The Role of Simulation in Problem-Solving Oriented Education: the global systems simulator

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Abstract

Introduction

The life cycle of knowledge is becoming shorter, the volume of knowledge is increasing exponentially, and ; knowledge is increasingly discipline specific. As a consequence knowledge acquired in formal educational institutions becomes obsolete more quickly and learning how-to-learn is increasingly important.

To face this new reality, there is need for a shift in emphasis from discipline based to problem based learning. Learning is centered around the student perspective on a problem. Knowledge from several disciplines must be synthesized. Students can learn better by grappling with typical cases, exploring the impact of their choices, and managing a set of variables which have many subtle relationships.

At the dawn of the age of personal computers with graphical user interfaces, Alan Kay, Apple's guru on the future of computing, wrote a thoughtful essay published in Scientific American on the subject of the use of computers for educational purposes. He observed that

> "Wonderful learning can occur without computers. But once the teachers and children are enfranchised as explorers, computers can serve as powerful amplifiers, extending the reach and depth of the learners.
>
> "Children learn in the same way as adults, in that they learn best when they ask their own questions, seek answers in many places, consider different perspectives, exchange views with others and add their own findings to existing understandings".

and concluded that

> "The heart of computing is building a dynamic model of an idea through simulation. Computers can go beyond static representations that can at best argue; they can deliver sprightly simulations that portray and test conflicting theories. The ability to "see" with these stronger representations of the world will be as important an advance as was the transition to language, mathematics and science from images and common sense."[1]

[1] Alan Kay, Computers, Networks and Education, Scientific American September 1991, page 146, 148

Twenty five years later, Kay's vision has yet to be fully realized. The art of building dynamic simulation models that help us see the world as it might be and to make wise and coherent choices is one that is very rare indeed.

Human activities are now of such a scale that the evolution of the earth system itself is to a significant degree determined by human decisions. This is the age of the anthropocene. Enlightened decision making is urgently required if humankind is to thrive in harmony with the finite endowment of the earth's resources. It is our hypothesis that simulation has a critical role to play in creating and communicating the understanding of complex dynamic systems needed for enlightened decision making

Understanding Complex Systems

It is increasingly recognized that complex systems pervade every facet of life - from patterns of traffic flow in road networks to evolution itself. In complex systems, behavior at the level of the system as a whole emerges from the dynamic interactions among the processes that constitute the system. The interrelationships are often non-linear and sensitive to starting conditions. The emergent behavior may be chaotic. New processes may emerge as the system adapts to new circumstances in unpredictable ways. Historically bound systems are fixed in space and time and are such that repeatability is not often possible. Mathematical descriptions of complex systems are insufficient because analytic solutions seldom exist, because the system behavior may be sensitive to parameter values and starting conditions, and because the descriptions are inaccessible to all but the mathematically literate. Computer based simulation is showing promise as a method for expressing theories of complex systems in sciences ranging from quantum physics to ecology to astronomy. In these sciences, the simulation model becomes a laboratory that may be used for experimentation. [Casti 1997], [Holland 1998], [Simon 1982].to increase our knowledge of the laws governing an objective and deterministic universe. According to the theory of human cognition, learning involves the formation of implicit and provisional models in the human nervous system that adapt as a result of experience. These models filter and interpret the physical phenomena reaching the sensory devices of the body such that effective actions can be taken. [Maturana et al 1980], [Maturana et al 1987], [Dennett 1996] The human cognitive apparatus is perhaps is well, if not uniquely, suited to 'look-ahead' or form expectations and make decisions based upon those expectations. However, the human cognitive apparatus has evolved to perform in relatively local space and time. The objective is to extend cognitive capacity in space and time and from the individual to the group. It is our hypothesis that appropriately designed computer simulators are an effective means for meeting this objective.

Synthesis: the missing link between science and problem solving

> "In the twenty-first century, the world will not be run by those who possess mere information alone. . . . We are drowning in information, while starving for wisdom. The world will henceforth be run by synthesizers, those able to put together the right

information at the right time, think critically about it, and make important choices wisely."

- Edward O. Wilson, Consilience, 1998

Scientific knowledge is seldom available in a form that is ready for use in problem solving and decision-making, nor does it explicitly address the problems confronting the decision-makers. Often it originates in more than one discipline; sometimes it is contradictory; it may be incomplete and/or subject to caveats. Its findings are couched in a technical language that may be inaccessible to the layman. When policy analysis is unable to assimilate science based information, the consequence is either problem-denial or decisions based on criteria usually not unrelated to the relative power of the various stakeholders in the problem domain.

This gap between science and public policy analysis is well recognized and presents challenges particularly in problems of management of the commons, such as fisheries management and climate warming. [Brewer 1986], [Clark 1986], [Ravetz 1986], [Skodvin 1999], [Wojciechowski 1998] It arises because the culture, institutions, and modes of behaviour of science have little in common with those of public policy analysis. [Skodvin 1999]

Public policy analysis and decision making implies choice: the future is not pre-determined, but can be influenced by what we decide to do; there are alternatives from among which we must choose and the choice to do nothing is a willful one. For science, the concept of choice has been problematic. Science seeks to generate 'objective' knowledge of the laws that govern the universe. These laws in conjunction with a starting condition determine the future of the universe and the concept of choice is precluded. Max Born, the Danish physicist and Nobel Laureate observed that:

> "Only two possibilities exist: Either one must believe in determinism and regard free will as a subjective illusion, or one must become a mystic and regard the discovery of natural laws as a meaningless intellectual game." [Bulletin of Atomic Scientists, 1957]

Another Nobel Laureate, Belgian chemist Ilya Prigogine, described the contradiction in the following terms:

> ". . . we owe to the ancient Greeks two ideals that have since shaped human history. The first is the intelligibility of nature, or in Whitehead's words, "the attempt to frame a coherent, logical, necessary system of general ideas in terms of which every element of our experience can be interpreted." The second is the idea of democracy based on the assumption of human freedom, creativity and responsibility. As long as science led to the description of nature as an automation, these two ideals were contradictory.

