Systems Dynamics and STELLA

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SYSTEM DYNAMICS: A SIMULATION MODELING PARADIGM

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System Dynamics, founded by Forrester and his associates at MIT in 1950s (Forrester, 1961, 1968), is based on general systems theory, incorporates cybernetics and information theory, and has become a unique, powerful simulation modeling methodology (Goodman, 1974; Richardson and Pugh, 1981; Roberts et al., 1983; Wang, 1987, 1988; Pidd, 1988; Barlas, 1989). System Dynamics holds that the macro behavior of a system is primarily determined by its internal micro structure. The systems approach emphasizes the connections among the various parts that constitute a system and applies feedback principles to model and analyze dynamic problems (Barlas and Fey, 1989).

According to System Dynamics, the core of system structure is composed of feedback loops (positive and negative) that integrate the three fundamental constituents of state, rate, and information. State variables (accumulations) are the major concerns which change through time (e.g., population size, biomass, etc.). Rate variables (flows) represent flows of material or energy between state variables and characterize the rate of change of these state variables as a result of specific processes. Information links between variables are established by auxiliary variables (converters). The standard symbols for structural diagrams in System Dynamics modeling are depicted in Fig. 2.1.

System Dynamics is a powerful and versatile approach, especially for studying dynamic characteristics of large complex systems. Initially developed for industrial systems, it has found applications in such diverse fields as business, economics, psychology, medicine, management, and ecology (e.g., Forrester, 1961, 1971; Meadows et al., 1972; Goodman, 1974; Meadows et al., 1974; Richardson and Pugh, 1981; Barlas and Fey, 1989; Wu and Barlas, 1988). A group of modelers in the Netherlands have applied System Dynamics principles to their simulation studies of ecological processes, especially for agricultural ecosystems (e.g., de Wit and Goudriaan, 1978; Ferrari, 1978; Penning de Vries and van Laar, 1982). Gutierrez and Fey (1975a,b, 1980) have developed and tested a System Dynamics model of secondary succession based on Odum's (1969) tabular model of succession. Although the validity and applicability of Gutierrez and Fey’s model are restricted by overgeneralized structural aspects, their study was the first which systematically illustrated how to build an ecological dynamic model using the SD method. Other ecological applications include those in management of natural resources and environment (e.g., Paulik and Greenough, 1966; Arnold and de Wit, 1976; Boyce, 1977; Clark, 1987).

Structure-function simulation, rather than pure function simulation (e.g., black box simulation), gives System Dynamics methodology the flexibility to integrate the holistic and reductionistic perspectives, thus providing greater explanatory power. Relying heavily on the computer, System Dynamics provides a framework in which one can apply the idea of systems theory to ecological problems. Using advanced computer simulation techniques, the method can have a high degree of realism by capturing the richness of real systems. Three features of System Dynamics, i.e., causality, realism, and simulation, make it an excellent modeling approach to studying dynamic, complex ecological systems.

System Dynamics modeling, in general, includes the following interrelated and iterative steps (cf. Richardson and Pugh, 1981; Roberts et al., 1983; Wang, 1987):

(1) Identification and definition of the problem and objectives. In this step, the problem is identified and defined. That is, for example, how does a population change through time in a landscape island and over a patchwork of islands? Can it persist? And under what conditions?

(2) Determination of the system boundary, identification of major variables, and construction of the causal-loop diagrams (influence diagrams). According to the defined problem, a system boundary has to be drawn properly to achieve an optimal choice of variables. For instance, major factors affecting population dynamics and species persistence in a habitat patch and over a landscape of patches should be identified. Furthermore, the direct influences among these variables need to be recognized and causal-loop diagrams, which describe the relationships in general, produced.

(3) Construction of flow diagrams (structural diagrams) and building of the corresponding computer simulation model. The flow diagrams concentrate on the type of each variable and specification of its particular relationships to others. The three types of variables (state, rate, and auxiliary) and their interrelations are depicted using the conventional System Dynamics symbols or slightly modified ones provided by STELLA, a newly-developed simulation software (see next section for details). The state variables and the associated flowing-in and -out rate variables are first portrayed. Then these rate variables, which may be determined by state and auxiliary variables, are specified by relating information links.

