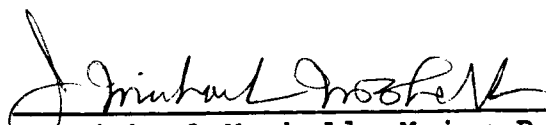
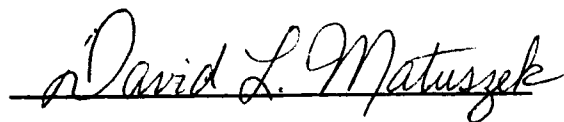


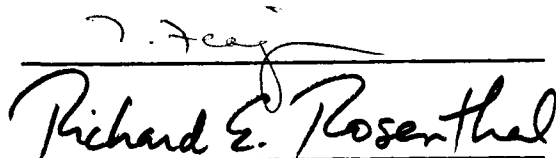
To the Graduate Council:

I am submitting herewith a thesis written by Carl Richeson Gregory entitled "An Illustrative Societal Model for Classroom Computer Simulation." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Computer Science.

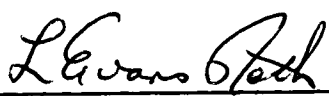

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AN ILLUSTRATIVE SOCIETAL MODEL FOR
CLASSROOM COMPUTER SIMULATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Carl Richeson Gregory

March 1983

3066055

DEDICATION

To my parents, who always see me through.

ACKNOWLEDGEMENTS

It's common to be reflective on an occasion such as this. As I've taken longer than most, I suppose I've more to reflect on. I would first of all like to thank all those souls currently sharing time and space with me on this planet. It's a terrific time to be alive and we're the reason why.

As for my current academic achievement, thanks first to Miranda for being there when I needed all the help I could get. Thanks to Bill Baird for the idea, the inspiration, and the constant pressure to make this work. Thanks to Dave Matuszek for naming the right time to write it down. Thanks to Joe Cornelius for all the napkin drawing sessions at Wendy's--you can see what they became in Appendix C.

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Last of all, I turn to my friends, contemporaries in one of the most breathtaking generations imaginable. Thanks to John Lennon for the music that is the rhythm of my life: rest in peace. Thanks to Willie and Eileen for the magic of your family; words can't recall the sweetness of the moments we have made. I have been fortunate to be in some special places at special times: UBC in the 60's, College House in '68, the CAI Lab in '69-'70, the Mason's in the early 70's, and Gentleware Corporation now. All special, all strong memories, too long to list now, but all part of my getting here. Chang-Yi, we will see Taipei together again some day. Hello Bob Brown, David Alvarez, and my primero amigo Arthur.

Finally, Mrs. Caruthers, am I old enough to read Elmer Gantry now?

ABSTRACT

A flexible classroom tool is designed to illustrate various aspects of complex systems and models of such systems. The tool consists of a model, a computer program for simulation using the model, and a classroom curriculum that describes games and exercises for use with the program. The subject matter of the model is the system of harvesting, converting, transporting, and consuming natural resources in a hypothetical society. Data structures and algorithms for implementing a computer simulation using the model are specified in a pseudo-Pascal format. The design steps and features of a curriculum for this tool are proposed, as well as steps for implementing and testing in a classroom environment.

The model design is guided by the foreknowledge of the final goals. These goals distinguish this study from more "traditional" computer-simulated model designs by stressing behavior illustration rather than behavior prediction. Both the specific model and the process of modelling are illustrated.

The desire for "flexibility" includes allowing the teacher to specify initial values, rules of interaction, which values may be interactively entered, and the scope of the system to be simulated, prior to the class activity. Flexibility also includes allowing students to choose interactively between various forms of output while

the simulation is running. Each change in specifying input variables or output functions effectively changes the model, so this design is really of a "class" of models rather than of a single model. The computer simulation implements the selection of one or more models from the class.

Particular design choices reflect the goal of an illustrative rather than a predictive simulation. A discrete -time and -event model is favored for allowing a gaming, interactive classroom format that is accessible to non-sophisticated users. A data structure is designed to allow components to be specified either by input or noninput state variables. Algorithms for selecting which way to specify components and for selecting output functions (i.e., for selecting the model to use from the class of models) are described.

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INTRODUCTION

This study concerns the design of a model that, when simulated on a computer, will serve as a tool for teaching the dynamics of complex systems. The subject matter of the model is the network of societal activities that harvest, convert, transport, consume, and renew natural resources. Such a network certainly qualifies as a complex system. The proposed tool is an interactive microcomputer-based simulation which may be used as a classroom demonstration or played as a variety of games. The games are either predefined as part of a supplied curriculum or designed and modified by the teacher or class.

Educational Objectives of the Proposed Classroom Tool

The eventual purpose of the simulation program is to provide controlled situations (games) in which to illustrate social processes, emphasizing the structural validity of the model. The purpose is not to perform social system "experiments" emphasizing the predictive and/or replicative validity of the model; Payne correctly questions the ability of social models to serve as tools for experimentation (Payne, 1982:275-285). Some specific educational objectives for using the program as a classroom tool may be stated.

First, the students should learn some facts about how societies manage natural resources. The complexity of this knowledge depends partly on the extent to which the base model is lumped for simulation, but some basic concepts such as the conservation of energy, the existence of renewable and non-renewable resources, entropy, and supply and demand are certainly on the agenda.

Second, the students should develop an appreciation for the holistic nature of the process of humans living in society and managing resources. That is, they should see the "system" involved and learn some facts about what systems are and how they operate. Meadows suggests a reasonable set of system features to illustrate: (1) the interrelationship of system elements, (2) the action of "limiting factors," (3) "boundaries" (where things go in a closed system), and (4) closed chains of causal relationships between elements, or "feedback loops." Associated with feedback are the phenomena of growth ("positive" feedback), equilibrium ("negative" feedback), oscillation (loops alternately positive and negative), and the meta-principle that "the system causes its own behavior" (Meadows, 1982).

Third, beyond the specific list of concepts to convey, some affective learning goals may reasonably be sought. Greenblat (1980) suggests that learning systematic, analytical approaches to solving problems is a

by-product of being a participant in a simulation. Consideration of Greenblat and Doerner (1980) suggests that "increased understanding of complex systems" as a general skill is also a suitable objective (see below). Included in this understanding is some familiarity with the advantages and limitations of using models to represent real systems.

Classroom Simulation and Games

The use of games and simulations for instruction is ancient. Military maneuvers and drills are perhaps the most consistent examples through history; the games of Go and Chess are abstractions of military strategy (Go was traditionally used to teach strategy to Chinese commanders). Games like the African stone game of Oh-Wa-Ree develop in their players the skills of memory, counting, and foresight that are useful in the marketplace. The use of engineering models for designing ships and monuments is also as old as civilization.

Becker notes that "the history of simulations has close connections with the history of the general systems approach that was conceived in the late thirties of our century," including the works of Tinbergen, Wiener, Hazen, Brown, and Forrester. Becker further notes that "the history of gaming is to a large extent the history of war games." But it was not until games at the Total War

Research Institute at the Naval War College of Japan were played for real at Pearl Harbor in 1941 that gaming became a large-scale activity in the military world. Business management followed the military lead, and everyone else has followed those two areas in using games for education and training (Becker, 1980).

Formal definitions of the terms "simulation," "game," and "model" as they are used in this study are given below. As classroom tools they typically mean scenarios in which students take on participatory roles and act for some time, gaining empathy for the characters they are portraying and understanding of the situation they are acting out. In recent years simulations that were enacted using scripts or commercially produced games (often board games) increasingly include a computer either as an element in the game or as the "referee," or both. This reflects the increasing accessibility of microcomputer technology to schools; it does not imply, however, that simulation is the major use of computers in education.

The current uses of computers in classrooms can be loosely classified as (1) management aids (bookkeeping, calculating), (2) instructional aids (drill and practice programs, tutorial programs, simulation programs used for demonstration), and (3) student learning tools (simulation programs with student participation, students programming). Management aids and instructional aids are now the

dominant uses of computers in education, with mixed results (see Dwyer, 1980). Programming is the fastest-growing use of computers in public schools (for examples of curricula, see Papert, 1980, and Moshell, 1982). The use of computer simulation is also growing (e.g., Hubin, 1980), but software of quality is time-consuming to produce (Braun, 1980, Frenzel, 1980, Hartman, 1982).

Mouat (1982) notes that "In simulation programs ... [students] see the direct consequences of their choices, and learn accordingly. 'It's a game-like format, but it requires the use of specific substantive knowledge and analysis,' says Dr. Patterson [Dr. Janise Patterson, program coordinator of the Wisconsin Center for Educational Research]." Greenblat (1980) asserts that students who participate in simulations make positive gains in terms of motivation, cognitive learning, changes in the character of later course work, and affective learning. There are also beneficial changes in the classroom structure and relations. These impacts are of special note in light of Doerner's (1980) observations regarding the difficulties people have in dealing with complexity.

Doerner notes three primary mistakes that people make when dealing with complexity: (1) insufficient consideration of processes in time, (2) difficulties in dealing with exponential developments, and (3) thinking in causal series instead of causal nets. These mistakes lead people

to a low assessment of their ability to act; continuous failure indicates to them a loss of control, causing fear. The consequences include a decreasing willingness to make decisions, increased delegating and scapegoating, reduced self-reflection and planning, and increased stereotyping.

In contrast, Greenblat states that participation in simulations help students to learn procedural sequences, gain in explicitness, learn a systematic analytical approach, learn better decision-making skills and "winning strategies." Their later course work contains more relevant inquiry and involvement in discussion. The students show increased empathy for others, self-awareness, insights, and personal efficacy and potency. While this does not mean that simulation as a classroom tool is a panacea for helping people deal with complexity, it clearly is an appropriate and possibly superior vehicle for giving students an understanding of complex systems.

Design Steps for Classroom Simulation Games

Klabbers (1980) proposes three formal stages of development of an interactive simulation/game. First, a "simulation model" is developed (conceptually, then formally). Second, the "simulation model" is embedded in an "interactive simulation." Third, the "interactive model" is embedded in a "game." This study enacts the first stage according to descriptions and methodologies by

Zeigler (1976). Algorithms for implementing the second stage are described, and designs are made for accomplishing both stages two and three. In addition, a fourth stage of "courseware development" is proposed. A curriculum is not written, but the design steps and features of a curriculum for this tool are proposed, as well as steps for implementing and testing in a classroom environment.

Greenblat and Gagnon (1979) suggest that a game designer takes on roles of both Sociologist and Advocate. Given that social models are notoriously controversial (see Payne, 1982, and Logsdon, 1980), and that the issue of resource allocation is especially so, care is needed to make the proposed classroom tool a neutral instrument for education. Thiagarajan and Stolovitch (1979) examine a more objective role in the design of "frame games," defined as "those games that are deliberately developed to provide a content-free instructional structure on which can be loaded locally relevant content." The model designed in this study is a variation of the frame game concept: where a single frame game may be used with different subject matters, this design creates the environment for a variety of games using the same content.

Step 1: Model Development

The model design is guided by the foreknowledge of the final goals, giving the design process both "top-down" and "bottom-up" characteristics. Interestingly, Swartout

and Balzer (1982) suggest that this is inevitable in design. The Conical Methodology describes the two processes as "definition" and "specification," respectively (Nance, 1981). It is assumed that (1) the audience is unsophisticated in the use of models, (2) the games will be interactive, so the simulation will be interactive, so the model will be nonautonomous, (3) the audience will learn as much about modelling and the use of models as they will learn about the particular subject of the games, and (4) the games will illustrate relationships within the modelled system rather than attempt to make hard predictions about a particular "real-world" system.

These goals distinguish this study from more "traditional" computer-simulated model designs, which are usually developed to accurately duplicate some "real" system and are used to conduct experiments (Payne, 1982). For example, Forrester's World Dynamics model (Meadows, et al., 1972) concerns the world social and economic system; its predictions have been discussed (despite qualifications made by research studies) as the basis for real policy decisions. Languages developed for simulation (for example, GPSS) are often batch-oriented, and are usually intended for sophisticated users interested in implementing such predictive models. In contrast, this study designs an interactive system for unsophisticated users, whose purpose is illustration rather than prediction. The

distinction is similar to Becker's separation of "conceptual" and "empirically based" models (Becker, 1980).

Zeigler (1976) defines the "real system" to be that part of the real world which is of interest, a source of "behavioral data" usually measurable by observation. A "model" is a set of instructions for generating pseudo-behavioral data. To follow the model instructions and generate data ("model behavior") is to perform a "simulation" of the model. Thus, simulation is an activity; "a simulation" is a performance. Simulating may be done by humans, but in this study it is assumed that the simulation will be performed by a computer program.

In Zeigler's scheme, there exists a hypothetical "base model" which consists of instructions capable of accounting for all the input-output behavior of the real system. The base model is usually considered too complex to be fully known, and is described only informally.

Zeigler's informal description format, used in this study, consists of (1) general descriptions of the "components," or parts from which the model is constructed, (2) a list of "descriptive variables" specifying each variable's value range, symbolic representation, and a general description of how the variable describes its associated model component (also included are "parameters" which describe constant model characteristics), (3) an informal description of the interactions between the

components, and (4) a diagram of the causal pathways of the model.

The base model is simplified into a "lumped model," so called because the simplifying process usually involves "lumping" many variables into one broader descriptive variable. It is this model which is simulated. The lumped model is specified both informally and formally as a sequential machine of the form

$$\langle \text{INPUTS, STATES, OUTPUTS, } \delta_h, \lambda \rangle$$

Readers unfamiliar with sequential machine notation are referred to Zeigler (1976:50-75).

Step 2: Simulation Development

Since a "computer program" is, like a model, a set of instructions, some confusion may exist about whether a program is a model or the simulation of a model. The operational distinction is made here between a model and a program which is the instrument for translating the rules of the model into activity by the computer. If a machine were custom-built to electronically enact the simulation of a model, its wire circuits would perform the same translating function as that attributed to a computer program.

A "simulation program," then, is a computer program written to cause a computer to follow the rules defined by a model. A "computer simulation" is the execution of a

simulation program--a single, repeatable event that produces behavioral data. An "interactive simulation" is a computer simulation of a nonautonomous model.

When formally specified as a sequential machine, the lumped model is quite close to directly specifying a computer program. This is especially true when, as indicated above, the foreknowledge of the classroom goals and computer environment play some part in the model design. The state variables, input variables, and output variables may directly correspond to program variables. The transition function and output function are seen as sets of algorithms awaiting program implementation.

The design of the simulation program thus involves two steps: (1) representing the variables and functions of the formal model description as variables, functions, and procedures in a specific programming language, and (2) designing any additional program elements (including variables and procedures) necessary to make the program generate behavioral data for the model. While the validity of the model is based on the correspondence between the model's behavior and the behavior of the real system, the validity of the simulation program depends on the degree to which the data generated by execution of the program corresponds to the "true" model behavior (presumably generated by error-free humans).

In this study the data structures designed to represent the state, input, and output variables are described, along with the algorithms used to manipulate them in performing the state transition and output functions, in Chapter 4. Program additions include the allowance of graphic, text, or audial output, and keyboard or "game paddle" input during program execution. The programming language proposed is Rascal(tm), an animation-oriented dialect of Pascal (see Moshell, Amann, and Hughes, 1982).

A specific programming addition has interesting implications for the model description. A "selection" phase of program execution is designed to allow the user(s) to specify the values of the state variables prior to simulation of the model. In this phase it is also possible to specify which of the state variables are input variables, as well as certain forms of output. Since each configuration of state and input variables, and output functions, constitutes a new formal model definition, the program simulates a class of models rather than one model.

Step 3: Game Development

A "game" is sometimes considered to be a set of rules, at other times an activity of "play." In this study, the terms "game" and "play" have parallel meanings with "model" and "simulation": a "game" is a particular set of rules to be followed by a player or players; "play" is the activity of people following, or pretending to

follow, the rules of a game. A "computer game" is a game played using a computer program either to enforce the rules or to participate as a player. A "simulation game" becomes, by this definition, a contradiction; in most literature it means a game that, when played, simulates some model of a real system.

The type of game(s) desired plays a role in the model design, particularly in choosing the six categories described above. Klabbers sees six steps in his last phase of game design: (1) specify the purpose of the game, (2) define player role(s), (3) define the game steps, (4) make role descriptions, (5) test and adjust the game, and (6) run the game. The "frame game" aspect of this study is realized not in the ability to interchange the content of the game, but in the ability to repeat the above process using the simulation program. Each selection of a state selects a model from a class of models, based on the definition of state and input variables, and output functions. Each input variable requires one or more players, thus defining one or more roles. A discussion of possible game scenarios and play characteristics appears in Chapter 4.

The important characteristics of the games are that they be interesting, that they involve as many (or as few) players as desired, that they be accurate in the situations presented to the participants, and that they clearly

illustrate their subject matter (if necessary, by exaggerating the results being illustrated and diminishing results not being illustrated). It is not the purpose of this study to devise specific classroom games (although certain types of games are suggested), but rather to define a model of a social system within which games may be defined. As discussed previously, there is a symbiotic relationship between the design of the model and the ultimate purpose of supporting simulation games.

The game steps depend on the time base of the model. A continuous time base is commonly used in "real-time" programmed games (often called "simulation-type games") such as are commonly found in video arcades. A continuous time base is also analogous to games without "turns" such as soccer. A discrete time base creates a more "turn-oriented" game; rather than having events queued up in order of the time at which they are to occur, time passes in regular steps, each of which presents a new game state to the players. If all inputs occur in a regular sequence at each time step, then play happens in "turns": consider baseball or chess. The game steps are also affected if the model is probabilistic or time varying. The use of a computer allows some blurring of the time distinction. A discrete time-based simulation program may execute so quickly as to give the illusion of continuous play, while

a continuous time-based program may pause at regular intervals to create the effect of turns.