And went on to conclude that:

> “ This (contradiction) requires a new formulation of the laws of nature that is no longer based on certitudes, but rather possibilities. In accepting that the future is not determined, we come to the end of certainty” [Prigogine 1997]

The culture and institutions of science enshrine the so-called scientific method, by which one arrives at objective scientific knowledge of real-world phenomena that is accepted provisionally as truth until it is contradicted by further application of the method. One pillar of the scientific method is the use of controlled and repeatable experiments to test hypotheses. Here the emphasis is on analysis - reduction to the point where controlled experimentation is possible. Another pillar of the scientific method is prediction: a hypothesis may be conditionally accepted if phenomena predicted from the hypothesis are observed. The scientific method has proven to be most effective in areas such as chemistry, physics, and biology where knowledge is context independent - that is where the process under study has weak interactions with the processes that constitute its context. The scientific method has been less effective in dealing with complex context dependent systems where controlled experimentation is not possible and where emergence is an important phenomenon. [Holland 1998] It has had least success in systems in which human beings are an integral component. In these systems, not only is controlled experimentation not possible, but as well prediction is not possible to the extent that the future is influenced by choice. Perhaps the relative lack of progress in the social sciences noted by Edward O. Wilson may be attributed to reliance on scientific methods borrowed from the physical sciences that are inappropriate to the problem domain of the social sciences. [Wilson, 1998]

If science may be characterized as knowledge-seeking, objective, reductionist, analytic, deterministic, and technical, problem solving and decision making is at the opposite end of each of these poles. It is useful to consider public policy analysis and decision making as two distinct processes. Public policy analysis involves developing an understanding of the problem domain such that the full consequences of various resolution interventions can be assessed and the alternative outcomes from which choices must be made can be identified. Decision-making is the process of selection from amongst the alternatives. It is the job of policy analysis to synthesize all of the knowledge pertinent to the problem domain and to communicate the resulting understanding to those delegated responsibility for making the decision. Decision processes in matters of public policy almost always involve communication of understanding to a much broader community of stakeholders - often the ‘public’ at large. Unlike science, policy analysis and decision making do not have the luxury of waiting until understanding is complete; decisions must be made in the face of the uncertainty of incomplete knowledge and risks must be subjectively evaluated. The expression of choice is subjective; outcomes may be valued differently by different individuals or groups. Those who benefit from a particular outcome may have to compensate those who lose; choice involves understanding the real tradeoffs among interests and negotiating until a choice can be made that is most acceptable to all parties. Issues of public policy are almost always historically bound and context dependent and involve humans as an integral part of a complex system.

It is clear that methods for synthesizing knowledge originating in the sciences, both physical and social, are critical for problem solving and public policy analysis and subsequent decision making. However, unlike science where methods of analysis are mature, methods of synthesis are not well developed, particularly for systems involving humans, with the consequence that consensus on the validity of synthetic understanding is difficult to achieve. The body of theory from which synthetic methods may be drawn is general system theory and cybernetics. [Weiner 1948], [Ashby 1956], [Bertalanffy 1968], [Maturana etal 1980], Simon 1982] But, this body of theory has largely been ignored by institutions of higher learning as it does not fit into the disciplinary framework with its emphasis on analysis.

Synthesis of scientific knowledge in support of public policy analysis has employed several methods: blue ribbon panels, formal models, and policy exercises.

The first and longest established is the 'blue ribbon' panel, consisting of experts from the various fields, with a mandate to seek consensus on the problem domain and to make policy recommendations. Blue ribbon panels are convened as subcommittees of national academies of science, presidential commissions, and international working groups; the authority of the panel rests on the credentials of the members. Panels use the techniques of persuasion to support the policy recommendations that emerge from their deliberations. While persuasion may trigger action, it seldom conveys understanding, since it relies on rhetorical technique and selective arguments. Northrop Frye has observed that argument relies on the arrangement of data. Arrangement means selecting for emphasis, and selecting for emphasis can never be definitively right or wrong [Frye, 1990]. Panels are effective when the scientific knowledge is complete and consensus can be easily reached, but are not effective when knowledge is incomplete and there are conflicting interests. Interest groups advocating different policies can convene their own experts and thereby confuse the decision-making process. Panels communicate to the policy process by means of a written report directed to the sponsoring agency; they seldom engage directly in the decision process. There is a tendency for panels to make policy recommendations judged to be 'politically acceptable' even though it may be known that the recommended policy may not be sufficient to deal with the problem.