The mathematical equations, which quantitatively reflect the flow diagram, are usually written in DYNAMO or STELLA. Of course, they can be written by other computer languages such as FORTRAN, C, or PASCAL. With STELLA, the accumulation equations are automatically written by the software. However, writing the equations for rate and auxiliary variables is the most challenging and most important task. It often requires both information from different areas of ecology and expertise in mathematical model building. In addition, it is important to notice that every variable and equation in a System Dynamics model should be physically or biologically meaningful.

(4) Collection of data and estimation of the parameters in the model. As in many comprehensive models, it is impractical and impossible for a model builder to personally collect all necessary field data because of the limitation of knowledge, time, and energy. Therefore, the data to be used for testing the plausibility of the equations and approximating the values of coefficients are frequently obtained mainly from published literature and documentation. In addition, it may be necessary to base some of the estimations on experience of experts in particular fields according to the availability of data and other information.

Although this step of data collection and parameter estimation is listed fourth, some numerical data and other information have to be used in the second and third steps too.

(5) Verification of the computer simulation model. During this step, the program is debugged and assured to perform properly. In other words, the goal is to make sure that the program is doing what it is intended to do. Model verification can be done by a series of test runs under different conditions and judged by simulation modeling experience and professional expertise. STELLA facilitates the process by drawing the flow diagrams on the screen and then preventing the modeler from writing any equation inconsistent with the given diagram.

(6) Validation of the model. Different from verification, the goal of validation is to determine whether the model is an accurate representation of the real system. Validation can be achieved through the calibration of the model, which is an iterative process of comparing the behavior of the model to that of the actual system. Discrepancies between the two and the insights gained are used to improve the model. The process is repeated until the accuracy of the model is judged acceptable. The validation process is not an isolated procedure, but an integral part of model development.

(7) Simulation experimentation and conclusions. During this phase, the validated model is used to test relevant hypotheses and to simulate an array of alternative sets of conditions for the variables, which are designed according to the objectives. From the analysis of the simulation experimentation, conclusions about dynamics of the system under study can be drawn and, moreover, further implementation of the model may be identified.

STELLA: A CUTTING-EDGE SIMULATION SOFTWARE

The simulation language, DYNAMO, associated with the development of the System Dynamics methodology, has been used in most of existing SD models. However, this study uses the newly-developed simulation software, STELLA (acronym for Structural Thinking Experiential Learning Laboratory with Animation; see Richmond, 1985 and Richmond et al., 1987). The software was first released in August 1985 by High Performance Systems, Inc., Hanover, New Hampshire and has become increasingly popular with upgrades and refinements. It is compatible with Macintosh computers. As “a revolutionary new piece of software,” STELLA was designed to facilitate System Dynamics modeling and make it available for even those lacking computer experience and mathematical expertise (Richmond, 1985). The 1989 Jay Wright Forrester Award was given to Barry Richmond of High Performance Systems for STELLA and its manual, as “the best published piece of work in the field between 1984 and 1989” (Forrester Award Committee, 1985).

STELLA is icon-oriented and thus brings model conceptualization and formulation much closer than they would otherwise be (Fig. 2.2). There are no compile delays and no need for writing timescripts of variables in equations. Once a structural diagram is completed, STELLA writes the equations for all levels internally in the form of first-order difference equations and also provides a list of variables necessary to formulate all rate and auxiliary variables mathematically. It provides a wide array of special built-in functions, optional integration methods (Euler's, the 2nd and 4th order Runge-Kutta), and high resolution output of both time-series and scatter plots. STELLA also has the capabilities of detecting and preventing logic errors effectively and animating system dynamics both diagrammatically and graphically. In addition, graphical or table functions can be directly used in STELLA, not only providing great flexibility in modeling, but also allowing the quantification of some seemingly “unquantifiables,” especially in fields such as ecology. In fact, STELLA is a System Dynamics “expert system”, or the first attempt at it, which possesses expertise in computational and structural logic, conceptualization, equation formulation, and model analysis (Richmond, 1985).