Clever design can also have its effect: most "historical simulation" (usually "famous battle") games, such as those produced by Avalon-Hill, have developed effective techniques for representing complex continuous-activity situations in discrete time games. An important corollary is that these techniques allow for contemplation between moves; most "real-time" games, especially in commercial arcades, are designed for fast play and reaction (and more coins per hour). The ultimate purpose of the games in this study is instruction, which implies some thinking on the part of the players. While a good curriculum can make an arcade game a learning tool (see Blank, 1982), the amount of thinking that can go on during play is limited by the speed of the game.

The "historical simulation" games have also evolved methods for introducing complex playing rules to beginners through sample games, providing increasing levels of complexity, playing difficulty, and realism as player experience grows. That kind of diversity is very desirable in a teaching tool, and is made possible by the ability of the simulation program to respecify game environments easily. However, the ultimate responsibility for instruction rests not with the games played or the tools used, but with the teacher and students.

Step 4: Curriculum Design

The impact of a computer simulation in a classroom is more that of the simulation than that of the computer. This is not to say that computers do not enhance simulations, but that their role is to provide the environment in which the simulation takes place. The computer may make the simulation more attractive or accessible, but the educational value of the activity lies with the simulation, not its vehicle. That educational value increases or decreases with the ability of the teacher and students to see the import of the simulation and make it work.

It is possible to build a tool so powerful that it cannot be used. Most teachers will probably appreciate a tool that can motivate and inform their students as quickly and as simply as possible. Most teachers will probably not be overflowing with data about the economic base of Tanzania, ready to configure such a profile for their class; they will rather expect at least some games to arrive with rules and setup already prepared, with some explanation of how to proceed and how to enlighten their students about what they are seeing and doing.

This suggests that a curriculum is an important element in making the model and its simulation into a useful classroom tool. This should include background reading, instruction in how to set up and play various games, exercises that cause the class to translate the

games and demonstrations into useful knowledge, actual scenarios that can be immediately demonstrated or played, and some discussion of the various ways in which the tool may be used in the larger context of the course being taught. The necessity for, and current lack of, curricula as part of educational software is being increasingly vocalized by the educational community (see Watt, 1982, Braun, 1980, and Dwyer, 1980). The models may be made more complex, with a corresponding increase in the power of the simulation program. But without accompanying curriculum material the tool is as educational as an arcade game.

A discussion of evaluating the effectiveness of game designs for education appears in Chapter 4. Elements of a curriculum are proposed in Chapter 5.

CHAPTER I

LITERATURE REVIEW

Literature providing background for this study includes source materials on (1) energy and resource management, (2) theory and techniques of modelling and simulation, (3) the use of simulation and games in education, and (4) the use of computers in education.

Energy and Resource Management

Since the early 1970s, when "energy crisis" and "ecology" became household terms in the United States, writing about the environment has become a booming business. Studies have been notable for their advocacy and controversy.

Most studies note the particular advantage (and current popularity) of viewing the Earth's environmental processes from an energy dynamics perspective. A number of materials are "facts books," supplying a great deal of data about current fuel production and consumption, pollution, etc. The "energy industry" (commonly meaning fossil fuel and nuclear producers, electric utilities, and related industries) regularly provides brochures to the public (see Gulf, 1979). Fowler (1975) and Christensen (1981) are good collections of such data from many sources, both arranged for use as educational resources. Energy and

Power (1971) is still a surprisingly current description of how energy is used in societies. National Geographic (1981) produced a more recent, and more general, view of the world energy picture. Sheahan (1976) and Goldin (1980, 1981) describe the developments in energy technologies. The National Science Teachers Association (NSTA) is a good continuing source of classroom materials dealing with energy and environmental issues.

Studies of the principles behind energy and environmental systems are somewhat rarer than books of statistics or policy recommendations. Environmental studies draw from many fundamental sciences, notable physics, biology, and chemistry, and from social sciences such as economics and sociology. An excellent and enjoyable physics background is Angrist and Hepler (1967). Evans (1980) provides formulas and algorithms for demonstrating and experimenting with the basic mathematics of environmental dynamics. Klopfer (1962) examined psychological phenomena in ecological systems (not to be confused with "human ecology," a sociological theory of some controversy). Adams (1975) discusses the role of energy processing as a foundation of social power structures. Scientific American (1982) devoted a special issue to an analysis of the mechanization of work. But the primary "foundation" source for this study is Odum (1971, 1972, 1976, 1981), who has developed a notation for describing energy flow networks and has

made extensive analyses of social and ecological systems as energy processors.

Some studies were commissioned for the purpose of proposing national policy (SRI, 1975, DOE, 1980, Barney, 1980). Other researchers are private advocates. Lovins (1975, 1977, 1981) has developed a concept of "soft," or decentralized, energy sources for society. Landsberg and Dukert (1981) discuss ways to make the changes in energy policies socially equitable. World Energy Production and Productivity (1981) is both a collection of factual reports and the transcript of an international discussion of future world energy policies. Gray, Gray, and Martin (1975) concentrate on communicating to their readers that personal environmental and energy choices can be nationally effective. This message defines a whole genre of ecological literature. As a counterpoint, Tucker (1982) says that the oil crisis is effectively over for the United States, Critchfield (1982) points to increased technology as the key to improving agriculture, and Simon (1982) argues against population control. No opinion seems to be without a spokesperson.

Meadows (1982) effectively surveys the world models that have been built and the reports produced from studies using these large computer-simulated models. The most widely reported model has been Forrester's, most notably by Meadows herself, et al., in The Limits To Growth

(1972). That study forecast great deficiencies in natural resources based on computer simulation results, and proposed specific world policy actions. Understandably, the report generated a great deal of controversy (see Logsdon, 1980). The study was sponsored by the Club of Rome, which later sponsored another report, Mankind at the Turning Point (1976). Both studies foresee disaster unless current world policies for managing resources are changed in specific and rather drastic ways. Logsdon refers to another Club of Rome study by Tingeren that proposed direct money transfers from developed to undeveloped nations. All Club of Rome reports were severely criticized for deficiencies in their models and for the degree of faith placed in the simulation results (see McLeod, 1976, and Logsdon, 1980).

O'Toole (1976) reports on the Delphi Study forecast of economic and social impacts of energy and resource limitations. The Harvard Business School report, Energy Future (1979), emphasizes conservation as a key part of U.S. national energy policy. The best part of that study is its discussion of the uses and limits of models. Payne (1982) persuasively argues that social models should not be used for policy-making, since they are untestable and therefore not experimentally sound. He does not think them useless, however, but misused.

The primary sources for model structure employed by

the present study are The Limits to Growth (1972) for its overall perspective, DOE (1980) for its categories of activity (the LEAP model), Luten (1971) and SRI (1975) for their stages of resource processing, and Odum (1971 and 1981) for symbology, design, a common measurement for material and energy flows through the system, and the inclusion of money flows in the model (see Chapter 3).

Theory and Techniques of Modelling and Simulation

Nance (1981) notes that "Zeigler's work has progressed the farthest toward a descriptive theory of simulation modeling." Zeigler (1976) is the principal source of modelling theory used in the present study. Payne (1982) is another good source, but omits discrete time models from his discussion. Simulation (1979) is a nice collection of articles on simulation techniques. Methods for simulating population dynamics are described in Krueckeberg and Silvers (1974); algorithms for population and physical systems simulation are provided by Evans (1980). Jensen and Barnes (1980) provide a good corollary background for working with network flow analysis.

The Use of Simulation and Games in Education

While formal game theory is not a major part of this study, some sources are noted. Owen (1968) is one of many basic textbooks introducing game theory. Becker (1980)

gives a good brief history of the development of game theory, systems theory, and simulation techniques. Blatner (1982) provides an in-depth look at the psychological and social roles of play.

The primary source of materials on the uses of simulation and games in education is the journal Simulation and Games (1979, 1980). This is a continuing forum for a field that is still developing basic theories, programs, and outlook.

The number of simulations about ecology and energy that currently exist is unknown. The number is growing, often using computers (discussed below), but often their distribution is localized to certain areas or groups of users. It is safe to say that no game whose subject is environmental management is as nationally popular as is Monopoly, or even as are most obscure card games or war simulations. Typical non-electronic games are described by Warns (1981) and Carey (1981). Simulation and Games regularly reviews new games. Play is usually on a Monopoly-like board, or is executed throughout the classroom with students taking roles and using various worksheets, cards, and other props. The scope of play varies from single activities (e.g., a power company) to world strategies. The games described by Carey have particularly good reference materials to accompany the games. The NSTA's Project for an Energy-Enriched Curriculum (PEEC)

should be a large source of classroom materials, but recent cutbacks by the Department of Energy have made further distribution of PEEC materials uncertain.

The Use of Computers in Education

The introduction of computers into public education, and society itself, is a recent and explosively growing phenomenon. Mouat's article (1982) is typical of daily media reports on how computers, particularly microcomputers, are impacting our lives. Dwyer (1980) and Frenzel (1980) discuss the impacts and future of Computer Assisted Instruction (CAI). Blank (1982) has managed to use an arcade game (Pac-Man) for instruction. Papert (1980) and Moshell, et al. (1982) have created environments in which students gain control over computers rather than just being taught by them. The Computing Teacher is one of the best of many new publications concerning the use of computers in education, and is a good source for theoretical discussions (e.g., Moshell, 1982, and Hartman, 1982) and previews of forthcoming developments.

In the particular area of electronic simulation, Evans (1980) and Hall (1981) describe programs for simulating such environmentally related systems as population growth, glacier movement, and power plant operation. Hubin (1980) describes physics experiments that are simulated in classrooms. Typically, these programs are used

for performing experiments in class. Students do not take roles, but provide starting data and may often stop the program execution, make adjustments, and then continue the program. (This is noteworthy in that role playing may be important in generating the effects listed by Greenblat, (1980) discussed in Chapter 1). Program displays are either tables of numbers or line plots, even when graphic TV screens are available. The scope of the programs is usually focused on a single activity rather than on large societal behaviors.

Two notable exceptions to the type of tools described are the "Energy-Environment Simulator" (Tenntronic, 1981) and Energy Czar (Atari, 1980). The "Energy-Environment Simulator" is a non-programmable electronic machine with four remotely connected "lap panels." It simulates energy flows through a whole society, with players using dials on the lap panels to provide continuously changing inputs. While its outputs are primarily numeric, a ticking clock, flashing warning lights, and a "disaster buzzer" combine with the role-activity required of the players to create play more typical of the non-electronic role-playing games (or of video arcade games) than of the other computer simulations.

Energy Czar also has a societal scope and requires regular input from the player(s). Its displays utilize color and show results both as numbers and bar graphs. It

also has the interesting feature of allowing "bias" toward nuclear, fossil fuel, or solar sources of energy. Where the "Energy-Environment Simulator" is a "reactive" game, Energy Czar requires strategy at each time step, and allows time to make decisions. Both are interesting as games; this crucial characteristic is needed when simple fascination with the medium is dulled by familiarity.

CHAPTER II

THE MODEL

The real system is measured using a set of "descriptive variables." Those which can be observed fall into two categories: "input variables" (causes, influencing the system from outside) and "output variables" (effects, reacting to input values). There are also variables which may not be observable, but which are essential to represent the "state" of the system. The set of all input-output pairs that may be obtained experimentally is called the "input-output behavior" of the system (definitions are from Zeigler, 1976).

The model may be described in terms of six attributes (Zeigler, 1976). First, time flows integrally, so the model is a "discrete time" model. Second, the descriptive variables can be represented by real numbers and discrete values, so the model is a "mixed state" model.

Third, no random variables appear, so the model is a "deterministic" model. Fourth, the real system is assumed to be influenced by its environment, so the model is a "nonautonomous" model with input variables not controlled by the model.

Fifth, the model's rules of interaction are stated in terms of descriptive variable values only, so the model is

a "time invariant" model. Finally, the model has more than one state, and so it has "memory."

Because the sets of input and output variables may be specified and respecified, the "model" is actually a set of models for a set of real systems.

The Real System: Behavior

Principal sources for descriptions of the real system are Odum (1971 and 1981), Fowler (1975), and Christensen (1981).

The input-output behavior of the real system concerns the human activities of (1) harvest of resources, (2) raw material processing (converting harvested resources into processed materials and manufactured goods), (3) consumption of foods and goods, and (4) the economic exchanges involved in (1)-(3) (including transportation). Processed materials include fuels; manufactured goods include tools which consume fuels and which, along with human labor, are required in all activities. A special form of processing is the construction of structures needed for each activity.

Resources may be classified as renewable or nonrenewable. Renewable resources are both "constant source," such as solar- or gravity- driven processes, or "recycled" resources renewed by natural (usually biological) processes. Technically, even mineral ores and fossil fuels

are being "renewed" by geologic processes, but their renewal rates are so slow that they are considered nonrenewable.

The Experimental Frame: Validity

The "experimental frame" describes the limited circumstances under which the real system is to be observed, a subset of the input-output behavior of the real system. A model is "valid" to the extent that the model's input-output behavior "agrees" with the input-output behavior of the experimental frame. Agreement depends on the nature of the comparison made between the behaviors.

The model is "replicatively" valid if its behavior matches behavioral data already acquired from the real system. The model is "predictively" valid if its behavior matches behavioral data from the real system before the real system data are acquired. The model is "structurally" valid if its behavior matches the real system behavior and the model truly reflects the way in which the real system operates (definitions are from Zeigler, 1976).

The "world" is described in three areas: Land, Water, and Air (see Appendix A). A generalized "society" is pictured by dividing human activities into "sectors" with areal dimensions: Farming and Ranching, Mining and Quarrying, Logging, Processing, Manufacture, Construction, Commerce, Residence, and Government take place primarily

on Land. Fishing takes place primarily on/in Water. Electricity Harvest and Transport take place in all three areas of Land, Water, and Air.

There is also a "foreign society" that provides the subject society with imported items and to which the society may export items. This "foreign society" is actually a composite of all other societies.

Whether or not the subject society is "industrial," "agricultural," or "developing" is assumed to be determined by the amounts of activities and resources in each sector; the general arrangement of all societies' sectors is assumed to be consistent no matter which subset is being examined.

A "whole world" frame may be constructed by simply removing all imports and exports (i.e., eliminating the foreign society). A "two nation" frame is constructed by expanding the foreign society to contain duplicates of all the sectors of the first society, with the two still linked through import and export.

To measure the validity of the model in this framework, a specific real system must first be identified and its input-output behavior measured. Behavioral data that the model must account for are measures of the resources, activity in each sector (including materials processed, labor, fuel and equipment consumption, monetary assets, and waste materials produced), and population dynamics.

Imports and exports are also behavioral data if the system chosen is not the whole planet.

The replicative validity of the model is the correspondence of model behavioral data (generated by simulation) to already observed behavioral data of the chosen real system. For most nations these data are routinely collected, either internally or by international economic or political organizations. Testing the replicative validity of the model is thus a straightforward process.

The predictive validity of the model is the correspondence of model behavioral data to behavioral data of the real system that has yet to be observed. Testing the predictive validity of the model requires some waiting. An approximation of predictive validity may be made from its replicative validity. If, given some past starting point, the model generates behavioral data that closely corresponds to current system behavior, then there is some indication that the model may generate corresponding behavioral data in the future. Social system behavior is notoriously unpredictable, however, and replicative correspondence is only an indication of predictive correspondence.

The structural validity of the model is the correspondence of the component interactions (instant functions and state transition functions) to the component interactions of the real system. The component interactions of

the real system are primarily measures of the level of activity (labor productivity, fuel consumption, waste production, etc.) and the relationships of components (which values are limiting in various functions, which sectors provide inputs to other sectors, etc.). The structure of a social system is quite difficult to describe in a generally acceptable way.

Measuring "correspondence" between behaviors may be somewhat arbitrary when dealing with social systems. Which is more "valid," a model with one datum equal to the real system datum but another datum disagreeing by a factor of 10, or a model with two data disagreeing with their corresponding real system data by a factor of 2?

The ultimate purpose of the model allows some license in measuring validity. Replicative validity is important if students are to take the model seriously as a teaching tool. Predictive validity is not as necessary; indeed an important instructive lesson can be made by asking students to think very cautiously about making predictions based on the behavior of a model. Structural validity is perhaps most important if the model is intended to illustrate the behavior of a real system. However, all forms of validity in an illustrative model are best "turned on their heads" and posed as questions rather than measures. The question of how to measure correspondence will probably generate more thought than any preferred

answer will. The structure of the modelled society may be beneficially questioned in the classroom, and students challenged to discuss both what they think is "correct" or "incorrect," and how they would construct a different model.

The model is the basis for both demonstration and participatory simulations. It presents a structure of relationships so that it can ask questions about the validity of the structure. The major requirement for the structure is not structural validity but clarity for illustration. Admitting an intuitively based structure allows parallels to be drawn with other models (for example, Forrester's model--see Payne, 1982:276-279, and Logsdon, 1980: 335-346), and the role of intuition in model construction (Payne, 1982:279-283, Zeigler, 1976).

The Base Model: Hypothetical Complete Explanation

The base model is a hypothetical entity; if completely specified, it would explain all of the input-output behavior of the experimental frame of the real system. It is described here in some detail, which is nonetheless incomplete.