The second approach is the use of computer based modeling. Models clearly have the potential for handling large amounts of technical information in a systematic and reproducible way. They have seldom met this potential when used for policy analysis, not just because formal modeling projects are costly and time consuming. Brewer makes the point that "the work is one sided; it presents but one perspective on a future rich in potentialities". Put another way, modeling in the sciences has retained the determinism of the scientific method and thereby preempts the role of the decision-maker. At worst, large-scale policy models are black boxes closed to adaptive possibilities and learning. They produce predictions with little room for policy intervention, or, when they incorporate 'objective' measurements of value, they make prescriptions that purport to be optimal. Large-scale models often lack transparency and fail to communicate an understanding of how the system works; they rely for their authority on the mystique of computer technology, arcane mathematics, and the scientific credentials of the modelers. [Brewer 1986]

The third approach is the use of policy exercises or workshops that engage scientists, decision-makers, interest groups and, in some cases, modelers in the decision making process. These policy exercises come in a variety of flavours and go by a number of names. Their origins may be traced to game theory [von Neumann et al 1944] and to the use of war gaming by the military. [Shubik 1982] Scenario analysis [Wack 1985], [Schwartz 1991], Adaptive Environmental Assessment and Management [Holling 1978], [Sonntag 1986], Integrated Assessment [Bland 1999] and Mediated Modeling [Van den Beit] are all examples of policy exercises. In these methods the emphasis is on the process for reaching a decision as much as the outcome itself. The policy exercise puts the policy issue in as broad a context as possible and seeks to build a common understanding of the elements of the underlying system. It is recognized that stakeholders may have different values and interests and that the probability of a consensus-based decision is increased if the real trade-offs among the interested parties are understood by all. This process almost always involves the development and analysis of a number of scenarios; sometimes models are constructed during the course of the exercise to support the scenario analysis. Choice and indeterminacy are implicitly recognized. While in an early stage of development, these methods show promise particularly in circumstances where the understanding generated in the process need not be communicated beyond the participants in the process.

An informed public is essential for effective public policy. There must be a broad-based consensus on the diagnosis of the problem before remedial policies can be implemented, particularly when those policies may have adverse impacts upon particular interest groups. Further, there must be broad-based consensus that the policy actions are socially just and fair - that private interests aren't served to the exclusion of the public interest. In this context, robust methods for the synthesis and communication of understanding of complex systems are critical. This paper suggests that 'systems simulators' may be an effective means for communicating the understanding of complex systems needed to inform public debate on issues of public policy.

Systems Simulators

Simulators are descriptions of complex systems representing the interrelationships among the processes that constitute the system; they combine observations of past states of the system with scientific understanding of processes. As such, simulators are explicit and communicable representations of the mental models that guide our perceptions and actions. Unlike verbal or mathematical descriptions of systems, simulators are active and can be experienced. Learning how the system works arises from the experience of using the simulator. The user will come to appreciate the complex system-as-a-whole behaviour as it emerges out of dynamic interactions among relatively well understood processes.

Unlike the deterministic models of classical science, the simulator approach is open to adaptation or learning. The simulators are designed in such a way that the system of feedback loops necessary to assure consistency among the constituent processes of the system is incomplete: those feedbacks embodying the behavioral responses that are subject to adaptation are excluded from the simulator because they are not knowable.

Consequently, the possibility of incoherency or disequilibrium arises. Incoherency is indicated by tensions that must be resolved by the user of the simulator. In this way the user becomes an integral part of the system as the source of novelty for adaptation, not an observer of a closed system.

These concepts have their origins in modern science. The work of Ilya Prigogine shows the indeterminacy of systems far from equilibrium and the possibilities of adaptation through the emergence of higher levels of order.[Prigogine 1984]. Indeterminacy is a property of evolutionary systems. The evolutionary principle is stated by Erwin Laszlo in the following terms:

> “The evolutionary paradigm challenges concepts of equilibrium and determinacy in scientific theories; and it modifies the classical deterministic conception of scientific laws. The laws conceptualized in the evolutionary context are not deterministic and prescriptive: they do not uniquely determine the course of evolution. Rather, they state ensembles of possibilities within which evolutionary processes can unfold.”[Laszlo, 1987]

Simulators are primarily learning devices that extend our powers of perception; they do not predict what will happen nor do they prescribe what should happen. Just as flight simulators support learning how the aircraft responds to the controls, simulators may be used for exploring the responsiveness of complex systems to potential individual or societal actions. Simulators are descriptions of complex systems representing the interrelationships among the processes that constitute the system; they combine observations of past states of the system with scientific understanding of processes. As such, simulators are explicit and communicable representations of the models that guide our perceptions and actions. Unlike verbal or mathematical descriptions of systems, simulators are active and can be experienced. Learning how the system works arises from the experience of using the simulator. The user will come to appreciate the complex system-as-a-whole behaviour as it emerges out of dynamic interactions among relatively well-understood processes.

To be effective, learning simulators must have the following properties:

Controllability The simulator user must be able to experiment with control settings that make “the airplane” fly safely, or crash. In this context, it is worth recalling the cybernetic theorem, the Law of Requisite Variety, which states that the regulation that the regulator can achieve is only as good as the model of the reality that it contains [Ashby, 1956].

> “It comes down to this: we cannot regulate our interaction with any aspect of reality that our model of reality does not include - whether as to its theoretical range or as to its observational facilities and resolution - because we cannot by definition be conscious of it” [Beer, 1981].

Transparency The question “why” must be answerable at all levels. The user must be able to ‘see’ all of the values of the state variables and parameters for both history and scenarios. He must be able to see the connective structure of the model or how the processes that constitute are interrelated. He must be able to understand the nature of each transformation: how variables going into a transformation give rise to the output variables.

Correspondence between model and the reality it represents. The simulator must be seen to correspond to the real world without oversimplification.

Scenario Range - Simulators must be designed to accommodate a wide range of scenarios so that all of the stakeholders in the debate can see the full consequences of the actions they advocate.