While System Dynamics provides a tremendously powerful framework for understanding the dynamic behavior of complex systems, STELLA, as an extraordinary implementing tool, not only greatly eases the modeling processes, but enormously enhances its learning utility. For instance, without the tedious and time-consuming task of writing and debugging programs, the modeler can allocate much more energy and time to understanding the modeled system itself. Designed especially for System Dynamics modeling, STELLA can also be used as a convenient differential equation solver or non-System-Dynamics-oriented modeling practices (both ways of using STELLA have been exemplified in this study). STELLA makes simulation modeling available, feasible, and affordable to the majority of scientists. It is expected to break new ground for simulating biological complex systems (Costanza, 1987).

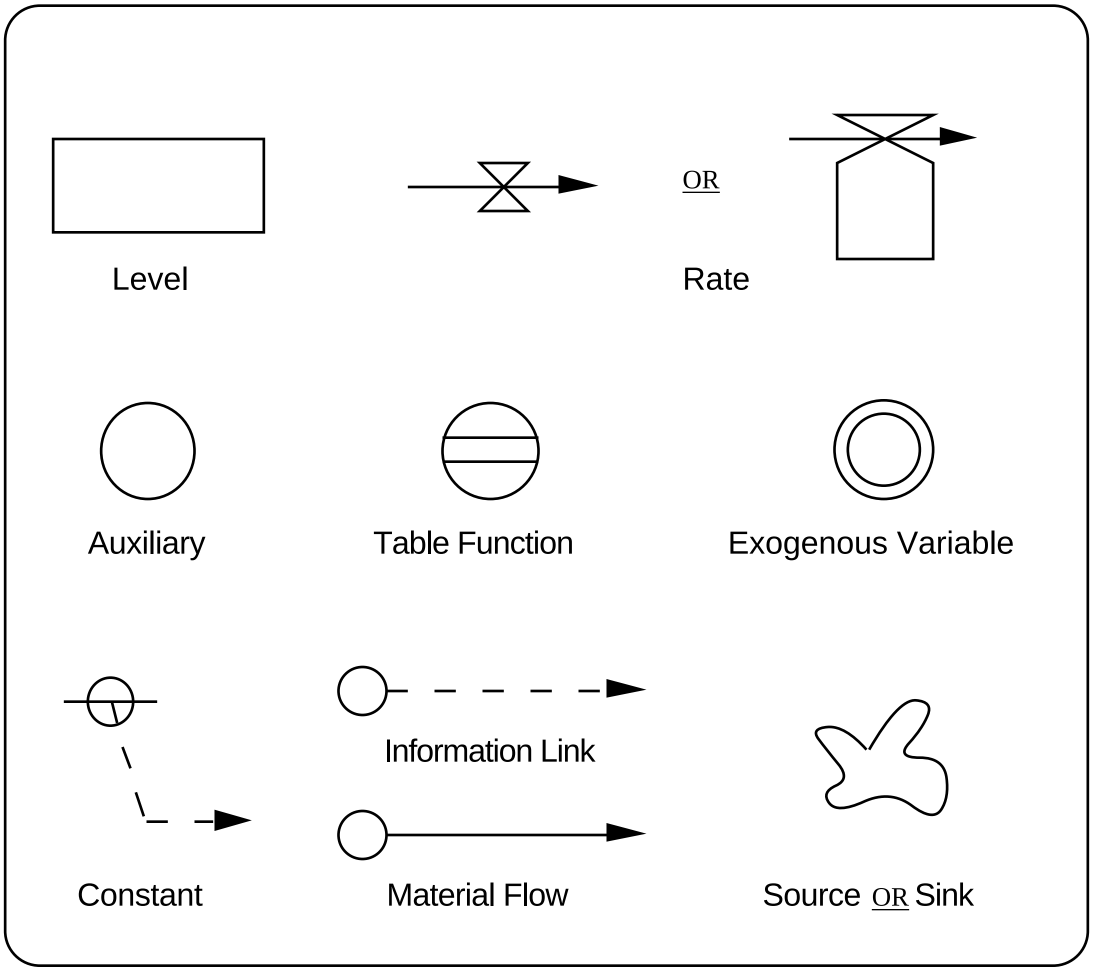

Fig. 2.1. Standard symbols used for structural diagrams in System Dynamics modeling.