The base model first divides the input-output behavior of the real system into two parts: (1) general system parameters, and (2) sectors of human activity. General system parameters are "global" components: Resources

(renewable, nonrenewable, and areal measures), Waste Materials, and Function Parameters. These are composite measures of many variables; a detailed list of general system parameters is given in Appendix B.

The base model considers ten general sectors of human activity which are further subdivided into a total of 38 activities (see Appendix A). The list of sectors is drawn from many sources, principally Cook (1971), Starr (1971), Christensen (1981), the DOE (1980), and Nwosu (1981). The selection is also influenced by the Standard Industrial Criteria (SIC) Codes and U. S. Census categories (Class Notes, 1973).

The role of humans in the ecosystem is seen as one of producing temporary storages of high-quality energy (Odum, 1981). The major sectors of activity in this regard are the Harvest and Conversion of resources. Harvest is the capture of raw materials from the resources. Conversion is the change of raw materials into another (usually higher-quality energy) form. Another form of Harvest converts resources directly into electricity, considered here a converted (or "processed") material. Conversion may be generally divided into two stages: Conversion of raw materials into processed materials (or "Processing") and Manufacture of processed materials into manufactured goods. The steps of resource processing are distilled

from Luten (1971), Adams (1975), SRI (1975), DOE (1980), and Hafele (1981).

Residence is the sector of human living (population dynamics are measured within this sector) and of human consumption. The Government and Military sector is a somewhat "catch-all" sector of public organization and services. While the government owns and directs many of the other activities in many real systems, the base model assumes that Government, strictly delineated, produces no tangible materials, only services. Residence "produces" only waste materials, but supplies Labor for all other sectors. Both sectors, like most others, consume fuel and require equipment and structures.

All materials must be transported between sectors, and a composite of all Transportation activities is represented by two structures (from other sectors to Commerce, from Commerce to other sectors). A Transportation "site" is a unit, like a company; trucks, trains, planes, ships, pipelines, and power lines are "equipment."

Commerce is a somewhat more abstract sector, being mostly a storage area for exchanging materials between other sectors. All material transfers are assumed to move from their source sector to the Transportation sector to the Commerce sector to the Transportation sector to the destination sector.

A specialized form of Conversion is Construction, in

which processed materials become structures. Construction is a composite of activities that is assumed to take place in each sector.

Foreign Country is a sector designed to represent the interface between the modelled society and all other societies.

Harvest, Conversion, Manufacture, and Construction sectors are each considered to have eleven descriptive variables. Sites provides an areal measure of the activity. Input, Output, and Waste materials are materials flowing in and out of the sector. Materials flow is measured in energy equivalents (see Odum, 1981, and Fowler, 1975, for conversion factors). The other type of flow modelled is that of money, measured in dollars. Money is assumed to flow in the reverse direction of materials (Odum, 1971, 1972, 1976, 1981); so Income and Payments are the inflow and outflow, respectively, of money while Assets is the amount of money stored in the sector. Labor, Equipment, Fuel, and Structures are required to make each sector operate. Labor is drawn from the human population; equipment is drawn from Manufactured Goods, Fuel from Processed Materials. Structures are produced by the Construction sector.

Each sector also has internal parameters (such as "area per site" and "labor productivity") used to aid the

computation of component interactions and state transition functions.

Commerce and Transport, rather than having Input or Output, have storages of Raw Materials, Processed Materials, and Manufactured Goods. Otherwise the descriptive variables for Commerce and Transport correspond to the variables for other sectors.

Residence has no Input, Output, or Labor, but instead has descriptive variables for Population and the associated Workforce. Otherwise the descriptive variables for Residence correspond to the variables for other sectors.

Foreign Country has only nine descriptive variables: Raw Materials (import, export), Processed Materials (import, export), Manufactured Goods (import, export), Assets, Income, and Payments. This reflects the model's view that the exchange of goods and money are the relevant features of the interface between the subject society and all other societies. Foreign Country has internal parameters (exchange rates of goods and money--prices and costs) and descriptive and transition functions.

A partial expansion of resources by location (Land, Water, and Air) is given in Appendix A. Major sources for the resources list are Hubbert (1971), Dyson (1971), SRI (1975), and Evans (1980). An incomplete expansion of the human activity sector components, listing descriptive variables, is also given in Appendix A. Both lists, while

incomplete, indicate the probable limit to the amount of detail that can be manageably simulated. The number of interactions between the components listed in the Appendices is staggering. The obvious strategy for building as complete a model as possible is to severely lump the given base model, then add detail a component at a time.

The Lumped Model: Simplification

The lumped model is a simplification of the base model. Appendix B contains an informal description of the sectors remaining in the lumped model. Comparing appendices A and B shows how the number of components is reduced by the lumping process.

1. Informal Description

a. Components. The general system parameters are reduced to (1) total Resources (renewable, nonrenewable, and areal totals), (2) total Waste Materials, and (3) Function Parameters. There are ten sectors of human activity, most corresponding to the general sectors of the base model. They are not subdivided in the lumped model, except that there are now three forms of Harvest: Renewable Resources Harvest, Nonrenewable Resources Harvest, and Electricity Harvest. There is no Government sector. Transport is a single sector, with transported materials

grouped according to route (from sectors to Commerce, from Commerce to sectors, Imports, Exports).

b. Descriptive variables and parameters. The descriptive variables for each sector are the same as for the base model, with the exception of the Transport sector. Transport has four occurrences each of variables measuring Manufactured Goods, Processed Materials, and Raw Materials, depending on the route the materials are taking (see Appendix B).

c. Component interaction. The flow of materials is assumed to be Output-driven. That is, the Output of each sector is a direct function of the area in use. The area in use is determined by the number of sites (each with an associated number of structures). Structures and Equipment deteriorate according to their "lifetime" and must be replaced. The Output produced requires Input materials, Labor, and Equipment; the Equipment requires Fuel.

The Input, Fuel, and Equipment requirements are met with purchase and transport from the Commerce sector. The Labor requirement is met with hiring from the Residential sector. The Structures requirement is met with purchase from the Construction sector. Transport is commercial, so this sector is not involved in moving Labor or Structures (which are built on-site). Residential transportation is

included in "Residential Equipment" and is seen as consumption, not transport. All Output is sold and transported to the Commerce sector. Commerce pays Transport for its service.

Payment for materials is drawn from the Assets of the purchasing sector and adds to the Assets of the selling sector. Payments for Labor adds to the Assets of the Residential sector.

Resources are depleted by the Harvest sector. Waste materials are produced by all sectors. Renewable resources are increased by annual energy income (solar, etc.), natural cycling, and renewal processes. All materials decrease by their entropy factor, producing heat which escapes the system.

The Outputs at time t are computed, and the material and monetary transfers required by the Output production. The depletions and additions to all storages are then computed for time $t+1$. If any storage falls below zero, a warning is displayed and the step is not taken. Rather, the instant functions at time t are recomputed using new input variable values.

d. Diagrams. Diagrams representing the sectors and the flows of materials and money between them are given in Appendix C.

2. Formal Description

The model is represented by the sequential machine

$$\langle \text{INPUTS}, \text{STATES}, \text{OUTPUTS}, \delta_h, \lambda \rangle$$

where

$$\text{INPUTS} \subseteq X \quad (\text{RANGE } \alpha) \\ \alpha \in \text{inputvariables}$$

$$\text{STATES} \subseteq X \quad (\text{RANGE } \beta) \\ \beta \in \text{statevariables}$$

$$\text{OUTPUTS} \subseteq X \quad (\text{RANGE } \gamma) \\ \gamma \in \text{outputvariables}$$

Transition Function :

$$\delta_h : \text{STATES} \times \text{INPUTS} \rightarrow \text{STATES}$$

Output Function :

$$\lambda : \text{STATES} \times \text{INPUTS} \rightarrow \text{OUTPUTS}$$

$$X(\text{RANGEa}) = (\text{RANGEa})_1 X(\text{RANGEa})_2 X \dots X(\text{RANGEa})_i \dots$$

$$\text{inputvariables} \subseteq \text{descriptivevariables}$$

$$\text{statevariables} \subseteq \text{descriptivevariables}$$

$$\text{outputvariables} \subseteq \text{descriptivevariables}$$

A complete formal description of the lumped model with transition and output functions is given in Appendix D.

CHAPTER III

DATA STRUCTURES AND ALGORITHMS

Certain data structures, and corresponding algorithms for manipulating the data, are developed to implement the model as a computer simulation. The data structures are not necessarily language- or machine- specific, but are represented using the Pascal programming language as a convenient and clear notation.

The Energy Network: Designing the Simulation

Both integral and real variables are used, so the model is a "mixed state" model. State changes are discrete, allowing the state transition algorithm discussed below.

A discrete time base is chosen over a continuous time base. Discrete time steps are familiar to the unsophisticated user through games with clear turns of play, such as chess or baseball. It may be argued that the probable familiarity of students with the "continuous play" format of arcade games or soccer makes a continuous time base more familiar. However, a discrete-time computer simulation without pauses between time steps can give the appearance of continuously running time. With pauses, a full sense of "game turns" can be created. The decisive advantage of discrete time is that it more easily allows a

computer program to choose between "continuous" and "single step" play modes. A simple switch indicates that a pause is or is not to occur after each time step; with a continuous time base, some clocking procedure is required to be sure that a pause is in the proper place in the queue of impending simulation events.

State Description and Transition

The state variables describe the components of the model. State variables may be simple (that is, internal), input variables (with values assigned at each time step by the players), or output variables (with values displayed to show the "state of the game"). Obviously, some simple or input state variables may also be output; other output variables are given values by some operation on other state variables.

The "state of the game" at any time step is defined as the set of all simple and input variable values. Those output variables that are also simple or input are included. Other output variables are calculated by functions at each time step.

1. Data Structures

The state of the game is represented by a "state node" (in Pascal called a "record type"), which is a composite of other data structures (see Appendix E).

Society is subdivided into "sectors" of activity. A

"sectorrecord" node is a collection of descriptive variables for a sector (farming, fishing, commerce, etc.).

A "quanta" node contains the values of variables which are summative and/or descriptive, including total resources (renewable and nonrenewable), waste materials, and general system parameters (human population, etc.).

A "staterecord" node consists of an array of sector-record nodes (one for each sector), a quanta node, and additional variables relating primarily to the simulation (time, for example).

A "statepointer" is a pointer to a staterecord node.

The simulation defines four variables as statepointers: nowstate, newstate, startstate, and zerostate. As the names imply, startstate is the state of the model at time $t=0$, nowstate is the state of the model at time t , nextstate is the state of the model at time $t+1$. Zerostate is a state with all variables set to zero for quick "clearing" of states.

2. Algorithms

There are many types of activity sometimes called "initialization" (see Appendix F). One is the preparation of the program for execution at the very start of a simulation session, called here "bootup." A second is the assignment of values for a particular model configuration: which variables are input, etc. This type of initialization is called here "setup." A setup of nowstate is

called "adjustment"; a setup of startstate is called "reset." Setting nowstate equal to startstate is called "restart."

State transition (see Appendix F) is accomplished by applying the state transition functions to the appropriate variables in the nowstate node, with resulting values being stored in the newstate node. Once the state for the impending time step has been thus defined, transition is accomplished by exchanging the nowstate and newstate pointers.

Model Selection

When a set of state variables are selected to be input variables, or a particular output function is chosen, a specific model is selected from the class of models defined.

Input Variable Selection

1. Data Structures

A "padlrec" node (see Appendix E) consists of an offset, a maxvalue, and a title. It "points" a given input device to its associated input variable in this way: the integer offset is the displacement in bytes from the start of the staterecord node to the input variable; the maxvalue is the largest real value the input variable may assume (zero is the smallest), and the title records a

character string associated with the variable.

A "valptr" node is an address which may be considered either as an integer or as a statepointer.

The simulation defines a padltabl array consisting of a padlrec node for each potential input device.

2. Algorithms

Certain "primitive" routines are required to "point" a given input device to a given input state variable (see Appendix F).

Function SEEKPADL allows the user to identify the paddle desired as an input device by pushing its button. Procedure POINTPADL calculates the offset from the start of the staterecord node of the desired input variable.

A series of "menu" routines (in the setup procedure, Appendix F) allow staterecord variables to be given values or marked to be input variables. When a variable is to become an input variable, the routine finds the offset and input device using the above primitives, then assigns the offset, maxvalue, and variable title to the padlrec node in the padltabl array corresponding to the selected input device (Appendix F).

The input variable algorithm then consists of (1) reading the value of each input device, (2) scaling the value to the value range specified by maxvalue, and (3) placing the scaled value into the variable, based on its offset (Appendix F).

Output Function Selection

Output functions are of two types: (1) calculation of operations on state variables (a subset of the "instant" functions), and (2) display of output results. "Function selection" consists of choosing between graphics and text output displays; each format implies corresponding state variable operations.

At each time step, a specified portion of the state of the model is displayed. In text format, the values of the output variables and function results are displayed in tabular form. In graphics format, a "game board" is assumed, in the form of a regular grid. Each output value is represented in one or more grid squares as either a dynamically moving bar graph, as a warehouse full of regularly stacked "bricks," as a "scatterplot" (an increasingly or decreasingly dense plot of random points within a square), or as a plotted line graph.

A pause (or not) after each time step is also considered to be an output function.

1. Data Structures

A "node" node may take six forms, specified by "item" (see Appendix E). A "tank" or "boardnode" node consists of a background color, a foreground color, and a maxvalue. The colors are any permissible colors for an assumed graphics output device; the maxvalue is the largest real

value that the represented variable may assume (zero is the smallest). A "warehouse" node contains a count of the number of "bricks" displayed and the position at which the next brick will appear. A "locusts" node contains a count of the number of points plotted; each associated "scatter-node" node contains the position at which a point has been displayed in a scatterplot. A "linegraph" node contains the x-position of the next point to plot in a line graph. All forms of node have a "next" value, which is a "nodelink," or pointer to a "node" node.

The "board" array consists of maxcols columns and maxrows rows of nodelink pointers. The number of grid squares actually used depends on the output scale chosen.

At bootup, all board items are boardnode nodes. Each boardnode contains the background color to fill the grid square, the foreground color to graph the variable value, and the maximum variable value. If a variable is to be represented in a certain grid square as a dynamic bar graph, the board node is changed to a tank node. If the variable is to be represented as a warehouse, a warehouse node is pointed to by the board node. If the variable is to be represented as a scatterplot, the board node points to a locusts node, which points to a list of scatternode nodes. If the variable is to be represented as a line graph, the board node points to a linegraph node.

This arrangement minimizes the space that the board array occupies in memory. Only those nodes associated with model variables use additional information nodes.

2. Algorithms

a. Screen graphics primitives. Screen graphics primitives set the scale to be used and initialize board nodes according to what representation will be used in the corresponding grid square (see Appendix F).

Changing the board scale (PROCEDURE scaleboard) affects the size of the displayed squares and the number of squares displayed. A scale increase of one doubles the dimensions of the squares and halves the number of rows and columns displayed.

Each board node that will represent a variable must be initialized (PROCEDURE initsquare) so that the proper configuration of nodes is present. The maximum value that the square can represent is set, and initial management values are assigned.

b. Screen text routines. Text mode display consists of simply writing the numeric values of selected variables, with identifying titles, on the display screen. At each time step the variables are redisplayed at the same screen locations, creating an "odometer" effect rather than a "scrolling" screen.

c. Screen graphics routines. Screen graphics routines manipulate board nodes to display bar graphs, warehouses, scatterplots, or line graphs (see Appendix F). In all cases, the current value of the represented variable is represented as a percentage of the maximum value that the square can represent.

A dynamic bar graph is managed with a tank node (PROCEDURE pour). The square is divided into an upper and a lower portion. The size of the lower portion reflects the current value of the variable. The lower portion is filled with the foreground color, the upper portion with the background color.

A warehouse is managed with a warehouse node (PROCEDURE stackbricks). The square is filled with the background color, and bricks displayed with the foreground color. Bricks are neatly stacked, row by row from left to right, from the bottom to the top of the square. The number of bricks displayed reflects the current value of the variable. Bricks are added or removed depending on whether the current variable value is greater than or less than the previously displayed value. A pointer always records the position of the next brick to be displayed.

A scatterplot is managed with a locusts node and a list of scatternode nodes (PROCEDURE swarm). The square is filled with the background color, and points displayed with the foreground color. The number of points displayed

reflects the current value of the variable. Points are added or removed depending on whether the current value is greater than or less than the previously displayed value. Since the location of each point is randomly chosen, the list is maintained to insure that the points can be found for removal. There is no test for duplicate point positions in the interest of saving time; this means the square rarely is completely filled with the foreground color, even when the variable value equals the square maximum.

A line plot is managed with a linegraph node (PROCEDURE lineplot). The square is filled with the background color, and points displayed with the foreground color. The height of the point within the square reflects the current value of the variable. Each new point is displayed to the right of the previous point. A pointer always records the x-position of the next point to be displayed.

d. Output selection routines. Output selection simply sets two global boolean variables, pixmode and singlestep. If pixmode is TRUE, output is displayed graphically, else output is displayed textually. If singlestep is TRUE, a pause occurs after each time step, else no pause occurs.

Simulation Steps

The algorithm for the complete simulation loop is shown in Appendix F. The "main loop" of the program consists of five steps.

First, the program checks for a stopping condition (user interrupt or completion of sufficient time steps). If the loop stops, one of four things may happen: (1) the user may quit the program; (2) the user may do an "adjustment" by calling SETUP with NOWSTATE, then continue the program; (3) the user may do a "reset" by setting NOWSTATE to STARTSTATE, then continue the program; (4) the user may do a "restart" by calling SETUP with STARTSTATE, then doing a "reset."