The Global Systems Simulator

The Global Systems Simulator is an interactive computer based simulation model designed as proof-of-concept for an evolutionary systems approach to the problem domain addressed by the World3 system dynamics model of Jay Forrester. It is the minimum structure needed to explore the concepts of 'sustainability' and 'carrying capacity' at the global level. It recognizes that the earth system is for practical purposes closed to material flows but open to radiant energy from the sun and as such is open to unpredictable evolutionary change in the form of human learning. The user/society uses the simulation model to explore possible trajectories of the earth system subject to possible or potential human decisions . Exploration involving interaction between the model and its user community is a learning process and the source of novelty for adaptation.

Background
In the 1970's, Jay Forrester and his colleagues at MIT developed the World Dynamics Model, a computer based simulation model focused on the growth of human populations and the limits to growth imposed by the Earth’s finite natural resource base. The result of the project was a report to The Club of Rome, entitled The Limits to Growth, which predicted the collapse of human populations and drew public attention to the issue of the carrying capacity of the globe. It stimulated debate between those advocating measures to curb population growth and those confident that new technology would emerge capable of extending the limits to accommodate foreseeable population growth.

The World Dynamics Model belongs to the deterministic natural science paradigm in that it represents a closed system and presumes that the future of the system is predictable to the extent that the model captures the time invariant laws of motion of the system. The laws include implicitly in the feedback structures the response of humankind to changes in the state variables. This structure precludes human learning and adaptation and denies evolutionary change. It makes the user of the model an observer of the system rather than an integral part of it.

The global systems simulator, designed and implemented by Robert Hoffman and Bert McInnis in the early 1990's, was intended to address in concept what were perceived to be the shortcomings of the World 3 model. .A new approach to global modeling was needed - one that would recognize that the future is subject to choice and that the choices we make are based on our understanding of the consequences of those choices. The new approach should include the model user/society as an integral part of the system rather than as an observer of a closed system.

The new approach emphasizes learning and the communication of understanding rather than prediction and prescription. The use of simulators to support learning by doing is similar in concept to the use of flight simulators to train pilots. Model users, individually or in groups, interact with simulators to explore the consequences of possible actions and create scenarios in systems where factors interrelate in subtle ways. Complex behaviour for a system-as-a-whole emerges out of dynamic interactions among relatively well understood processes.

Structure

The GSS represents the physical substrate of the Earth system. It consists of a number of processes including:

- population dynamics
- food consumption
- services derived from the stock of artifacts
- food production
- artifact production
- materials recycling
- pollution treatment
- energy production from renewable and non-renewable sources
- materials production from forestry, agriculture and mining
- knowledge generation that can make the processes for transforming materials and energy more efficient with respect to energy, labour and capital

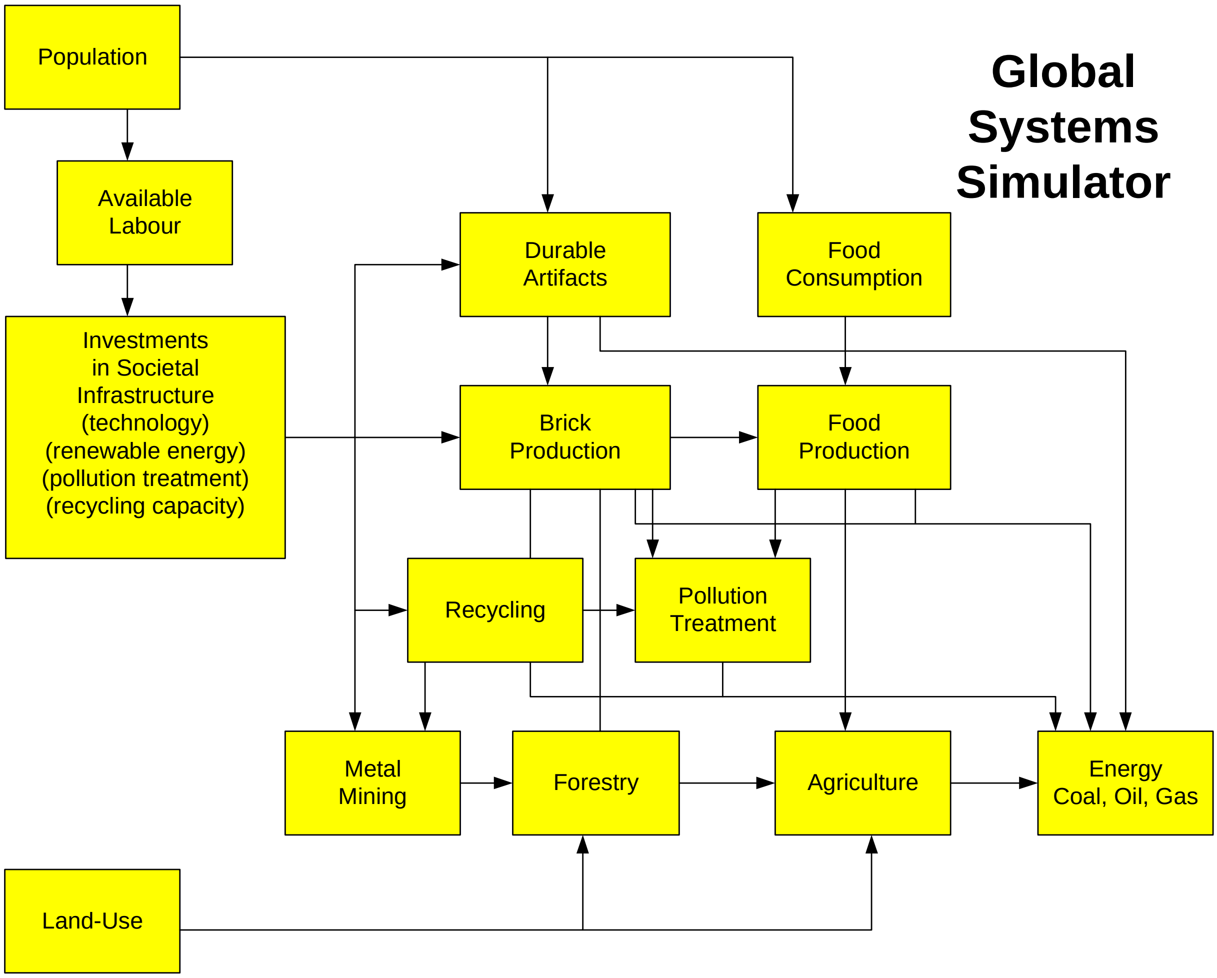
Energy, raw materials, finished goods, waste materials, pollutants, human effort, and technology embodied in artifacts including production capacity, are the flows that link the various processes.

