fuel conversion efficiency parameters come from an independent study of heating system efficiency. The only data for calibration of the output of the model are aggregate measures of the total amounts of fuels consumed in the residential sector in a year. The amount of energy required for space heat is not observed at all.

The residential heating model also illustrates the application of the validity criteria. The data that the model must agree with over the historical period include the annual consumption figures for the various fuel types. The principal control variables are the thermostat settings for the houses, along with thermal characteristics, which can change as owners improve the insulation, and the conversion efficiency of the space heating equipment which can improve as units are replaced or converted to use other fuel types. As data on the housing stock are available for two census years, estimates have to be made about the stock and its characteristics over the historical period. The end result is a plausible model of energy use for residential heating which reproduces the annual data on the consumption of fuels for residential heating.

Software tools

The data management problems of SERF are well beyond the capacity of the unaided user. The data include 100000 time series of input or control variables, the 400000 time series of historical data for the years 1961-1981, and the many simulations and associated scenarios, including the text description of the projections of the historical variables.

SERF is embedded in a software system called the Scenario Writing and Management Instrument (SWAMI) and it is SWAMI which presents SERF to the user in the hierarchical form of Figure 2. SWAMI helps the user to create scenarios, modify existing scenarios and view the results of simulation resulting from the scenarios.

As part of building a new scenario, SWAMI lets the user examine the documentation of existing scenarios in the scenario data base, and it allows the user to select components for the new scenario. This is particularly helpful, as rarely does a user wish to set 100000 time series over 50 years. However, even with the ability to use mixtures of existing scenarios, the user is likely to want to provide projections for some of the control variables.

The setting of even a few input variables over a period of 50 years is tedious, and graphical methods are provided which allow the user to display the historical time series from 1961 to 1981 and then to draw the projection from 1982 to 2031. When the user is satisfied with the projection, it is automatically digitized and added to the scenario. As the scenario is built up from existing scenarios and input from the user , SWAMI asks for statements eXplaining why each step is taken. When the scenario is complete, these statements constitute its documentation.

Once a scenario is complete, it can be run by SWAMI and the results stored as a simulation. Provision exists for displaying variables, or combinations of variables, in the simulation at each level of the SERF hierarchy. It is in this way that the various tensions are displayed.

It is also possible to add models to SERF, to populate them with data and to connect them to the simulation framework. SERF models are written in an interpretive language called the Terminal Entry and Review Facility (TERF) which is used for manipulating and displaying historical data, for the building of models and for the model input and output.

The software tools, consisting of SWAMI, TERF and related graphics facilities, have all been developed at Statistics Canada to support the building, documenting and running of scenarios in SERF to produce simulations. SWAMI supports the display of variables , at various levels of aggreg4tion, from the simulations and maintains the data base of scenarios and formulations.

TERF supports the building of models, the display and manipulation of data and it manages the data base associated with SERF. It is the supporting software that makes SERF a powerful tool for exploring alternative futures.

Tensions

The key to understanding the alternative futures in SERF simulations is the resolution of tensions. Tensions arise from the way in which the components are linked together, and the present implementation of SERF has six areas in which tensions can arise. There is a tension between the availability of labour in the demographic component and the use oflabour in the consumption, fabrication and assembly, and material resources components. A tension can arise between the availability of materials and primary energy in the material resources component, and their use both in the fabrication and assembly, and material resources components. There is a potential tension between the exploration activity, which yields producible reserves, and extraction from these reserves. The availability of professional services from the education sub-component of the consumption component, and their use in the consumption, fabrication and assembly, and material resources components can also give rise to a tension. There are, as well, tensions in the exchange of domestically produced materials, goods and services for those produced in other countries, and between the stock of productive capacity and its utilization.

Tension resolution in the first four areas is carried out by adjustment of the control variables and repeated simulation. In the cases of trade and investment there are mechanisms in place which the user can set to converge to a desired state. Provision exists to implement decision rule models to assist in the resolution of the other tensions, but to date no such models have been implemented.

The design approach and economic models

SERF is a prototype simulation framework and a partial implementation of the design approach. The question to consider now is where SERF and the design approach fit in the present spectrum and in the historical evolution of socio-economic models.

The design approach grew out of input-output modelling, and SERF illustrates this as it incorporates the Canadian input-output table as part of its calibration data. There is, however, much more to SERF: the use of models that incorporate engineering or design information, the separation of control variables, the absence of imposed equilibrium, and the emphasis on the exploration of alternative futures, in contrast with the predictions of the future derived from econometric models. The difference between the design approach, as exemplified in SERF, and macroeconomic modelling needs emphasis to avoid any confusion.

The principal difference, just stated, between the design approach and macroeconomic modelling is the emphasis on exploring alternative futures in the former and the prediction of the future in the latter. This difference derives from the absence of automatic equilibrating mechanisms in simulation frameworks built using the design approach, and the incorporation of equilibrium in the specification of the macroeconomic models. If there are no equilibrating mechanisms built into the representation of the socio-economic system, the user must choose how to achieve equilibrium, once it is agreed that this state is either necessary or desirable. As the desired state can be arrived at in a variety of ways, and over different time periods, the user is left with a set of simulations representing alternative futures, and a well documented set of policy decisions which led to the scenarios which produced each of them.