If the loop does not stop, the program updates the values of the input variables in NOWSTATE by calling INPTFN to read the input devices (on the Apple these are game paddles).

Third, the program calls INSTANTFN to calculate those values which are "instant functions" of state variables.

Fourth, the program calls OUTPTFN to show the current state of the game in the mode specified in SETUP (graphics or text display).

Fifth, the program calls TRANSFN to apply transition functions to current values of NOWSTATE, calculating new

values for NEXTSTATE. "State transition" is then accomplished by simply exchanging the pointers NEXTSTATE and NOWSTATE.

If singlestep execution has been specified, the program then pauses until a keyboard key is pressed, otherwise the loop is repeated.

CHAPTER IV

GAME DESIGN

Every permutation of input-simple variables is a different model, but the number of games has, theoretically, no limit. The same model may be simulated with different goals, time limits, or with different characterizations of the roles for each player providing input. Play with a "single step" model (with pauses after each time step) will have a different character than play with a "continuous" model. A model with graphic output functions may require a different strategy of play than a model with report-like text output functions. Whether or not the same scenario may be replayed to refine strategies can drastically change the nature of a game.

All of this variation is, of course, intentional. The model design intends that the simulation program be a very flexible tool; it supports both games presented in the courseware and games which can be invented in the classroom. Some suggestions for game characteristics are presented here. This is not intended to be either exhaustive or preferential, but merely to develop the flavor and spirit of the types of games that can be designed using the models.

Setup Phase

The setup phase defines not only the initial conditions of the game, but the game itself. Setup for classroom use will most likely be a task for the teacher. Predefined configurations may be used.

Some examples of the factors involved: specifying zero values for all activities relating to mining, processing, and manufacture sectors effectively describes an agricultural society. Specifying a large population with low industrial activity values and high imports creates a situation faced by "Third World" societies, while low birth rates and high industrial activity values looks more from the perspective of "Developed" societies. An industrial society with high transport from large resource values faces different tasks than an industrial society with low resource values and high imports.

Two tasks are involved: assigning the values to amount and rate variables in the initial state, and constructing a verbal picture of what the configuration "means" in terms of what kind of social system the game will be working with.

Goal Definition

Once the setup is described, Klabbers first step asks, "What's the purpose of the game?" This is largely

not a function of the simulation program, but rather of the classroom.

One goal likely to be present in every game is the survival of the configured society. Survival may mean different things in different contexts: a stable versus a growing population, for instance. Attaining a certain "standard of living," measured in either resources or money per capita, might be contrasted with the other measures of "the good life," like houses per capita or energy per capita.

Other goals might be more concerned with the structure of the system in general. The players may try to "shape" the society so that labor is divided evenly among sectors, or so that more labor is used in commerce than in manufacturing. They might want to make exports exceed imports. More generally, play could concentrate on finding and manipulating positive and negative feedback loops than on the particular content of the game scenario.

Goals may be competitive or noncompetitive between players, depending on the role assignments.

Role Assignment

For the simulation, role assignment is simply a matter of declaring a state variable to be an input

variable. The "meaning" given to the role in the classroom is part of the definition of the particular game to be played.

Each of the above configurations may be "played" with different roles defined. If rates of mining, production, manufacture, transport, and commerce are each input variables, the players providing those inputs may be told they make up the "industrial sector" of the society. They might cooperate with the "agricultural sector" toward keeping the society alive, yet compete with them for monetary assets. Both groups might compete with players inputting values for import and export (i.e., a "foreign country").

Play Mode

Games may be loosely divided into "reactive" and "strategic" in design. "Strategic" games have time for players to contemplate their next action before they are actually required to do so. "Reactive" games allow no such time, causing play to be quicker and any player strategies to be devised either before or after actual play. To facilitate strategic games, a "single step" mode causes the simulation to pause at each time step, and the program continues only after a key is pressed (and, presumably, input decisions have been made). "Continuous" mode has no pause, and input decisions must be made more quickly.

Output Mode

Two types of display are possible: Text (primarily numeric values showing state variable quantities) and Graphics (primarily pictures representing, through movement and changes in size, state variable quantities). It is likely that text information will be more useful in a single step game, while graphics are more amenable to a continuous game, but any combination may be chosen. The same initial setup may be played with either mode, and both output and play modes may be changed during play, after any time step. In addition, a "hard copy" of what's on the screen may be obtained. This is particularly useful for strategic games. When Graphics mode is being used, obtaining a paper copy of the screen requires a particular type of printer to be connected.

Outcome Evaluation

After a game has been played, it may not be completely clear what the outcome is, due to the complexity of the system. In fact, each play probably has many facets to its outcome that are worth discussing. Running out of resources or labor are, of course, results to note. Whether or not the goal of the game has been attained (see #2 above) should be discussed. Where individual players

ended up, and how they got there, and what that configuration means to the society being modelled, are all important topics whose examination is part of the learning process.

Restart and "Freeze Framing"

Once a particular play is finished and evaluated, the same scenario may be initiated again, perhaps with different players and/or new strategies. Different goals may be set for the same starting conditions. Perhaps the same play may be continued from the stopping point, again with the benefit of some discussion or changes in players. Or a completely new setup may be established.

Suggestions for Evaluating Game Design

While this study does not propose to undertake an evaluation of the model, simulation, games, and curriculum required to build a complete classroom tool, some thoughts on the elements of such an evaluation as must eventually be done are in order. As described earlier, there are three measures of the validity of the model. The simulation may be evaluated according to how well it replicates the behavior of the model.

The games made possible by the simulation, however, require a more complex evaluation. We must ask, how well does the simulation build an environment for game creation

and play? What are its strengths, what are its limitations? What kinds of games are not possible, and what kind are?

About the games themselves, how "effective" are they? Are they useful and precise instruments for teaching what we wanted to teach? Given an arbitrary teaching goal, can a game be constructed to aid in reaching it? How usable, how user-friendly, is the gaming environment? Is there an effective balance between programming power and accessibility by an unsophisticated user?

Unless the answers to these questions reflect a sound and useful gaming environment, it is useless to ask how well the teacher and students performed in using the simulation.

The correct way to approach evaluation of the games is to first examine the intent, then the execution. Consideration of game intent leads directly to examination of the curriculum design. A game may be evaluated separately as a game, but the responsibility of making games into teaching tools rests with the curriculum.

1. Principles to Keep in Mind with Curriculum Design

Recall that Greenblat (1980) describes in six categories the effects of participating in a simulation game: student motivation, cognitive learning, later course work, affective learning in general and in relation to the subject matter, and classroom structure and relations.

If Greenblat's assertions are correct, then all impacts she describes are possible teaching goals. The curriculum will define which goals are attempted, and how progress toward the goals is to be measured.

The curriculum may directly address goals of cognitive learning, and may indirectly or directly affect classroom structure and relations. Because media are also messages, the curriculum may make certain affective learning goals through the way in which examples and exercises are organized. Increases in student motivation and in later class performance are desirable, of course, but are unlikely to be formal curriculum goals.

The means for attaining curriculum goals center around the simulation and the games the curriculum constructs. Evaluation of the curriculum requires looking not only at its goals, but also the effectiveness with which it uses the tools at hand.

Some cognitive information should be transferred. Students should learn rudiments of systems phenomena: feedback loops, limiting factors, interrelationships, and boundaries (Meadows, 1982). Students should also learn rudiments of the design and use of models: lumping, discrete time representation of continuous action, role definition, and perhaps most importantly, the limitations of models and their results (particularly when given the aura of authority that comes with computer simulation).

Finally, students should learn rudiments of social systems concerned with energy: entropy, supply and demand, renewable and nonrenewable resources, waste and recycling.

The curriculum design should reflect a desire to stimulate thinking on the part of the students. While this might seem an obvious goal of any teaching curriculum, it must be remembered that a certain tension always exists in playing games between acquiring new skills (required of players if they are to play well) and repeating by rote skills already acquired (required of players if they are to improve their play).

It is the particular ability of computer-based games, especially colorful "real-time" games, to create fast action that also creates the problem of "reactive" play. This is not a "problem" in arcades, of course, it is a goal: thinking increases the time between coin insertions; hand-eye coordination and reaction-time refinement are the players' goals.

If developing strategy, reflecting on the complexities of interactive systems, discovery of new insights regarding the use of models or the use of resources, or any other thinking is desired of the players, it is the curriculum, not the game itself, that must stimulate them. The principle technique is one of suggesting playing scenarios (starting state, roles, playing strategy) and asking questions of the players.

One form of exercise involves exploration: "Try this and see what happens." This may be used to reveal cognitive information in a way that also encourages investigation. Another form of exercise is demonstration: "Use this setup and make these choices to see what a 'feedback loop' is."

A more pointed type of exercise asks students to analyze events in a game: "Why did that choice produce that result?", "Given this game, what will happen if these choices are made: a,b,c?". A slightly more elaborate form of this type of exercise sets particular goals that test the students' accumulated learning: "What choices would produce these effects?". Note that while some exercises require experimentation, these types of exercises require reflection, planning, and evaluation by the players away from the game.

A perhaps more ambitious curriculum might ask students to design their own game, requiring role definitions, goals, and a description of what can be learned from their game. Where Greenblat sees three roles for students playing a game (game role, game player, classroom student), this expands their "meta-roles" to those of game designer and teacher.

An obvious, though perhaps easily overlooked, goal is for students to gain experience through playing the game(s). After this is recognized as an educational

benefit and worthy goal, the question arises, "Experience with what?" Game playing, certainly; successful game strategies come only through experience. Experience in social interaction comes at two levels: the immediate interplay between players, and the projected social relationships made between the roles specified in the games. Some students will have, for a day at least, experienced the responsibilities of directing a society's economy.

The curriculum is responsible for extending the personal interplay of two classmates into the vicarious experience of two economic decision-makers. A potentially discouraging method is to create exercises asking students to compare their game roles to roles they recognize in the "real world." A more hopeful method is the creation of exciting roles and scenarios that students can lose themselves in.

2. Principles to Keep in Mind with Game Design

If the curriculum defines the intent of the games, the goals still live and die by the effectiveness of the games' execution. A game must meet requirements of playability, teachability, durability, and "learnability."

a. Playability. Thiagarajan and Stolovitch (1979) cite "Kaplan's Law of Hammerability ('Give a kid a hammer and he will find hundreds of things that need hammering')." While this basically says that what is used is

useful, an important corollary is that, given an uninteresting hammer, the kid will find nothing that needs hammering. No exercise can teach with a game that is not played or playable.

The first requirement of playability is coherence. The players must be able to understand what is going on, what they are to do. The goals of the game, and the actions and skills required to attain them, must either be obvious or easily learned. Complex games usually require "preliminary" games that allow players to learn the rules in stages and gain familiarity with simple roles and skills before more complex actions are required of them. Elaborate manuals are no substitute for playing experience.

The most ambiguous, yet most crucial, requirement of playability is fun. Games that are not fun are, quite simply, not played. It may even be said that they are not games but tasks. Evaluating fun may be a frustrating task: it is likely to be easy to say what is not fun, but not what is or what would be.

Sometimes, it is fun to play a game which lets you be yourself; at other times it is fun to be not yourself. A crucial element of play is spontaneity (Blatner, 1982); in the case of the simulation described here, the ability of the game to create a situation and role in which a player

can "be lost in the role" is likely to be most important in allowing play to be fun.

If a game or type of game is to be played repeatedly, boredom is a danger. Therefore it should engage the players' interest. It should be on their minds when they are not playing; a degree of anticipation enhances both play and learning.

b. Teachability. Beyond being fun, the game is trying to teach something.

Play should require thought, not just reaction. The situation created by the game should be realistic, if not necessarily real. While not providing a tool for forecasting the energy future of the United States, the game should still appear to faithfully show social realities in general terms.

The teacher should feel that the game is a useful instrument. It must serve his or her goals. Teachers should be able to see where the game fits into the larger scope of what they are teaching and be able to use the game within their own means. If teachers don't or can't or won't use a game, it won't teach anyone anything.

c. Durability. Durability involves not only getting all the bugs out of the game program, but also including in the game design features sometimes called "idiot-proofing."

The major requirement of debugging is that the game should work the same way for the same conditions. In the case of the stochastic model, pseudorandom values may create the appearance of different game behavior, but given the same setup and the occurrence of the same random value, the game should proceed to the same state every time.

In regard to making the game "idiot" proof, the first danger is not the chaotic player but the devious one. A complex game always has the possibility of being "won" by taking advantage of a quirk in the rules, or by using some other tactic or strategy dependent not on the scenario of the game but on the meta-fact of it being a game. For example, a game whose goal is to preserve energy resources should not give the illusion of success to a strategy of stopping all industrial activity, although that would certainly preserve the resources.

An extension of this idea is the more general principle that the game should have a clear expression of what the goals are and of when they are reached. There should be at least one "completion" (if not "winning") strategy; the game should not drag on forever.

There is, in addition, the ever-present danger of the "great unknown." In an interactive game, the players are in charge of what is input; the computer must be able to handle whatever is sent without "crashing."

d. Learnability. It is a subtle truism that what is taught should also be learned. Both teachers and students must be able to learn not only what the game tries to convey, but more basically how the game is played. The rules should be as immediately grasped as possible; nothing kills enthusiasm for a game more quickly than having to spend an hour just reading the rules. The rules should also have a high retention factor--they should make sense, so that play isn't frequently interrupted by having to remember how to play.

Two aids to learnability in games are (1) to have one or more "sample" games to play that specifically illuminate one or two complex rules, and (2) to have more than one "level" of complexity of play. Levels of complexity are usually achieved by adding rules to sample games until a "full" game is played.

3. The Play of the Game

A game may look terrific by all these criteria and still not play well. Some points may be considered in evaluating the effectiveness of the actual play of the game.

a. Preparation. How easy and flexible is the setup phase of the game? Is it too flexible to be done easily? How clearly are goals defined, and how useful are those

goals to the class? What roles can be defined for play?
Can roles be changed during play?

b. Play. If play is continuous, does the "flow" seem natural, too fast, or too slow? If play is in steps with pauses, can the players see the "turns" as part of a continuing process? Is there time to make decisions? Is play smooth enough to keep interest?

Do players get the information (graphic or textual) they need to choose their actions? Does the information make sense? Is it always clear to the students what is happening?

Is it clear to the players what effects their choices have? Is it clear who is causing which effects? Is it clear when the game reaches (one or more) conclusion?

c. Classroom effect. Are the students talking to each other, assuming roles? Are the students thinking or reacting? Can the class evaluate what happened after a game has been played?

This is by no means a comprehensive list of questions, but it illuminates some of the features of game design and play to be considered when evaluating the game as a classroom tool.

CHAPTER V

CONCLUSION

Implementation Issues

1. Microcomputer Base

The decision to implement the simulation on the Apple II microcomputer is primarily based on the desire to make the game available to the public schools. With the notable exception of the PLATO system, microcomputers are currently the major form that computer technology takes in public education.

The chosen language for implementation is Rascal(tm), a dialect of Pascal with additional commands that facilitate color graphics and animation. This system is currently implemented only on Apple II computers.

The computer simulation must make some sacrifice for using the inexpensive, but small, microcomputers rather than a larger system. Allowances must be made for lower-resolution graphics, slower response time, and reduced arithmetic accuracy. This last price would probably be too high to pay for a forecasting simulation.

2. Segmentation Decisions

The microcomputer's small memory makes it impossible to have the entire program in main memory at one time. So the program routines are divided into segments, only one

of which will be resident at a time.

The first obvious segmentation choice is to separate selection and bootup routines from "run-time" input, output, and transition routines. Since bootup and selection are mutually exclusive processes, they each occupy a different segment. Further segmentation of the run-time routines is impractical, since it slows down the play of the game.

3. Response Time

Except for pausing at each time step in singlestep mode, the game's playability depends on the appearance of smooth movement. This means that when a player turns a paddle or presses a key, something should "immediately" happen. If in continuous mode, there should be an illusion of "flowing transition" as resources decline or grow, goods are transported, people are born or die.

The critical points for response time in the main program loop are input and output. Function calculations are much faster.

Output may take two forms: text or graphics. A special procedure, WSTRING, allows numeric values to be displayed with pictures, but its operation slows down the animation. So text displays are primarily numeric, while graphic displays are pictorial and animated. Neither provides the total amount of information about the state of the game; the graphics give an overall but relative

"feel" for the current state of affairs, while the numeric values give details for strategizing (primarily for the singlestep game). In terms of time requirements, graphics are generally slower than text displays, but when the screen is full of either pictures or text, updating becomes roughly equivalent.

Input requires reading the value of each input device. The response time for the program is very fast; for the user, however, the response time depends on how quickly the program can read the inputs, calculate the functions, show the output, and get back to the input devices again. If the time between "reads" is longer than the time it takes the user to send the next input (i.e., turning the paddle), then the response time seems slow.

Curriculum Design

It is unrealistic to expect teachers to be immediately sophisticated in the use of the simulation program for creating instructional games in the classroom. It is the crucial role of the curriculum to make the teacher aware of the possibilities the program presents, provide examples of its use, set guideposts for what can be taught, and provide tools for evaluating the effect of the program in the class. The following curriculum materials should be developed if the simulation program described by this study is to become an effective classroom tool.