The Earth system has an endowment of natural resources, a human population, and stocks of artifacts, production capacity and knowledge that serve as the starting point for scenarios. The processes are subject to user control resulting in a system that is over-determined in terms of its control variables.

The structure of the GSS is depicted in the Figure 1 below. The yellow boxes are sub-models, each of which contains the representation of one or more processes. The arrows indicate the sequence of calculations. Each sub-model is calculated over the full time horizon of the simulation before proceeding to subsequent sub-models . It follows that the user sees results for all time periods and all sub-models before proceeding to adjust the settings of the control variables for all time periods. This proves to be advantageous as the user has information about future time periods when setting the control variables for earlier time periods.

Figure 1 GSS Structure

The group of sub-models shown in Figure 2 represent the minimum structure needed to explore the concept of sustainability.



The GSS model was designed to incorporate and illustrate the following principles:

- The earth system receives a flow of energy from the sun and has finite endowments of material resources. In the GSS, these endowments consist of land, coal, oil, gas, hydro-electric potential, and a mineral resource.

- The human population requires a flow of nutrition and a stock of artifacts for its survival and well-being.

- Land supports the growth of trees and crops. Crops are the source of nutrition. Trees are a source of both wood, a material from which artifacts can be made, and energy.

- Coal, oil and gas are non-renewable, endowment-limited sources of energy while hydro-electric potential, trees and solar radiation are renewable, rate-limited sources of energy.

- The mineral resource is a non-renewable endowment-limited source of material, called metal, from which artifacts can be made.

- Two kinds of processes are represented: those that are naturally occurring and those that are purposeful in the sense that they have been put in place and are operated to serve human ends (in the GSS, tree growth and forest regeneration are naturally occurring; most other processes such as mining, ore concentration, exploration, recycling, pollution treatment, planting and harvesting, materials transformations, and artifact production and use are purposeful).

- Purposeful processes require effort to put them in place and to operate them.

- There are two sources of effort: human labour and energy. The availability of human labour is limited by the size of the source population.

- In some processes, energy used in combination with an appropriate artifact, such as an engine, can substitute for human labour as a source of effort.

- Improvements in process efficiency are not free; rather they require an investment of effort in the form of human labour devoted to increasing the stock of knowledge.

- The efficiency of processes is embedded in the stocks of productive capacity and artifacts and these stocks reflect the knowledge available at the time they were put in place.

- Production from endowment-limited resources is subject to diminishing returns to effort, which is represented in different ways in different process. For non-renewable energy production, the amount of effort required to find resources increases per unit producible energy as the limit of the resource is approached. For mineral production the amount of effort required for ore concentration increases as a function of accumulated production. In agriculture three kinds of land are distinguished according to yield potential and the highest yield land is produced first. Sites for hydro-electric energy production are ordered by quality and highest quality sites are used first (by quality is meant the investment per unit of generating capacity).