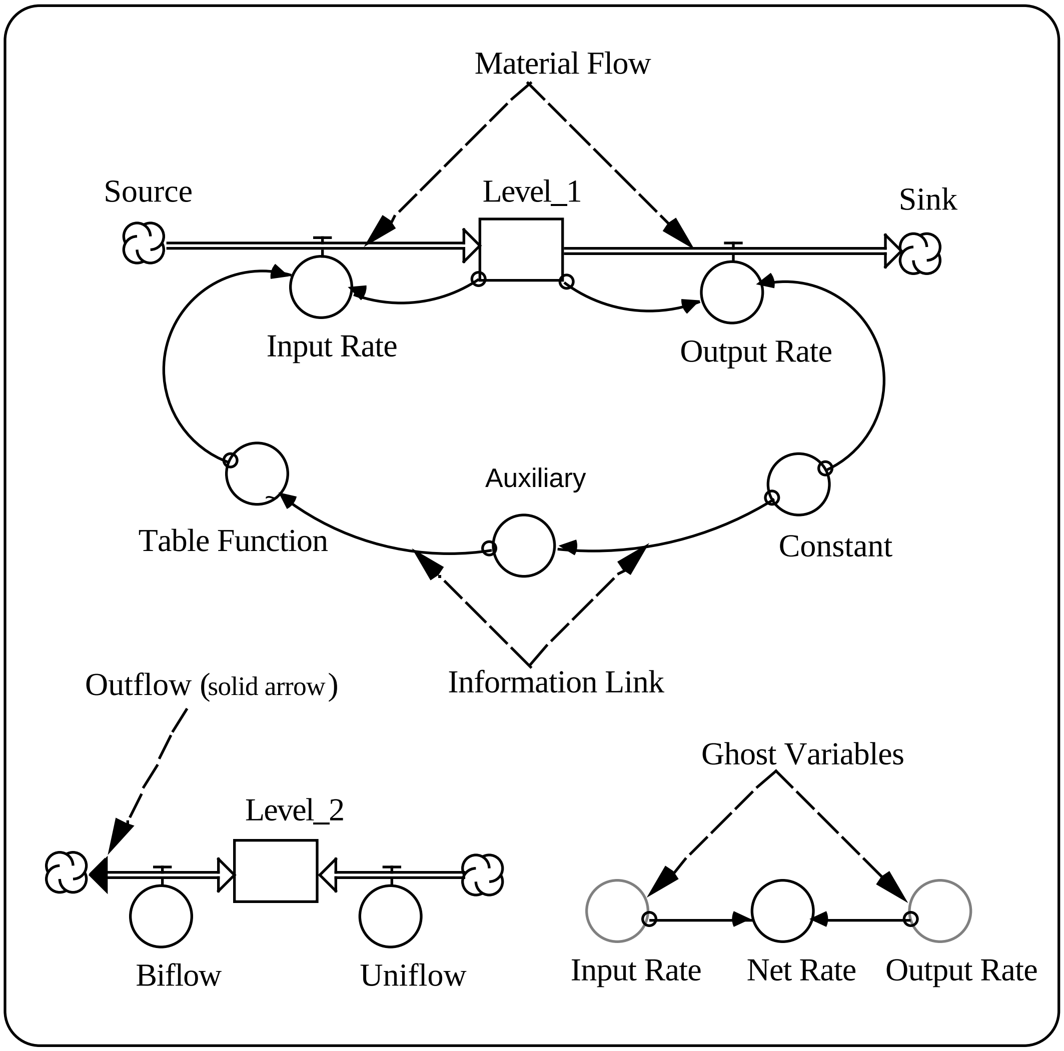

Fig. 2.2. Symbols used for structural diagrams in STELLA II. Ghost variables are surrogates of state, rate, or auxiliary variables which are usually used for reducing the crossovers of lines and for computing additional variables of interest.