1. Instructions for the Teacher

The user's manual should contain some background for the novice user, including the mechanics of starting a program. The first encounter with the simulation program should be in one or more "walk through" exercises, with care taken that something interesting should happen quickly. For example, the user might be instructed to retrieve a scenario from disk storage and run it, with the manual explaining what is being seen. More complicated selection and input operations can be added step by step in tutorial fashion. An important element is the inclusion of some "error" situations, to give the user confidence that supposed "disasters" can be resolved. A description of the model, its assumptions about the subject matter, and its behavior and limitations should also appear here.

Since the user in question is assumed to be a teacher, another section should discuss various uses of the simulation program in the classroom. Teaching objectives can be small (a one-time demonstration), or large (a "mini term" course in systems, models, and/or environmental behavior). Suggestions for class organization should be definite enough to provide security for the teacher, while leaving room for the teacher's individual method and innovation if desired. Student exercises and answers, as well as some anticipated student dilemmas and their resolution, should also appear here.

Since the user in question may not always be a teacher, the classroom use section should be separable from the rest of the material.

2. Background Readings

This section is for both teachers and students.

First, it should include readable discussions of systems, systems theory, and the value of looking at world phenomena from a systems perspective. This discussion should also cover the historical development of systems theory, thus emphasizing that systems theory is a construct for understanding, not holy writ.

Similarly, there should be a discussion of modelling, simulation, gaming, and computers, again emphasizing readability and the use of these tools for learning. Both advantages and limitations should be discussed. There are two forms of behavior and attitude to address with caution here. First, computer and mathematics anxieties make formal and abstract thinking difficult for many people, teachers and students alike. Second, and perhaps more subtly dangerous, there is a tendency among many people to defer to any complex tool, especially mathematical models and computers. With familiarity and clear description, users should be led to see that models and simulation programs are not awesome in either a positive or negative way.

Finally, there should be a brief description of the

subject matter: the uses of natural resources by human society. Though this section could be quite extensive, it should be limited to supplying supplemental information for the model's particular viewpoint. All three discussions should have bibliographies of suggested further readings. None of these readings should be prerequisite to operating the simulation program or playing games.

3. Game Descriptions

The rules for operating the program should be transmitted via a series of learning games, the first being quite simple and involving only a portion of the model, the later ones adding more complicated activities and demonstrating more features of the program. The game descriptions should assume that the players have gained the basic familiarity with the program developed by the user's manual.

Each game is developed in this way: the players are told what the scenario is, and what roles will be used. Instructions are given for setting up the scenario, either by menu selection or by retrieval from disk. Some titles (role names) are given to every input variable. The games at this point should be designed and chosen so that the course of play is pretty obvious regardless of further reading of the rules. Students are likely to experiment with or without design, so it is best to go ahead and encourage it.

After encouraging some exploration, the game description should discuss what various results "mean" in a larger sense than the displays seen on the screen. These meanings are best given by dictating some predesigned inputs and describing what the output will be and what kind of "real world" social effects it implies. Some exercises can be posed here (e.g., "predict what will happen") for which the teacher has been given answers. But the students should be encouraged to think of themselves and their use of the simulation tool as the source of answers to questions.

After giving the players controlled exercises in using the program, some games should be suggested with only goals given (e.g., "try to double the population and stabilize") and a variety of input roles proposed from which they may choose. As with the user's manual tutorials, care should be taken that the players are able to successfully achieve something interesting at regular intervals, without needing to spend hours in training and background study.

The point of the suggested games should reflect the subjects of the background readings. While one game might be designed to illustrate the relationship between prices and supply, another would show the more abstract phenomenon of a positive feedback loop. The descriptions and exercises, of course, drive the points home. The same

game could illustrate systems, modelling and environmental principles.

Final Thoughts

The ultimate test of this instrument is its operation in a classroom. Duke (1980) says that the testing of games is subject to the "rule of ten," i. e., tests with different audiences on "ten separate occasions, the final three of which should require no further significant adjustment or modification." No design element of this study--model, simulation, game, curriculum--should be considered complete until such testing has been completed.

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APPENDICES

APPENDIX A

INFORMAL BASE MODEL DESCRIPTION

Resources By Location

- I. Land surface
 - A. Human activity
 - 1. Raw Materials
 - 2. Processed Materials
 - 3. Manufactured Goods
 - 4. Waste Materials
 - 5. Human Population
 - B. Unused land area
 - 1. Forest
 - 2. Plains
 - 3. Mountain
 - 4. Desert
 - 5. Wetlands
 - 6. Coast
 - 7. Tundra
 - 8. Jungle
 - C. Biomass
 - 1. Living
 - a. Trees
 - b. Nondomestic Vegetation
 - c. Nondomestic Animals
 - 2. Dead
 - a. Plants
 - b. Animals
 - c. Wastes
 - D. Minerals
 - 1. Fossil fuel resources
 - a. Oil
 - b. Gas
 - c. Coal
 - 1) Hard
 - 2) Soft
 - 2. Metal ores
 - a. Basic Metals
 - b. Uranium
 - 3. Rock and other ores
 - a. Sand
 - b. Clay
 - c. Stone
 - E. Other potential energy storages
 - 1. Thermal
 - a. Geopower
 - 2. Radiant--solar flux

- b. Solarpower
 - F. Other substances
 - 1. Sustenants
 - a. Nitrates
 - b. Phosphates
 - c. Water
 - 1) Groundwater
 - 2) Ice
 - 2. Toxicants
 - a. Nuclear waste materials
 - b. Industrial pollutants
 - c. Other poisons
 - d. Groundwater acidity
- II. Water surface
 - A. Human activity
 - B. Unused water area
 - 1. Fresh Water
 - a. River
 - b. Lake
 - c. Ice
 - 2. Ocean
- III. Water volume
 - A. Human activity
 - B. Unused water volume
 - 1. Fresh Water
 - a. River
 - b. Lake
 - c. Ice
 - 2. Ocean
 - C. Biomass
 - 1. Living
 - a. Vegetation
 - b. Animals and Fish
 - 2. Dead
 - a. Plants
 - b. Animals and Fish
 - c. Wastes
 - D. Dissolved and suspended Minerals
 - E. Other potential energy storages
 - 1. Thermal
 - a. Geopower
 - 2. Mechanical--solar flux
 - a. Waterpower
 - b. Hydropower
 - 3. Radiant--solar flux
 - a. Solarpower
 - 4. Mechanical--gravitation
 - a. Tidalpower
 - F. Other substances
 - 1. Sustenants
 - a. Dissolved Oxygen
 - b. Dissolved Carbon dioxide

- c. Dissolved Nitrogen
 - d. Nitrates
 - e. Phosphates
 - 2. Toxicants
 - a. Industrial poisons
 - b. Acidity
 - c. Heat
- IV. Atmosphere
 - A. Human activity
 - B. Unused
 - C. Biomass
 - 1. Living
 - a. Airborne Bacteria
 - b. Birds and Flying Insects
 - 2. Dead
 - a. Airborne Wastes
 - D. Other potential energy storages
 - 1. Mechanical--solar flux
 - a. Windpower
 - 2. Radiant--solar flux
 - a. Solarpower
 - E. Other substances
 - 1. Sustenants
 - a. Atmospheric Oxygen
 - b. Atmospheric Carbon dioxide
 - c. Atmospheric Nitrogen
 - d. Atmospheric Ozone
 - e. Atmospheric Water
 - 2. Toxicants
 - a. Sulphur dioxide
 - b. Carbon monoxide
 - c. Acidity
 - d. Heat

Components of Human Activity Sectors

Sector: HARVEST [Resource-to-Raw materials]

(Resource: "food";
Raw material: "commodities")

FARMING

- 1. Input (Land Resources, Transport from Commercial)
 - resources (sustenants, water, plant stocks)
 - waste materials (biomass)
 - processed materials (seed, plant nutrients)
- 2. Output (Transport to Commercial)
 - raw materials (crops, recycled waste)
- 3. Waste materials
 - (heat, fuel wastes, materials, emissions)

4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (tractors, threshers,
harvesters)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
barns, storage silos, housing
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

RANCHING AND LIVESTOCK PRODUCTION

1. Input (Land Resources, Transport from
Commercial)
resources (sustenance, water, animal stocks)
waste materials (biomass)
processed materials (feedstocks, animal
nutrients)
2. Output (Transport to Commercial)
raw materials (livestock, recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (ranch equipment)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
housing, stockyards
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

FISHING

1. Input (Water Resources)

- biomass resources (fishstocks, water crops)
- 2. Output (Transport to Commercial)
raw materials (fish, recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (boats, nets)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
storage, docks, housing
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Resource: "oil ";

Raw material: "crude oil")

OIL DRILLING

- 1. Input (Land Resources)
fossil fuel resources (oil)
- 2. Output (Transport to Commercial)
raw materials (crude oil), recycled waste
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (drilling equipment, pipe)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
rigs, housing, storage
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Resource: "gas";
Raw material: "natural gas")
GAS DRILLING

1. Input (Land Resources)
fossil fuel resources (gas)
2. Output (Transport to Commercial)
raw materials (natural gas), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (drilling equipment, pipe)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
rigs, housing, storage
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "hard coal ore";
Raw material: "hard coal")
HARD COAL MINING

1. Input (Land Resources)
fossil fuel resources (hard coal ore)
2. Output (Transport to Commercial)
raw materials (hard coal), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (diggers, trains, belts)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mines, housing, storage
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction

- for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
 12. Global Parameters

(Resource: "soft coal ore";
Raw material: "soft coal")

SOFT COAL MINING

1. Input (Land Resources)
fossil fuel resources (soft coal ore)
2. Output (Transport to Commercial)
raw materials (soft coal), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (diggers, trains, belts)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mines, housing, storage
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "uranium ore";
Raw material: "uranium")

URANIUM MINING

1. Input (Land Resources)
metal ores (uranium ore)
2. Output (Transport to Commercial)
raw materials (uranium), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (diggers, trains, belts)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mines, housing, storage
8. Assets
dollars

9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "basic metal ore";
Raw material: "basic metals")

METAL MINING AND QUARRYING

1. Input (Land Resources)
metal ores (basic metal ores)
2. Output (Transport to Commercial)
raw materials (basic metals), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (diggers, trains, belts)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mines, housing, storage
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "rock";

Raw material: "stone")

ROCK MINING AND QUARRYING

1. Input (Land Resources)
rock and other ores (sand, clay, stone)
2. Output (Transport to Commercial)
raw materials (stone), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (diggers, trains, belts)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)

7. Structures (Purchase from Construction)
mines, housing, storage
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "timber";
Raw material: "logs")
LOGGING

1. Input (Land Resources)
biomass resources (trees)
2. Output (Transport to Commercial)
raw materials (logs), recycled waste
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (saws, chains, bulldozers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
housing
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

Sector: HARVEST [Resource-to-Processed materials]

(Resource: "geopower";
Processed material: "electricity")
GEOTHERMAL ELECTRICITY HARVEST

1. Input (Resources) [Renewable]
thermal energy resources (geopower)
2. Output (Transport to Commercial)
processed materials (electricity)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)

4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (generators, turbines,
transformers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
installations
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "hydropower";
Processed material: "electricity")
HYDROPOWER ELECTRICITY HARVEST

1. Input (Resources) [Renewable]
mechanical energy resources (hydropower)
2. Output (Transport to Commercial)
processed materials (electricity)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (generators, turbines,
transformers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
dams, installations
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "windpower";
Processed material: "electricity")

WINDPOWER ELECTRICITY HARVEST

1. Input (Resources) [Renewable
mechanical energy resources (windpower)]
2. Output (Transport to Commercial)
processed materials (electricity)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (generators, wind turbines,
transformers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
installations
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "solarpower";

Processed material: "electricity")

SOLARPOWER ELECTRICITY HARVEST

1. Input (Resources) [Renewable
radiant energy resources (solarpower)]
2. Output (Transport to Commercial)
processed materials (electricity)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (convertors, photocells,
transformers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
installations
8. Assets
dollars
9. Income from Commercial
for output

10. Payments to Commercial, Residential (Work Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "tidalpower";
Processed material: "electricity")
TIDALPOWER ELECTRICITY HARVEST

1. Input (Resources) [Renewable]
gravitational energy resources (tidalpower)
2. Output (Transport to Commercial)
processed materials (electricity)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (generators, turbines,
transformers)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
installations
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Resource: "water";
Processed material: "electricity")
POWER PLANT ELECTRICITY PRODUCTION

1. Input (Resources) [Non-Renewable]
water
2. Output (Transport to Commercial)
processed materials (electricity)
water
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (generators, turbines,
boilers, transformers)

6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
uranium, electricity)
7. Structures (Purchase from Construction)
steam power plants
nuclear power plants
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

Sector: CONVERSION [Raw materials-to-Processed
materials]

(Raw material: "commodities";
Processed material: "processed food")
FOOD PROCESSING

1. Input (Transport from Commercial)
raw materials (commodities)
2. Output (Transport to Commercial)
processed materials (processed food)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (food processing
equipment)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
fisheries, mills, slaughterhouses, stockyards
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Raw material: "crude oil";
Processed material: "petroleum products")
OIL REFINING

1. Input (Transport from Commercial)
raw materials (crude oil)
2. Output (Transport to Commercial)
processed materials (petroleum products)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (oil refining equipment)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
refineries
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Raw material: "natural gas";
Processed material: "refined gas")
GAS REFINING

1. Input (Transport from Commercial)
raw materials (natural gas)
2. Output (Transport to Commercial)
processed materials (refined gas)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (gas refining equipment)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
refineries
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures

11. Internal Flow Parameters
12. Global Parameters

(Raw material: "hard and soft coal";
 Processed material: "processed coal")

COAL PROCESSING

1. Input (Transport from Commercial)
 raw materials (hard coal, soft coal)
2. Output (Transport to Commercial)
 processed materials (processed coal)
 raw materials (recycled waste)
3. Waste materials
 (heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
 human population
5. Equipment (Purchase from Commercial)
 manufactured goods (coal processing
 equipment)
6. Fuel (Purchase from Commercial)
 processed materials (refined oil, coal, gas,
 electricity)
7. Structures (Purchase from Construction)
 processing plants
8. Assets
 dollars
9. Income from Commercial
 for output
10. Payments to Commercial, Residential (Work
 Force), Construction
 for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Raw material: "uranium";
 Processed material: "refined uranium")

URANIUM REFINING

1. Input (Transport from Commercial)
 raw materials (uranium)
2. Output (Transport to Commercial)
 processed materials (refined uranium)
 raw materials (recycled waste)
3. Waste materials
 (heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
 human population
5. Equipment (Purchase from Commercial)
 manufactured goods (uranium refining
 equipment)
6. Fuel (Purchase from Commercial)
 processed materials (refined oil, coal, gas,
 electricity)
7. Structures (Purchase from Construction)

- refineries
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Raw material: "metals";
Processed material: "refined metals")
METALS REFINING

- 1. Input (Transport from Commercial)
raw materials (base metals)
- 2. Output (Transport to Commercial)
processed materials (refined metals)
raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (metals refining
equipment)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
refineries
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Raw material: "stone";
Processed material: "processed stone")
STONE PROCESSING

- 1. Input (Transport from Commercial)
raw materials (stone)
- 2. Output (Transport to Commercial)
processed materials (processed stone)
raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)

- human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (stone processing
equipment)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
processing plants
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Raw material: "ores";
Processed material: "chemicals")
CHEMICAL REFINING

- 1. Input (Transport from Commercial)
raw materials (crude oil, basic metals,
stone)
- 2. Output (Transport to Commercial)
processed materials (chemicals)
raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (chemical refining
equipment)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
refineries
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Raw material: "logs";
Processed material: "lumber")

LUMBER

1. Input (Transport from Commercial)
raw materials (logs)
2. Output (Transport to Commercial)
processed materials (lumber)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (saws, cutters)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mills
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

Sector: MANUFACTURE [Processed materials-to-
Manufactured goods]

(Processed material: "processed food";
Manufactured good: "groceries")

FOOD MANUFACTURING

1. Input (Transport from Commercial)
processed materials (processed food)
2. Output (Transport to Commercial)
manufactured goods (groceries)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (machines, paper, cans,
plastic)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
packaging and canning factories, assembly
lines
8. Assets

- dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Processed material: "refined metals, petroleum
products, lumber";

Manufactured good: "appliances, light equipment")

LIGHT MANUFACTURING

1. Input (Transport from Commercial)
processed materials (refined metals,
petroleum products,
lumber)
2. Output (Transport to Commercial)
manufactured goods (appliances, light
equipment)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (machines, tools)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
factories, assembly lines
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Processed material: "refined metals, petroleum
products, chemicals";

Manufactured good: "vehicles, heavy goods and
equipment, weapons")

HEAVY MANUFACTURING

1. Input (Transport from Commercial)
processed materials (refined metals,
petroleum products,
chemicals)
2. Output (Transport to Commercial)

- manufactured goods (vehicles, heavy goods
and equipment, weapons)
- raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (machines, tools)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
factories, assembly lines
- 8. Assets
dollars
- 9. Income from Commercial
for output
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

(Processed material: "petroleum products,
chemicals";

Manufactured good: "medicine, household
chemicals")

CHEMICAL MANUFACTURING

- 1. Input (Transport from Commercial)
processed materials (petroleum products,
chemicals)
- 2. Output (Transport to Commercial)
manufactured goods (medicine, household
chemicals)
raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (chemical manufacturing
equipment)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
factories, assembly lines
- 8. Assets
dollars
- 9. Income from Commercial
for output

10. Payments to Commercial, Residential (Work Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

(Processed material: "lumber, chemicals";
Manufactured good: "paper products")