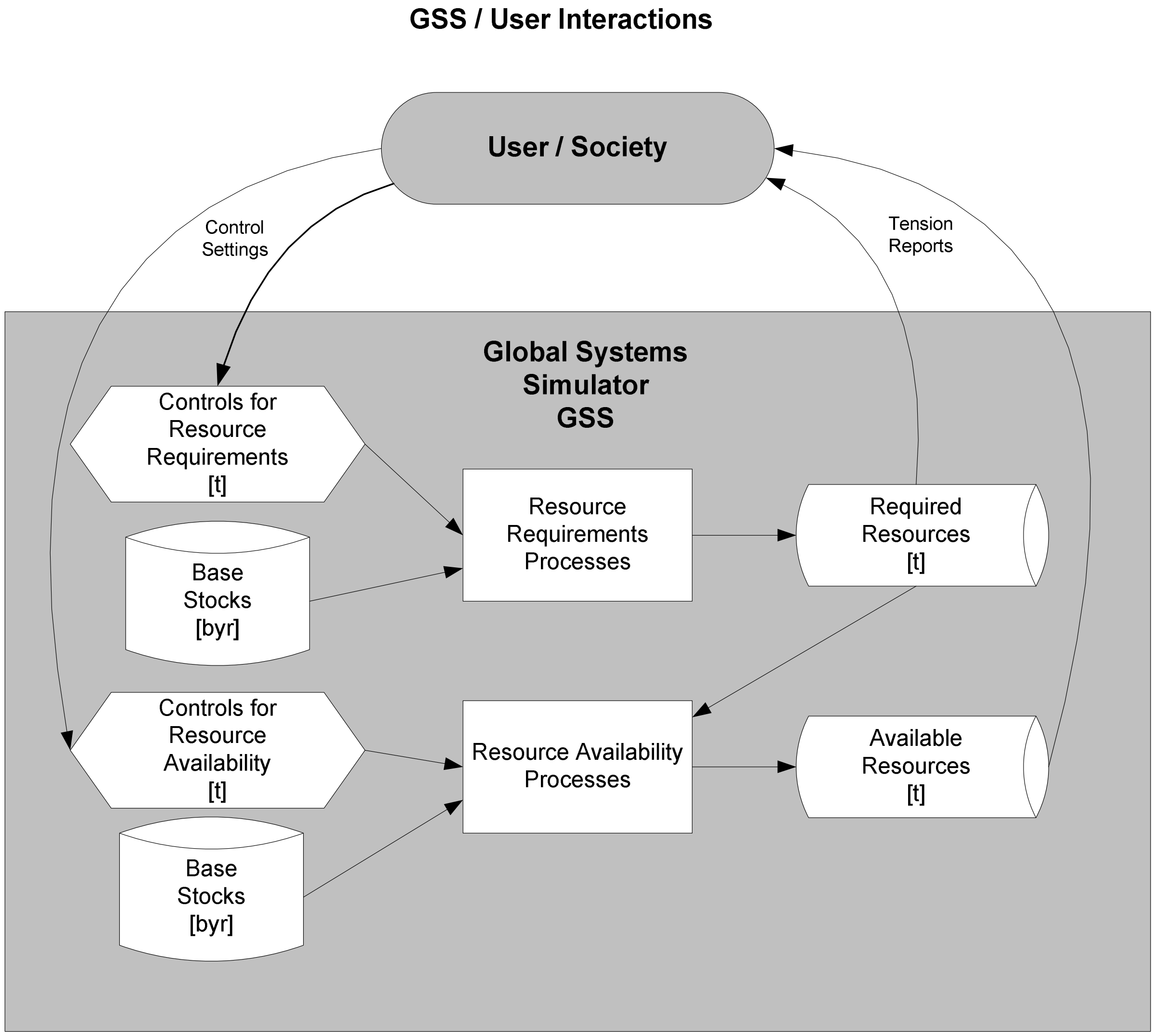
- The concept of 'externality' is represented in the GSS in its treatment of pollutants. Some processes generate a waste by-product or pollutant that, if released untreated into the environment, may accumulate and adversely impact other processes. In agriculture, yields decline as function of pollutants released. In forests, tree mortality is increased as a function of accumulated pollutants.

- It is also necessary to represent the concepts of reuse and recycling in a world in which there is a finite source of materials In the GSS, all artifacts are made from a variable combination of metal and wood (metal is non-renewable and endowment-limited; wood is renewable but rate-limited and subject to the competing use of wood as a source of energy). As artifacts reach the end of their lives, the metal component of the discarded artifacts may be recovered with the expenditure of effort, the amount of which is a function of the recovery ratio. The GSS is parameterized in such a way that the cross-over between the amount of effort per unit metal from the mine and from recycling occurs in the future.

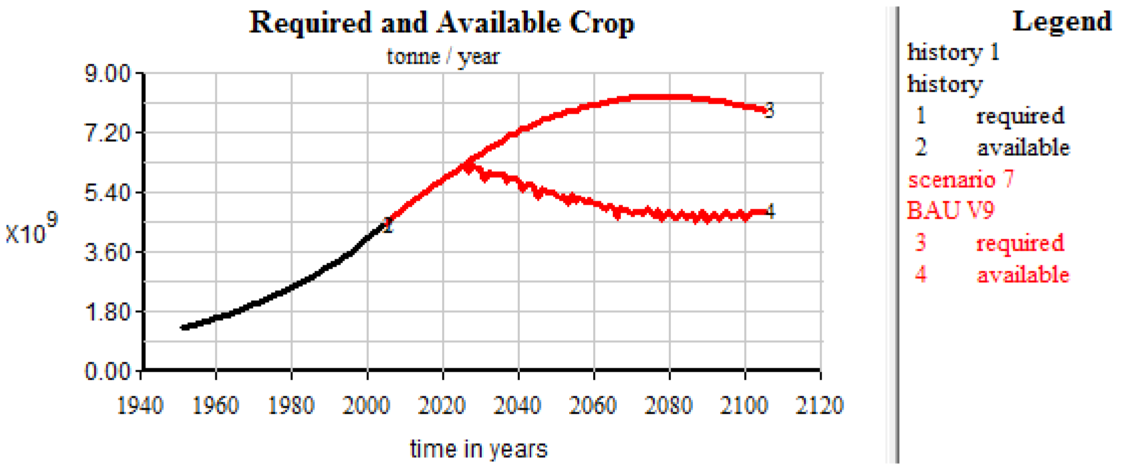
Tensions/Incoherency and User Engagements