The degree of aggregation and the use of financial information are different in a macroeconomic model and a simulation framework, which incorporates the design approach, such as SERF. A macroeconomic model uses highly aggregated variables, such as the value of consumption, investment, government spending, taxes, transfer payments, price, money supply, and trade, along with various rates such as real interest, inflation and foreign exchange. A design approach simulation framework uses, where possible, less aggregated variables, measured where appropriate in physical units or numbers. Examples are the number of people of a particular age, the number of houses built in a given year, and the number of joules of energy produced and required in the economy. In SERF, where a rich body of data has been taken from the Canadian input-output table, deflated values have been used as substitutes for physical quantities.

The treatment of the marketplace is a point of difference, as the macroeconomic model assumes that all of the goods and services subsumed in the aggregate price are traded. This excludes consideration of activities external to the marketplace such as environmental pollution. In the design approach simulation framework, such externalities are treated as part of the production process and in later implementations the intention is to link the production of pollutants directly to material inputs through process models.[29] This does not preclude placing a model of the market mechanisms in control space, however, and this is an important consideration in planning the next stage of this work.

The specification and estimation of a macroeconomic model differs from the design and calibration of a design approach model.[30] In particular, the use of data is different as in macroeconomic modelling the data are used to estimate the parameters in the model using an appropriate statistical technique, while in the design approach, data which have not been measured, such as lifetimes of capital stocks, are estimated and then the data set is used to calibrate the model. The calibration is successful if the model reproduces the data, given a set of historical input variables, and this is considered a necessary but not sufficient condition for a valid model.

The second validity condition in the design approach, that the model be plausible, is difficult to relate to econometric models. The econometric model is specified as a set of equations, which may be a plausible representation of the economy, viewed at a high level of aggregation. However, unless the equations are recursive, they must be transformed to a reduced form before good estimators of the reduced form parameters can be found, and then the equations have to be properly identified before a unique set of consistent estimators of the structural parameters can be deduced. The estimators of the structural parameters are required if any statement is to be made about the plausibility of the structural model.

A final area of difference between macroeconomic models and the design approach is in the application of control theory. Currie reviews the application of control theory in macroeconomics and he addresses the problem of modelling the expectations, and the response, of the society which is influenced by the policy decisions represented by changes in the control variables.31 He goes on to put a case for the use of "rational or consistent" expectations,32 even with the restriction of bounded rationality, 33 in policy design and he foresees the incorporation of models of expectations in the next generation of macroeconomic models. While the advocate of the design approach would support this prediction, the problem that must be addressed in macroeconomic models is the number of behavioural assumptions built into the model which could conflict with a superimposed control model of behaviour. The design approach avoids this problem by keeping the decision processes separate from the physical transformation processes in the system.

The design approach to socio-economic modelling shares with input-output modelling a disaggregated description of the socio-economic system. Where the design approach differs from the static input-output model is in its representation of supply and demand, its use of stock/flow models to provide buffering and tim.e lags, and in its use of physical as well as financial data. Leontief has co~tinued to develop the input-output model and, in his most recent work with a dynamic input-output model, he has examined the impact of automation on employment in the period 1963 to 2000, subject to four scenarios of future technological change.34 In doing this, 89 individual industries are used to represent the economy and 53 occupations were considered. The work of Leontief parallels the design approach work and provides another example of scenario analysis. It also illustrates how the subject of socio-economic modelling is evolving.

Along with the development of data classification, forecasting and computer power has gone the evolution of hardware, software and systems design theory to the point where 'fifth generation' computer systems and artificial intelligence are serious commercial considerations. The growth in computing power has made possible the adding of more complex relationships to econometric models and the attempts to apply control theory to them. The improvement of software tools and systems theory has laid the foundation for the present work on the design approach to socio-economic modelling.

Conclusion

The design approach is a philosophy for building computer-based simulation frameworks, which represent socio-economic systems, and for using the simulation framework to design alternative futures through repeated simulation. It is the exploration of alternative futures by the user, who forms part of the system, which distinguishes this approach from that of macroeconomics with its emphasis on prediction. The exploration and the involvement of the user result from the absence of optimization or equilibrating mechanisms in the physical representation of the socio-economic system. This ensures that the user, working alone or with the aid of a model of decision processes, controls the system. The policy decisions necessary to exercising this control are required to be explicitly stated, and they form a record of how the future, resulting from the simulation, was arrived at. In SERF, the prototype implementation of the design approach, the simulation framework and the data on vintaged stocks which form part of many of the models in the framework support the study of compositional and substitutional effects in a wide range of economic areas. Some examples of these areas are technology impact studies, natural resource development, alternative energy studies, pollution effects, and infrastructure requirements such as health care, education and transportation networks. The simulation framework is also suitable as an economic planning and policy analysis tool, as it makes explicit supply and demand differences which result from the planner's scenario and supports the analysis of how the tensions were dealt with.

From the perspective of a statistical agency, the design approach to socioeconomic modelling provides a framework for integrating historical data and it suggests priorities for data collection and research. In the case of SERF, which is used both at Statistics Canada and other organizations, there are benefits to be gained from understanding the data requirements of clients as case studies of SERF applications accumulate.

This paper has concentrated on the representation of activities in the socioeconomic system which can be measured, and the possibility of building models of decision processes to assist in the control of the simulation framework has been discussed only briefly. The study of adaptive models which change their operations, and the rules they apply, according to their inputs, is an active research topic in other fields and it is an important one if progress is to be made in the understanding of socio-economic systems and their representation.

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