PAPER MANUFACTURING

1. Input (Transport from Commercial)
processed materials (lumber, chemicals)
2. Output (Transport to Commercial)
manufactured goods (paper products)
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)
manufactured goods (machines, tools)
6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
7. Structures (Purchase from Construction)
mills, assembly lines
8. Assets
dollars
9. Income from Commercial
for output
10. Payments to Commercial, Residential (Work Force), Construction
for input, labor, equipment, fuel, structures
11. Internal Flow Parameters
12. Global Parameters

Sector: CONSTRUCTION [Processed materials and
Manufactured goods-to-
Structures]

(Processed material: "lumber, processed stone")
(Manufactured good: "heavy goods")

CONSTRUCTION

1. Input (Transport from Commercial)
processed materials (lumber, stone, steel)
2. Output (To each Sector)
structures
raw materials (recycled waste)
3. Waste materials
(heat, fuel wastes, materials, emissions)
4. Labor (Hire from Work Force)
human population
5. Equipment (Purchase from Commercial)

- manufactured goods (construction tools)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures
- 8. Assets
dollars
- 9. Income from each Sector
for output
- 10. Payments to Commercial, Residential (Work
Force)
for input, labor, equipment, fuel
- 11. Internal Flow Parameters
- 12. Global Parameters

Sector: TRANSPORT [Raw materials, Processed materials,
Manufactured goods]

(All materials)

TRANSPORT TO COMMERCIAL SECTOR

- 1. Input (From each Sector)
raw materials (all)
processed materials (all)
manufactured goods (all)
- 2. Output (To Commercial)
raw materials (all)
processed materials (all)
manufactured goods (all)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (trucks, ships, pipelines,
transmission, trains)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures
- 8. Assets
dollars
- 9. Income from Commercial
for service
- 10. Payments to Commercial, Residential (Work
Force)
for labor, equipment, fuel
- 11. Internal Flow Parameters
- 12. Global Parameters

TRANSPORT FROM COMMERCIAL SECTOR

- 1. Input (From Commercial)
raw materials (all)

- processed materials (all)
- manufactured goods (all)
- 2. Output (To each Sector)
 - raw materials (all)
 - processed materials (all)
 - manufactured goods (all)
- 3. Waste materials
 - (heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
 - human population
- 5. Equipment (Purchase from Commercial)
 - manufactured goods (trucks, ships, pipelines, transmission, trains)
- 6. Fuel (Purchase from Commercial)
 - processed materials (refined oil, coal, gas, electricity)
- 7. Structures
- 8. Assets
 - dollars
- 9. Income from Commercial
 - for service
- 10. Payments to Commercial, Residential (Work Force)
 - for labor, equipment, fuel
- 11. Internal Flow Parameters
- 12. Global Parameters

Sector: COMMERCE [Raw materials, Processed materials, Manufactured goods]

(All materials)

COMMERCE

- 1. Input (Transport from each Sector)
 - raw materials (all)
 - processed materials (all)
 - manufactured goods (all)
- 2. Output (Transport to each Sector)
 - raw materials (all)
 - processed materials (all)
 - manufactured goods (all)
- 3. Waste materials
 - (heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
 - human population
- 5. Equipment (Purchase from Commercial)
 - manufactured goods (machines, tools, paper, office equipment)
- 6. Fuel (Purchase from Commercial)
 - processed materials (refined oil, coal, gas, electricity)
- 7. Structures (Purchase from Construction)
 - inventory storage, office buildings, retail

- buildings
- 8. Assets
dollars
- 9. Income from each Sector
for output
- 10. Payments to all Sectors
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

Sector: RESIDENCE [Manufactured goods-to-waste
materials; Human population]

RESIDENCE

- 1. Input (Transport from Commercial)
resources (water)
manufactured goods (food)
human population
- 2. Output
human population
raw materials (recycled waste)
- 3. Waste materials
(heat, fuel wastes, materials, emissions)
- 4. Labor
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (appliances, chemicals,
vehicles, paper)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
homes, apartments
- 8. Assets
dollars
- 9. Income from each Sector
for labor
- 10. Payments to Commercial, Residential (Work
Force), Construction
for input, labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

Sector: GOVERNMENT AND MILITARY

GOVERNMENT AND MILITARY

- 1. Input (Transport from Commercial)
human population
- 2. Output (Transport to Commercial)
services
raw materials (recycled waste)
- 3. Waste materials

- (heat, fuel wastes, materials, emissions)
- 4. Labor (Hire from Work Force)
human population
- 5. Equipment (Purchase from Commercial)
manufactured goods (office equipment,
military equipment)
- 6. Fuel (Purchase from Commercial)
processed materials (refined oil, coal, gas,
electricity)
- 7. Structures (Purchase from Construction)
offices, factories, housing
- 8. Assets
dollars
- 9. Income from each Sector
taxes, revenues
- 10. Payments to Commercial, Residential (Work
Force), Construction
for labor, equipment, fuel, structures
- 11. Internal Flow Parameters
- 12. Global Parameters

Sector: FOREIGN COUNTRY [Imports, Exports]

(Imports--From Foreign Country To Commercial Sector:
"Raw materials, Processed materials, Manufactured
goods";

Exports--From Commercial Sector To Foreign Country:
"Raw materials, Processed materials, Manufactured
goods")

FOREIGN COUNTRY

- 1. Input (Import from Commercial)
Raw materials (all)
Processed materials (all)
Manufactured goods (all)
- 2. Output (Export to Commercial)
Raw materials (all)
Processed materials (all)
Manufactured goods (all)
- 3. Assets
dollars
- 4. Income from Commercial
for output
- 5. Payments to Commercial
for input
- 6. Internal Flow Parameters

APPENDIX B

INFORMAL LUMPED MODEL DESCRIPTION

General System Parameters

- I. Resources (from Christensen, 1981)
 - A. Renewable
 - 1. Geothermal Energy
 - a. Hot Rock
 - 2. Radiant Energy
 - a. Direct
 - b. Biological storage--biomass
 - 1. Living (non Human)
 - 2. Dead
 - 3. Biological "wastes"
 - 3. Mechanical Energy
 - a. Wind
 - b. Ocean Current
 - c. Hydro
 - d. Wave Action
 - e. Thermal Gradient
 - f. Gravitational Energy
 - 1. Tides
 - 4. Sustenants
 - a. Oxygen
 - b. Nitrogen and Nitrates
 - c. Phosphates
 - d. Carbon Dioxide
 - e. Water
 - B. Nonrenewable
 - 1. Geological Energy (Chemical)
 - a. Gas
 - b. Oil
 - c. Tar Sand
 - d. Oil Shale
 - e. Coal
 - 2. Geothermal Energy
 - a. Hot Steam and Fluid
 - 3. Nuclear Energy
 - a. Uranium--Fission
 - b. Water--Fusion
 - 4. Other Minerals
 - a. Basic Metals (Iron, Copper, etc.)
 - b. Rock and other ores (Sand, Clay, Stone)
 - C. Land surface
 - 1. Used
 - 2. Unused
 - D. Water surface

- 1. Used
 - 2. Unused
- E. Water volume
 - 1. Used
 - 2. Unused
- F. Atmosphere
- II. Waste Materials (from Human Activity--Toxicants)
 - A. Heat
 - B. Acidity
 - C. Carbon monoxide and other hydrocarbons
 - D. Sulphur dioxide
 - E. Industrial pollutants and poisons
 - F. Nuclear waste material
- III. Function Parameters
 - A. Renewal Rates (natural cycling)
 - 1. Solar radiation
 - 2. Reflection
 - 3. Production (photosynthesis)
 - 4. Respiration
 - 5. Land development, reclamation, soil erosion
 - 6. Waste recycle, growth
 - B. Entropy factors
 - C. Labor force (percentage of population)

Sectors of Human Activity

Human Activity Sectors:

- 1. RENEWABLE RESOURCE HARVEST
- 2. NONRENEWABLE RESOURCE HARVEST
- 3. ELECTRICITY HARVEST
- 4. CONVERSION
- 5. MANUFACTURE
- 6. CONSTRUCTION
- 7. TRANSPORT
- 8. COMMERCE
- 9. RESIDENCE
- 10. FOREIGN COUNTRY

Descriptive Variables of Harvest, Conversion, Manufacture, and Construction Sectors:

- 1. Sites
- 2. Input
- 3. Output
- 4. Waste materials
- 5. Labor
- 6. Equipment
- 7. Fuel
- 8. Structures
- 9. Assets

10. Income
11. Payments
12. Internal Flow Parameters

Descriptive Variables of Commerce Sector:

1. Sites
2. Raw materials
3. Processed materials
4. Manufactured goods
5. Waste materials
6. Labor
7. Equipment
8. Fuel
9. Structures
10. Assets
11. Income
12. Payments
13. Internal Flow Parameters

Descriptive Variables of Transport Sector:

1. Sites
2. Raw materials
 - from other sectors to Commerce
 - from Commerce to other sectors
 - from Foreign Country to Commerce (Imports)
 - from Commerce to Foreign Country (Exports)
3. Processed materials
 - from other sectors to Commerce
 - from Commerce to other sectors
 - from Foreign Country to Commerce (Imports)
 - from Commerce to Foreign Country (Exports)
4. Manufactured goods
 - from other sectors to Commerce
 - from Commerce to other sectors
 - from Foreign Country to Commerce (Imports)
 - from Commerce to Foreign Country (Exports)
5. Waste materials
6. Labor
7. Equipment
8. Fuel
9. Structures
10. Assets
11. Income
12. Payments
13. Internal Flow Parameters

Descriptive Variables of Residence Sector:

1. Sites
2. Waste materials

3. Equipment
4. Fuel
5. Structures
6. Assets
7. Income
8. Payments
9. Population
10. Workforce
11. Internal Flow Parameters

Descriptive Variables of Foreign Country:

1. Raw materials
 - Import
 - Export
2. Processed materials
 - Import
 - Export
3. Manufactured goods
 - Import
 - Export
4. Assets
5. Income
6. Payments
7. Internal Flow Parameters

APPENDIX C

DIAGRAMS OF LUMPED MODEL

The diagrams of Appendix C (Figures 1-13) represent various stages of material and money flows through the sectors of the lumped model. A description of each diagram is given below. The following abbreviations are used:

R	renewable resources
NR	nonrenewable resources
W	waste materials
RM	raw materials
PM	processed materials
MG	manufactured goods
I	input to sector
O	output from sector
L	labor
E	equipment
F	fuel
S	structures
\$	money

Storage symbols are from Odum (1971, 1972, 1976, 1981).

Diagram Descriptions

Figure 1. Base Model: Human Activity Sectors

Resources and Waste materials are measured outside of the human activity sectors. Construction and Transport contact all other sectors. Transport is the link between Foreign Country and Commerce; contact between Foreign Country and other sectors has no meaning other than to preserve symmetry in the diagram.

Figure 2. Activity Within Sectors

Inputs become Outputs and Waste (like weeds, Waste is whatever isn't used). Labor, Equipment, Fuel, and Structures are involved in this process for most sectors. Residence has no Inputs or Outputs, but has a self-cycling Population (a percentage of which is the Workforce). Construction has no Structures. All sectors contain monetary Assets.

Figure 3. Transport and Commerce

Commerce and Foreign Country contain storages of Raw Materials, Processed Materials, and Manufactured Goods. Transport contains four groups of these storages. Transport and Commerce use Labor, Equipment, and Fuel; Commerce also uses Structures. All three have monetary Assets.

Figure 4. Resources → Harvest

Renewable resources provide Inputs for the Energy Harvest and Renewable Resource Harvest sectors. Nonrenewable resources provide Inputs for the Energy Harvest and Nonrenewable Resource Harvest sectors.

Figure 5. Population/Workforce → Labor

The Residence Population provides Labor for all other sectors. Money flows from each sector to Residence in payment for Labor.

Figure 6. Construction → Structures

Construction Outputs are the Structures of all other sectors. Money flows from each sector to Construction in payment for Structures.

Figure 7. Resources → Raw Materials → Processed Materials

Raw Materials are the Outputs of the Renewable and Nonrenewable Resource Harvest sectors. These materials provide the Raw Materials in Transport going to the Raw Materials in Commerce. Money flows from Commerce to the Harvest sectors in payment for the materials. The Commerce materials then provide the Raw Materials in Transport going to the Conversion sector Inputs. Conversion pays Commerce for the materials. Commerce pays Transport for all materials transports.

Figure 8. Processed Materials → Fuel, Manufactured Goods

Processed Materials are the Outputs of the Energy Harvest and Conversion sectors. These materials provide the Processed Materials in Transport going to the Processed Materials in Commerce. The Commerce materials then

flow through Transport to the Manufacture sector Inputs, and to the Fuel storages of all sectors.

Figure 9. Processed Materials Payments

Commerce pays Energy Harvest and Conversion for the Processed Materials Outputs. Manufacture pays Commerce for the Processed Materials Inputs. All sectors pay Commerce for the Fuel. Commerce pays Transport for all materials transports.

Figure 10. Manufactured Goods $\rightarrow$ Equipment

Manufactured Goods are the Outputs of the Manufacture sector. These materials flow through Transport to the Commerce Manufactured Goods storage. The Commerce materials then flow through Transport to the Equipment storages of all sectors.

Figure 11. Manufactured Goods Payments

Commerce pays Manufacture for the Manufactured Goods Outputs. All sectors pay Commerce for the Equipment. Commerce pays Transport for all materials transports.

Figure 12. Waste Materials

All Waste materials flow to the total Waste storage. Some of the Waste is recycled into Renewable resources. Deterioration of materials, Structures, Fuel, and Equipment in each sector contribute to the Waste materials in that sector. All entropy is "deferred" to a total entropy measure for the composite Waste material.

Figure 13. Import-Export

Raw Materials, Processed Materials, and Manufactured Goods flow through Transport from Commerce to Foreign Country (Export) and from Foreign Country to Commerce (Import). Commerce and Foreign Country pay each other for the materials. Commerce pays Transport for some materials transports.