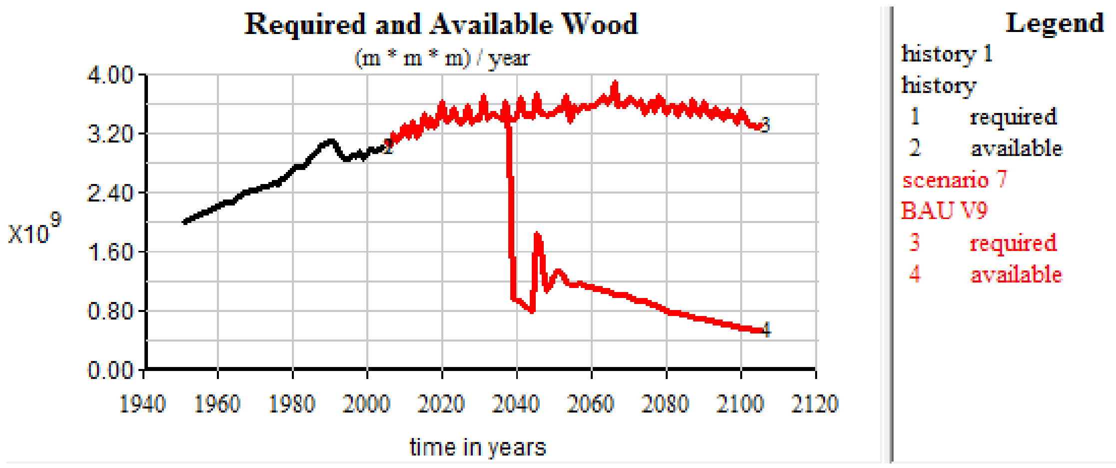
The GSS is designed in such a way that the system of feedbacks among the processes is incomplete: population driven requirements for raw materials, energy, crops and wood from the natural resource base are not made coherent with their availability. Availability may be limited by original endowments, regeneration rates, or insufficient investment in exploration or in production capacity. Likewise, requirements for labour are not made coherent with the availability of labour from the population. Differences between requirements and availability are tensions that must be resolved by the user, a surrogate for the society of which he is a member, who provides alternative settings for the control variables. It is this idea of tension arising from disequilibrium that makes the user of the GSS an integral part of the system as a source of novelty. The interactions between the GSS and the user are illustrated in Figure 2 below.

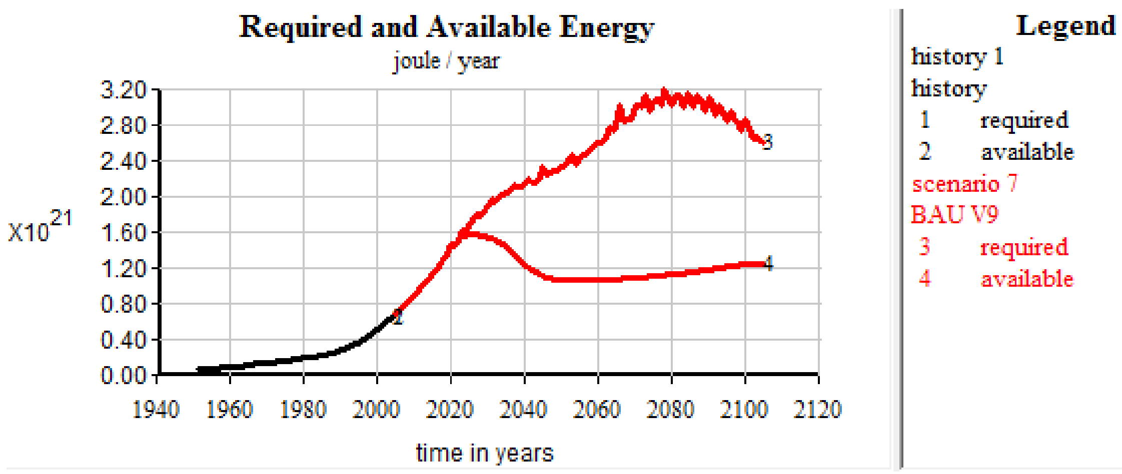
Figure 2 GSS-User Interaction



The first step in model use is for the user to supply settings for all of the control variables. Let us say, for example, that the user wishes to create a scenario continuing past trends in the control variables.to suggest that we intervene in the earth system much as we have done in the past. These actions are simulated and the simulator is executed and produces the following tension reports:







These graphs indicate that the scenario is not coherent beyond the year 2025. At that time, requirements for energy cannot be met; shortly thereafter requirements for agriculture crops cannot be met and by 2040 requirements for wood cannot be met. It is then up to the user to adjust the settings of the control variables to resolve the tensions. He can ‘see’ the settings of the control variables that produced output; in fact he can ‘see’ all of the variables in the model. The user may proceed by manipulating one control variable at a time to see how the system responds to each variable or he may proceed cumulatively, first changing one variable, then by adding another changed variable. It becomes clear that the size of the response is not independent of the order in which the control variables are manipulated. The modelling system provides facilities for comparing scenarios and keeping track of the input values that correspond to each scenario.

Planned Enhancements

1. Energy Sources and Carriers. The GSS currently represents both fossil (coal, oil, and gas) and renewable (hydro, biomass and other) sources of energy, but does not distinguish sources from carriers. It is important that the model represent the processes that transform energy sources into energy carriers, (hydro-carbon fuels, hydrogen, and electricity), and the stocks of artifacts (vehicles, buildings, infrastructure, etc.) that use fuels to provide the services (nutrition, shelter, mobility, recreation) needed to support human populations and to drive industrial processes. It is also important to recognize that all energy is not created equal: energy from different sources and in different carriers are not perfect substitutes.

2. Materials. The GSS currently has two representative materials; metal that is non-renewable, but recyclable, and wood, that is renewable. The materials list needs to be expanded to include at least plastics and concrete/cement.

3. Artifacts. At present the GSS has a single composite artifact. This needs to be disaggregated into at least a half dozen stocks, including residential buildings , commercial buildings, machinery and equipment, vehicles, transportation infrastructure, and other. Each artifact would have its own material composition.

4. Pollutants. At present GSS has a single representative pollutant that impacts agricultural yields and forest productivity. There is a need to disaggregate pollutants to differentiate pollutants to water, air and GHG emissions.

5. Agriculture and food. At present, the agriculture component represents agriculture land differentiated only by productivity. It would be desirable to introduce new categories of agriculture land: land suitable for cropping, both dryland and irrigated, and grazing land, and to develop components for plant nutrients, water use, and livestock.

6. Human diet. At present the only source of nutrition is food. It would be desirable to distinguish vegetable from animal components of diet and to represent explicitly the transformation of crops into meat and dairy products..

7. Water accounting. At present there is no accounting for water sources and disposition for irrigation and urban use. Introducing water accounting is problematic as water shortages are geographically specific.

8. Climate model. It would be desirable to add a simple dynamic climate model that would represent the carbon cycle and its impact on average temperatures. It would keep track of flows of GHG emissions from fuel combustion, industrial processes, and animal stocks, and concentrations in the atmosphere and theoceans.

9. Institutions and Finance. Introduce stock/flow consistent accounting for sectors including at least government, central banks, commercial banks, households and the production and goods and services.

10. Regionalization: It would be desirable to disaggregate spatially into a dozen regions and to keep track of exchange among them.

Many of the concepts and approaches needed for a new model have been developed and can be incorporated into the design for a new model. The work of Kenneth Boulding is the source of much inspiration. See Boulding (1978). The Earth system analysis described by H. J. Schellnhuber provides an appropriate conceptual framework. Schellnhuber (1999). Joel de Rosnay's concept of a macroscope apprpriately positions the model as a device to enhance human perception, much the way a telescope enhances the human capacity for perception. See de Rosnay (1979). This is akin to the design approach to socio-economic resource modeling. See Gault, Hoffman et al (1987).

The concept of evolutionary systems as open systems far from equilibrium had its origins in the work of Ludwig von Bertalanffy (1968) and there is now much literature on this subject. See for example Boulding (1978), Jantsch (1980), Laszlo (1987, 1996), Prigogine and Stengers (1884), Capra (1996), Prigogine (1997), Noble (2006), Dosi (2011), Goldenfeld et al (2011), Smolin (2013). The nature of technology as an evolutionary process is developed in Arthur (2009).

'Process' as a primary concept for transforming a time-stream of inputs of materials, energy and information into a time-stream of outputs and process modeling has a substantial literature. Activity analysis had its origins in the work of Koopmans and Leontief . See for example Koopmans (1951), Leontief (1993), Ayres (1972, 1978), Capra 1985), Gault et al (1987), Georgescu-Roegan (1971), Hoffman et al (1993).

For the concept of 'agent' or 'actor' as a primary concept for the analysis of human activities and agent based modeling, see Burns et al (1985), Beinhocker (2006).

Since the bursting of the finance bubble, much has been written on the role of money, debt and finance. See for example Graeber (2011), Keen (2009, 2011), Kinsella (2011), Soros (2008), Hudson (2012), and Wray (2012). Kinsella's stock flow consistent modeling for financial instability seems appropriate.

There are a number of models of the physical substrate of an economy whose dynamics are captured in stock-flow-process models. The concepts for these models originate in the materials/energy balances of Robert Ayres and colleagues. See Ayres (1970, 1972, 1978, 1993), Gault et al (1987), Hoffman et al (1993). A group led by Charles Hall advocate a biophysical based paradigm for economics that has much in common with stocks and flows approach. See Hall et al (2001) and Hall and Klitgaard (2006). A good and current example is the Australian Stocks and Flows Framework. See Poldy et al (2000), Turner and Poldy (2001), Foran and Poldy (2002, 2005), Lennox et al (2004), Turner et al (2011).

Much has been written on the development of various indicators of prosperity and sustainability. See Stiglitz et al (2011). The concept of ecological footprint is used to indicate sustainability. See Wackernackel (1994). For the concept of resource productivity, see Weizaecker et al (2009).

Experience in Learning Situations

The Global Systems Simulator has been used in a number of educational settings with some success. These experiences range from primary school, grade 7, at an educational workshop at Rutgers University involving a large group of inner city students, to senior secondary school students in four two hour sessions.

It is currently being used in a graduate course in systems methods offered by Royal Roads University in Victoria, British Columbia. These students were divided into teams of three or four and given the assignment to find scenarios that resolve all the tensions and to document the understanding developed in the sequence experimental simulations. This assignment is preceded by classroom time in which students are introduced to the concepts of the model and the mechanics of creating and comparing scenarios. Almost all the teams were successful in searching the space and finding scenarios that resolved the tensions. But very often the approaches and results found by the teams showed a wide range of variation. At the end of the exercise one student remarked that the tension free scenario created by her team could never be implemented because it would cost too much. The remark demonstrates the degree to which we are captured by frames of reference or conventional wisdom that we are accepted without question.

Recently, the model was used in as part of a project, the Anthropocene Curriculum Development, intended to develop and test curriculum around the theme of Anthropocene. The project involved a number of instructors and a group of graduate students. The particular seminar that made use of the GSS was on the subject of ‘wicked’ problems.

Concluding Remarks

Simulation modeling employing some the principles and lessons learned from our experience with this and other models show promise, but many challenges remain. While many students could engage in a model developed by others, there was no indication that students could design and implement such models. One of the missing elements is a good open source software tool that would support access to existing models, but which could be widely used for the design and implementation of models by others appropriate for problem domains of interest to them.

Thus, Alan Kay’s vision remains illusive, but well worth pursuing.

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