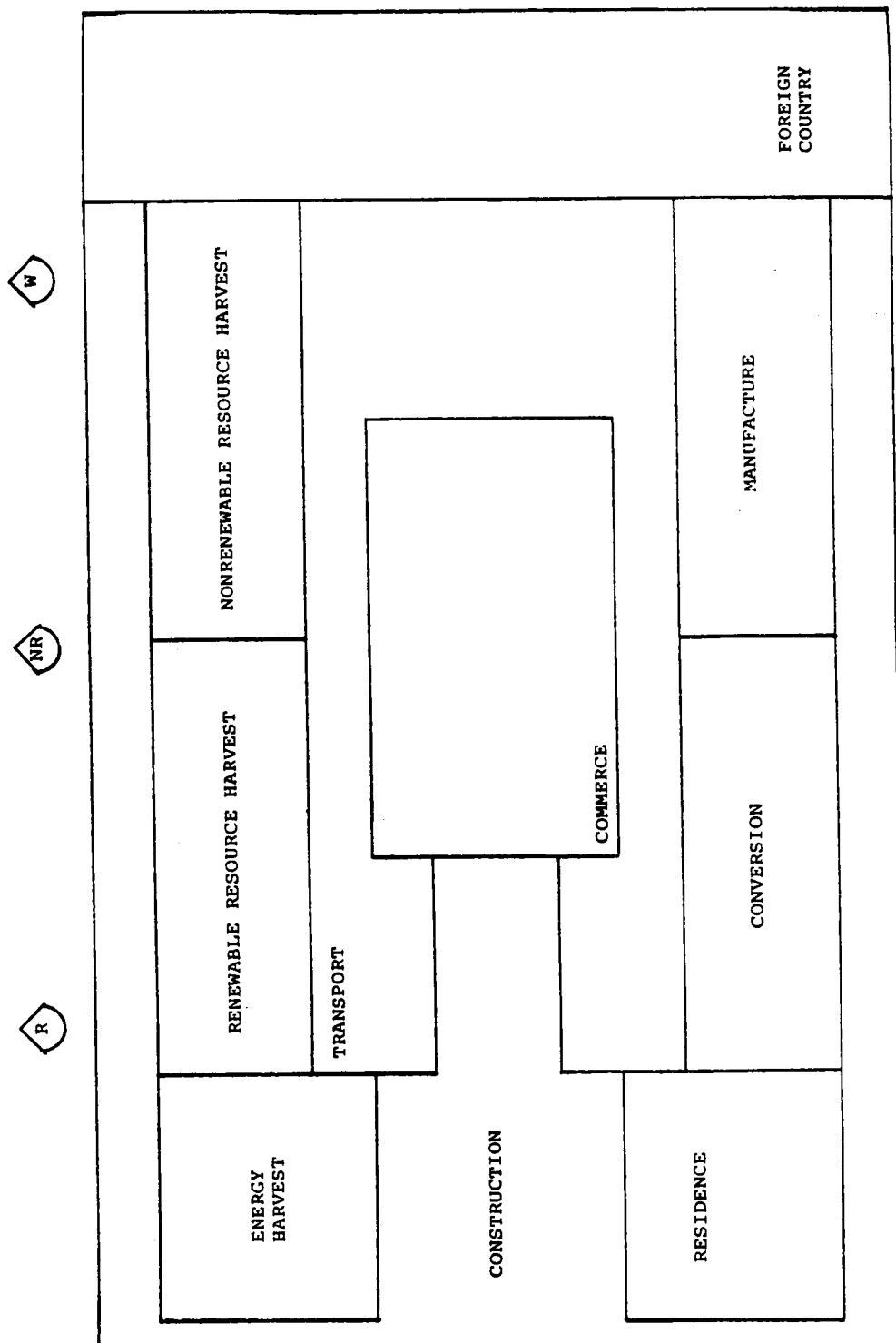


Figure 1. Base Model: Human Activity Sectors

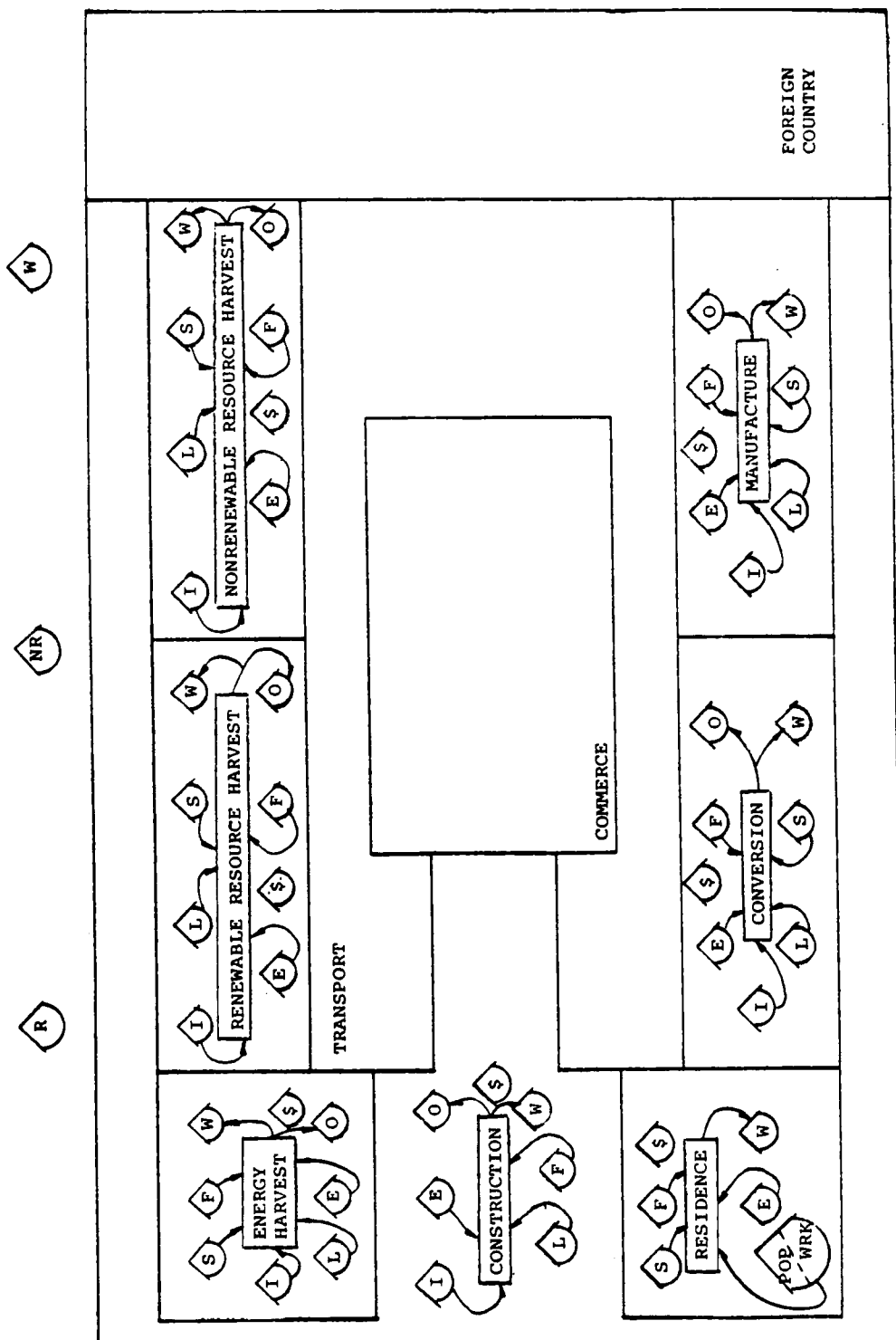


Figure 2. Activity Within Sectors

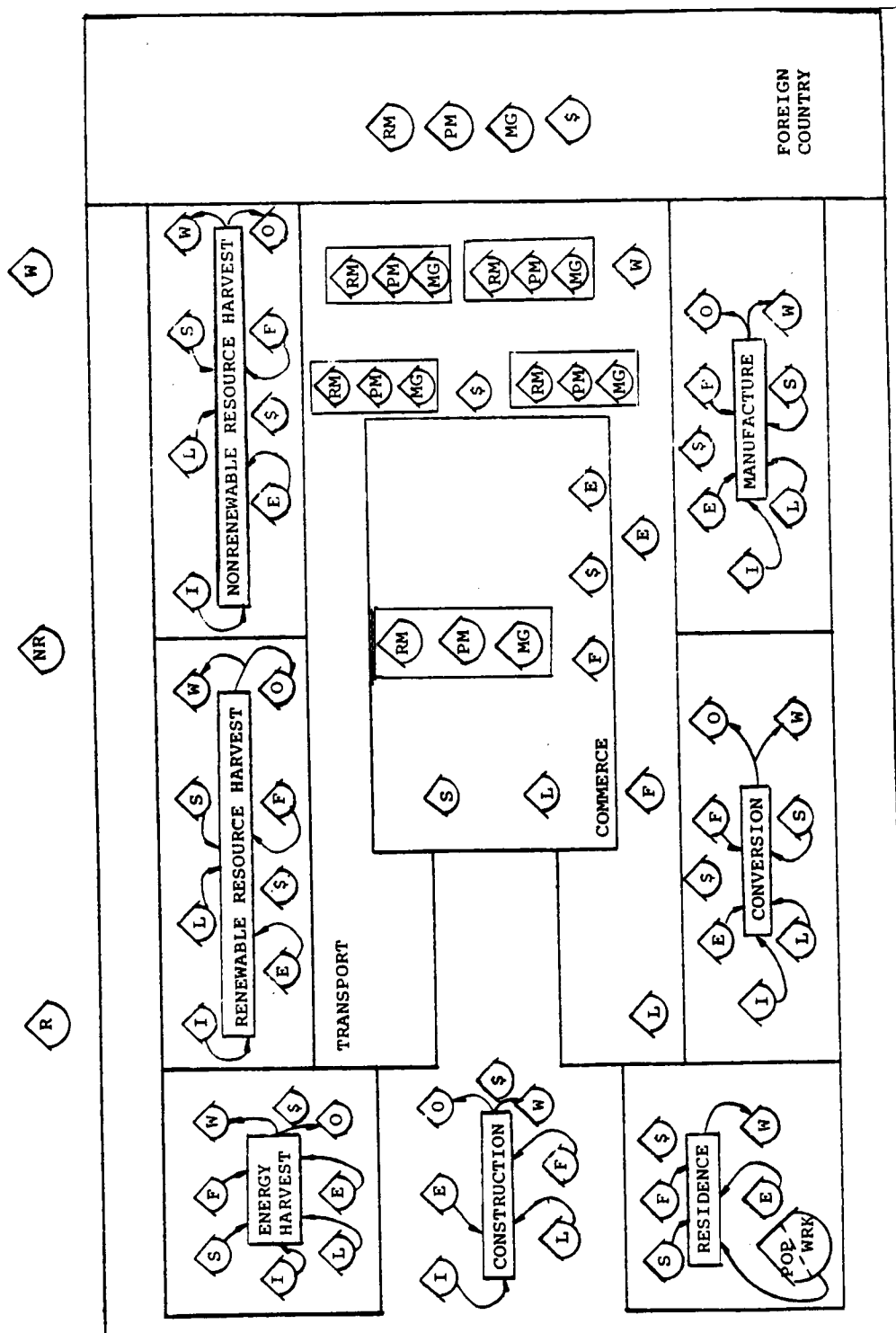


Figure 3. Transport and Commerce

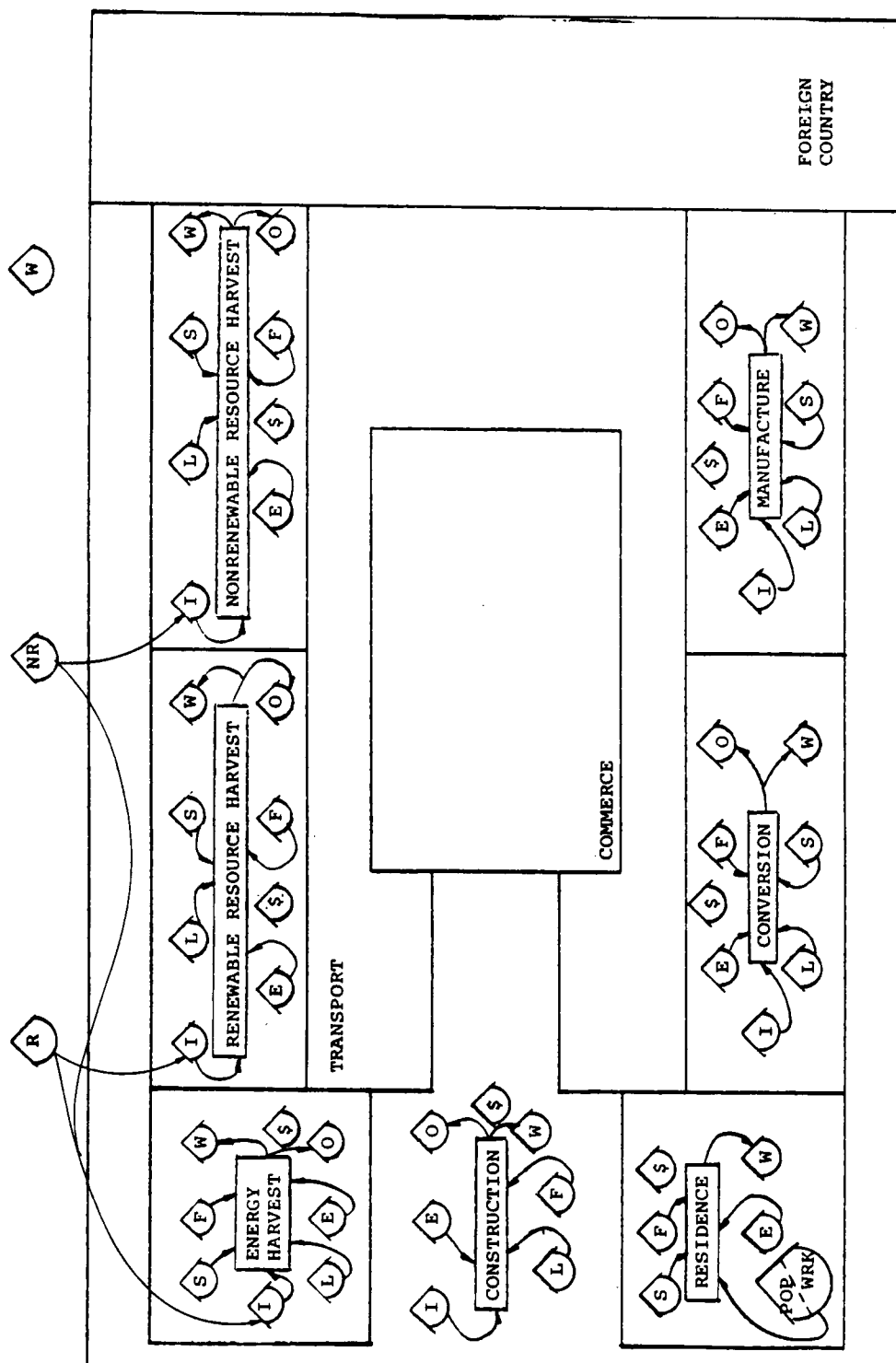


Figure 4. Resources → Harvest

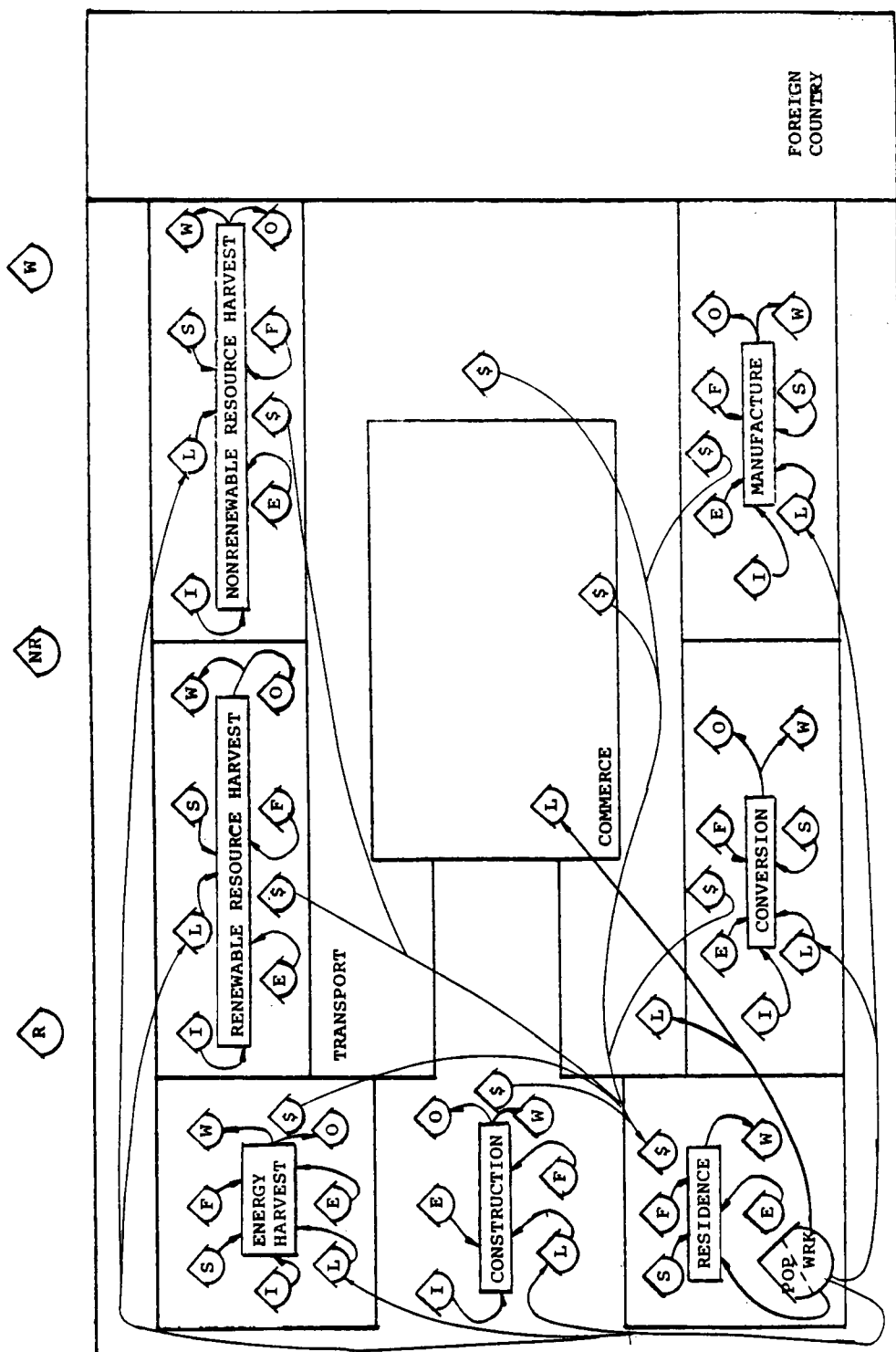


Figure 5. Population/Workforce → Labor

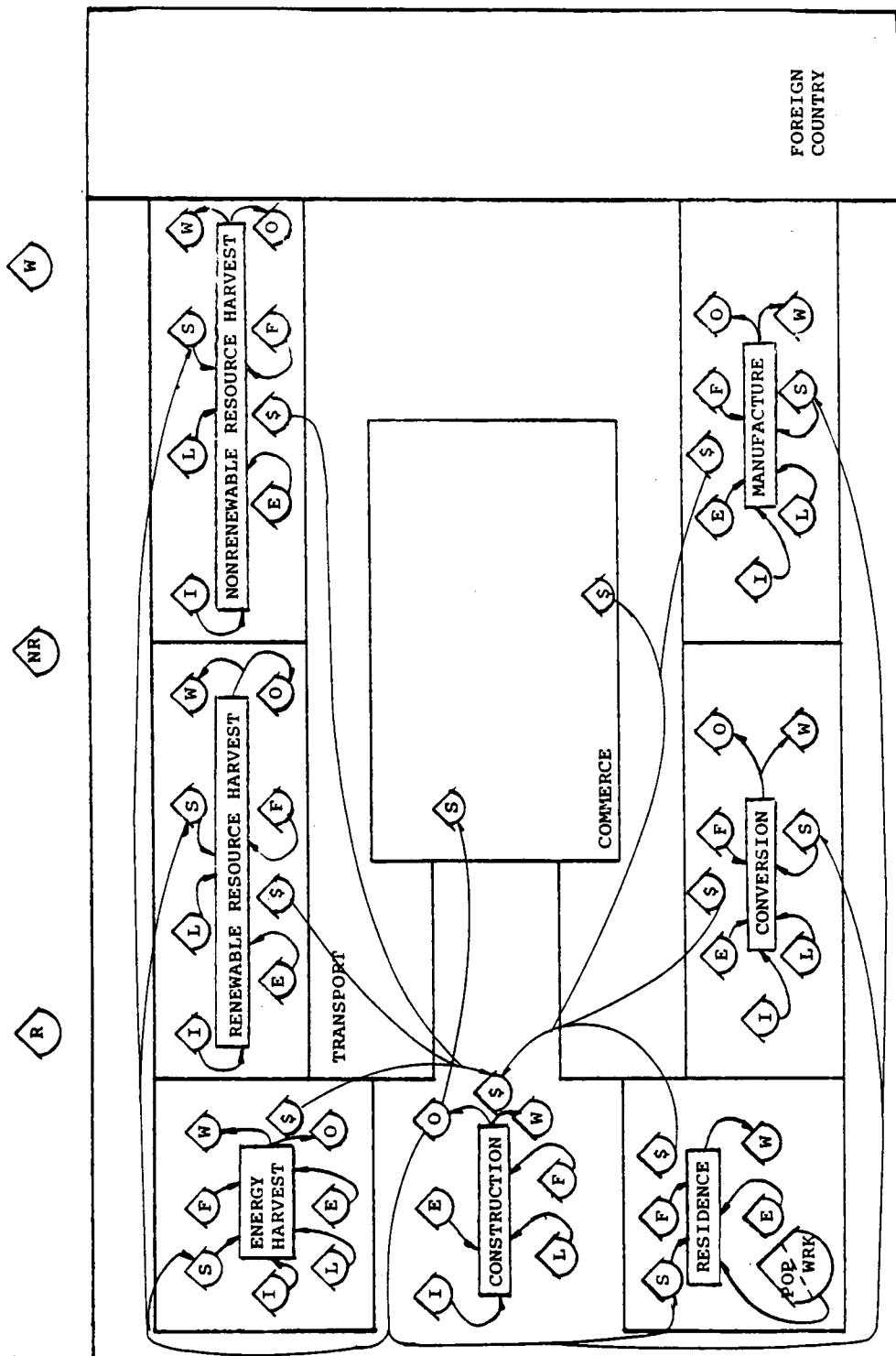


Figure 6. Construction → Structures

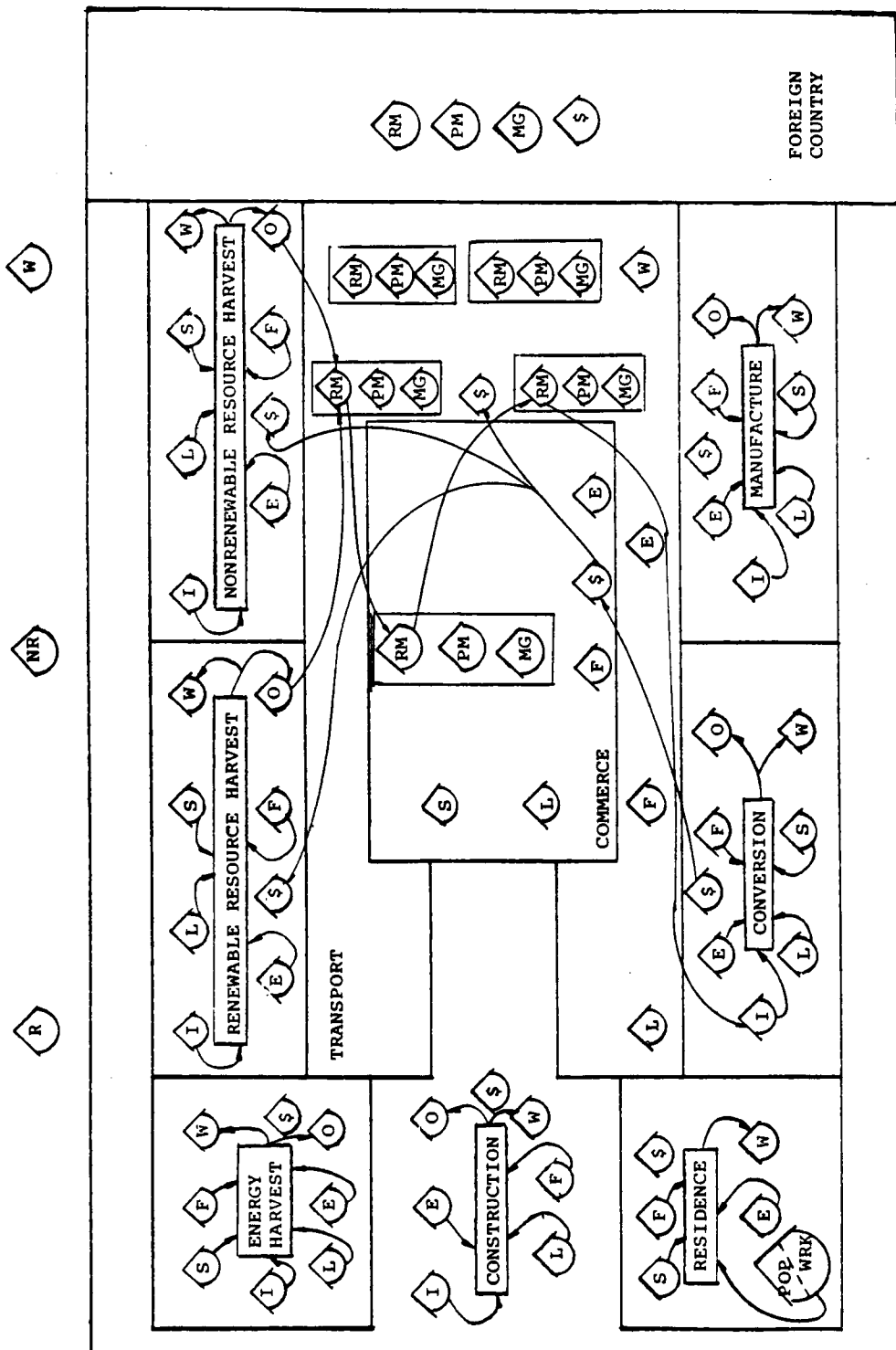


Figure 7. Resources → Raw Materials → Processed Materials

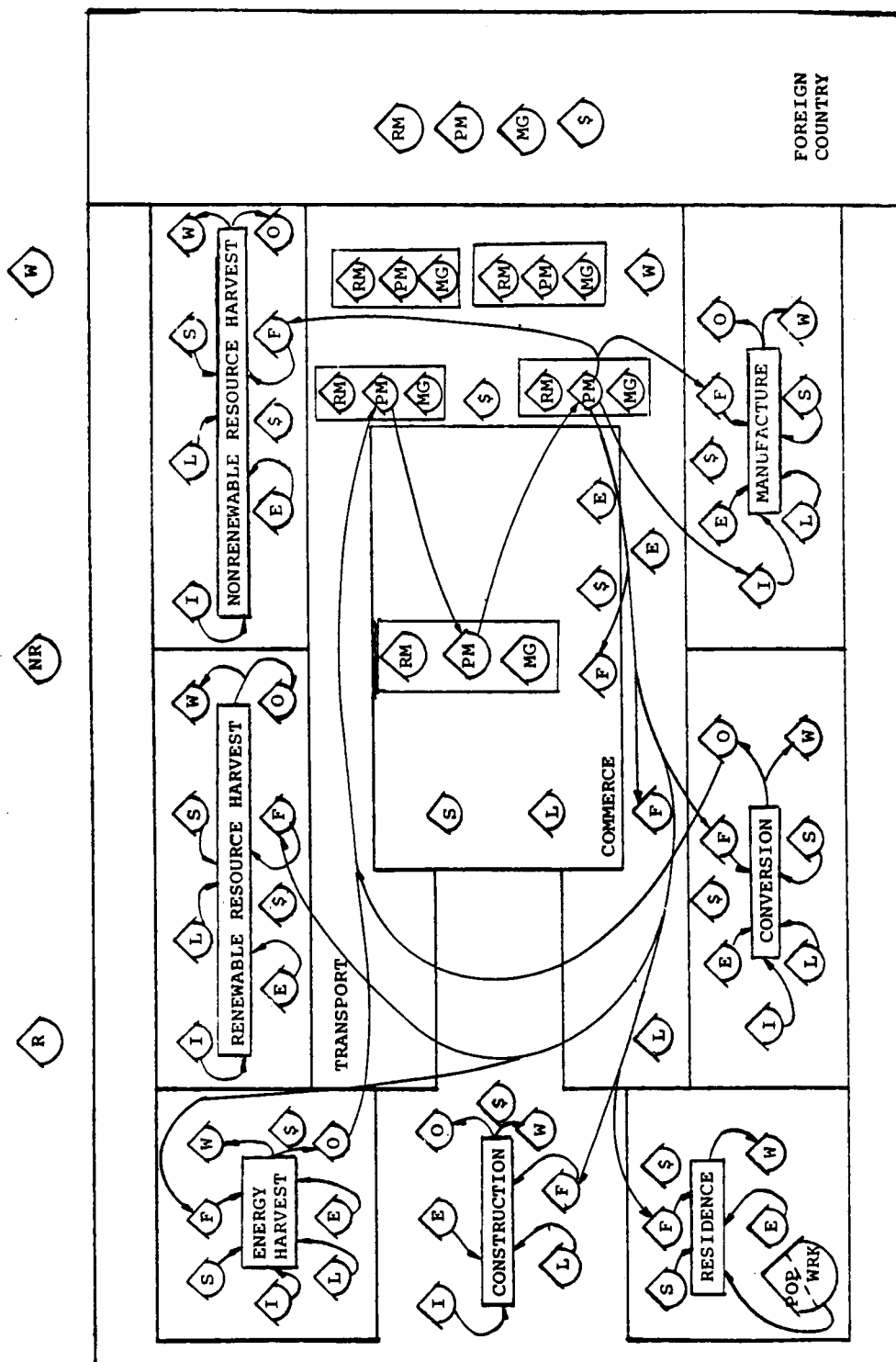


Figure 8. Processed Materials → Fuel, Manufactured Goods

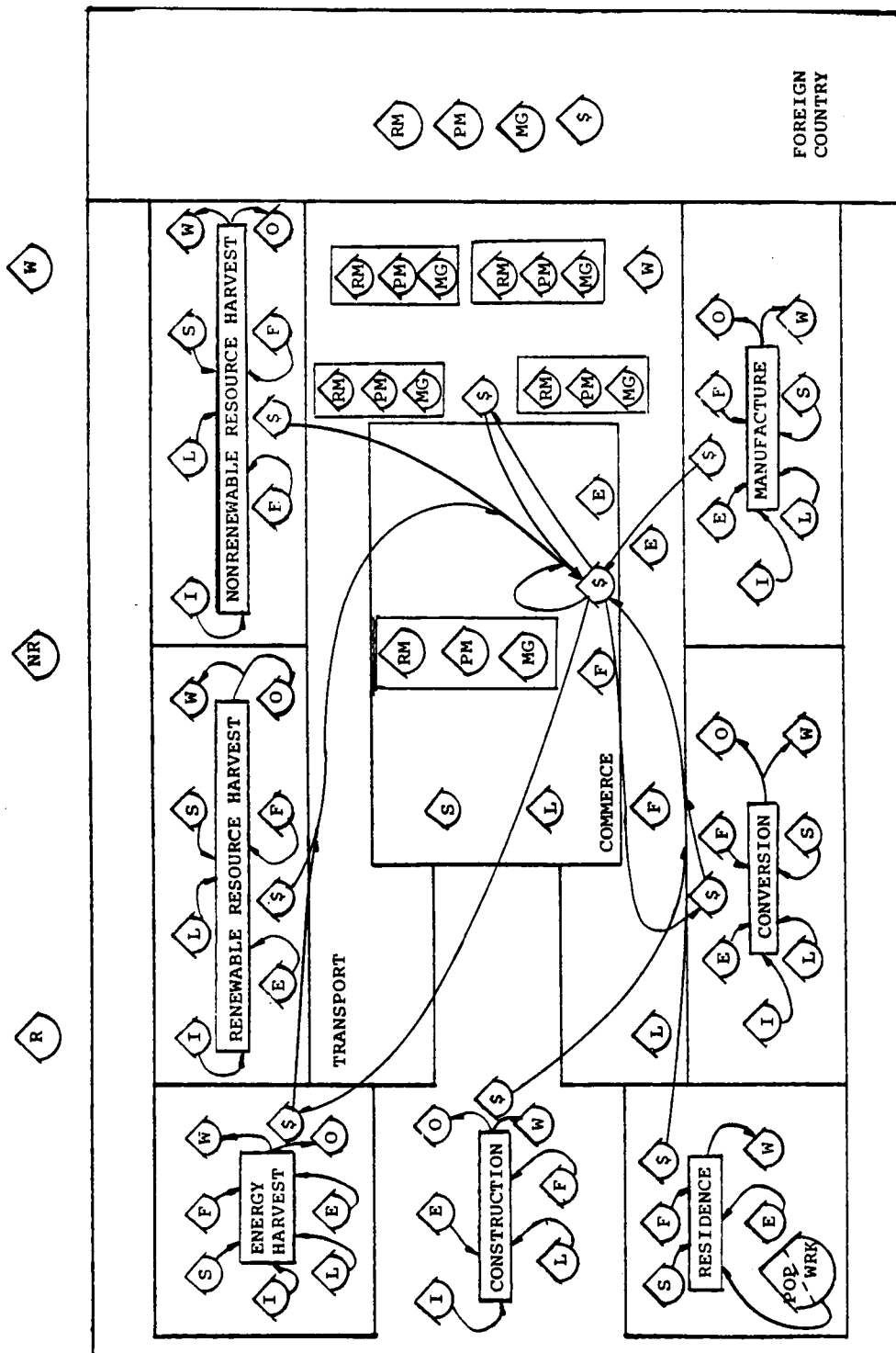


Figure 9. Processed Materials Payments

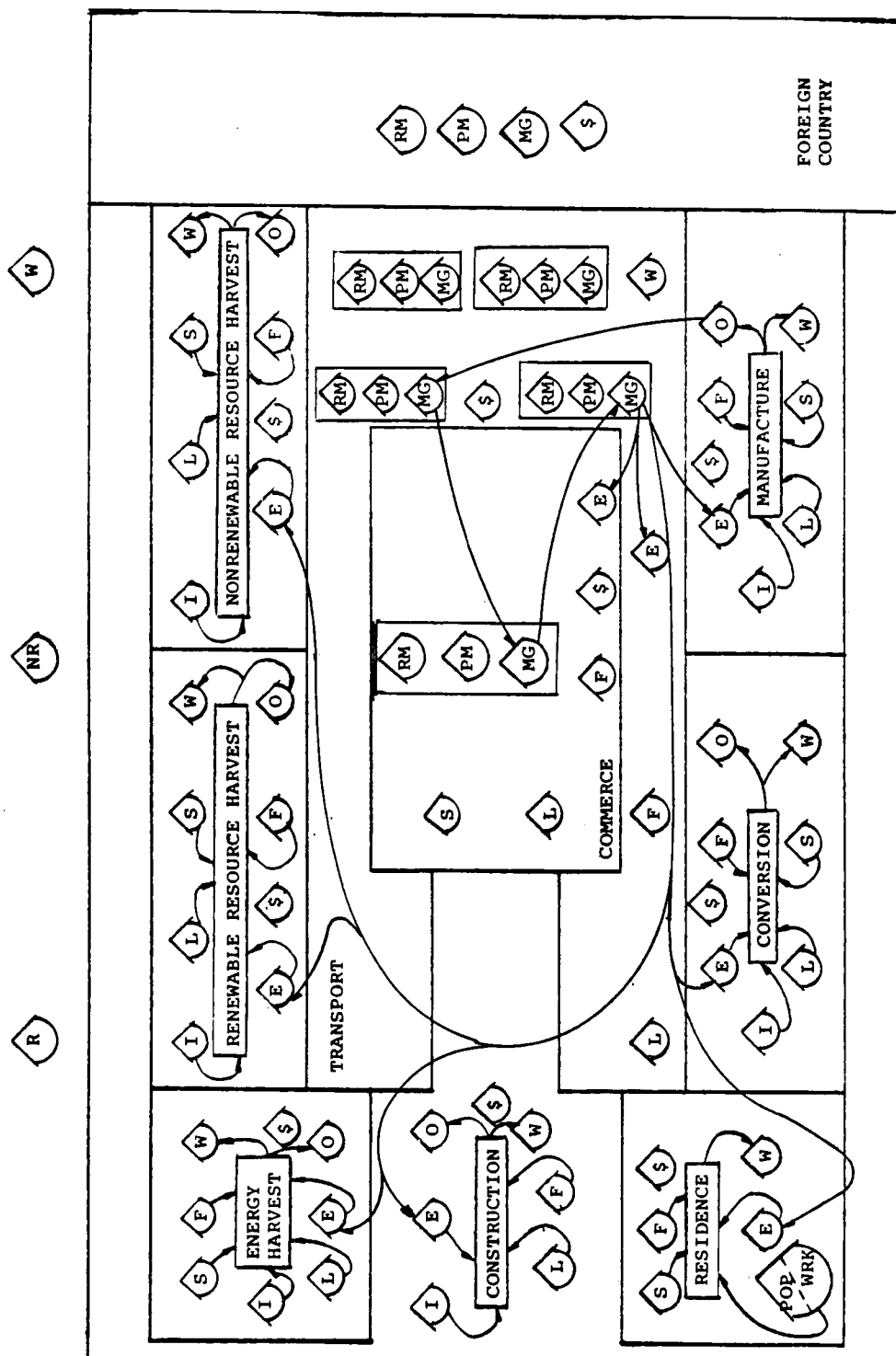


Figure 10. Manufactured Goods → Equipment

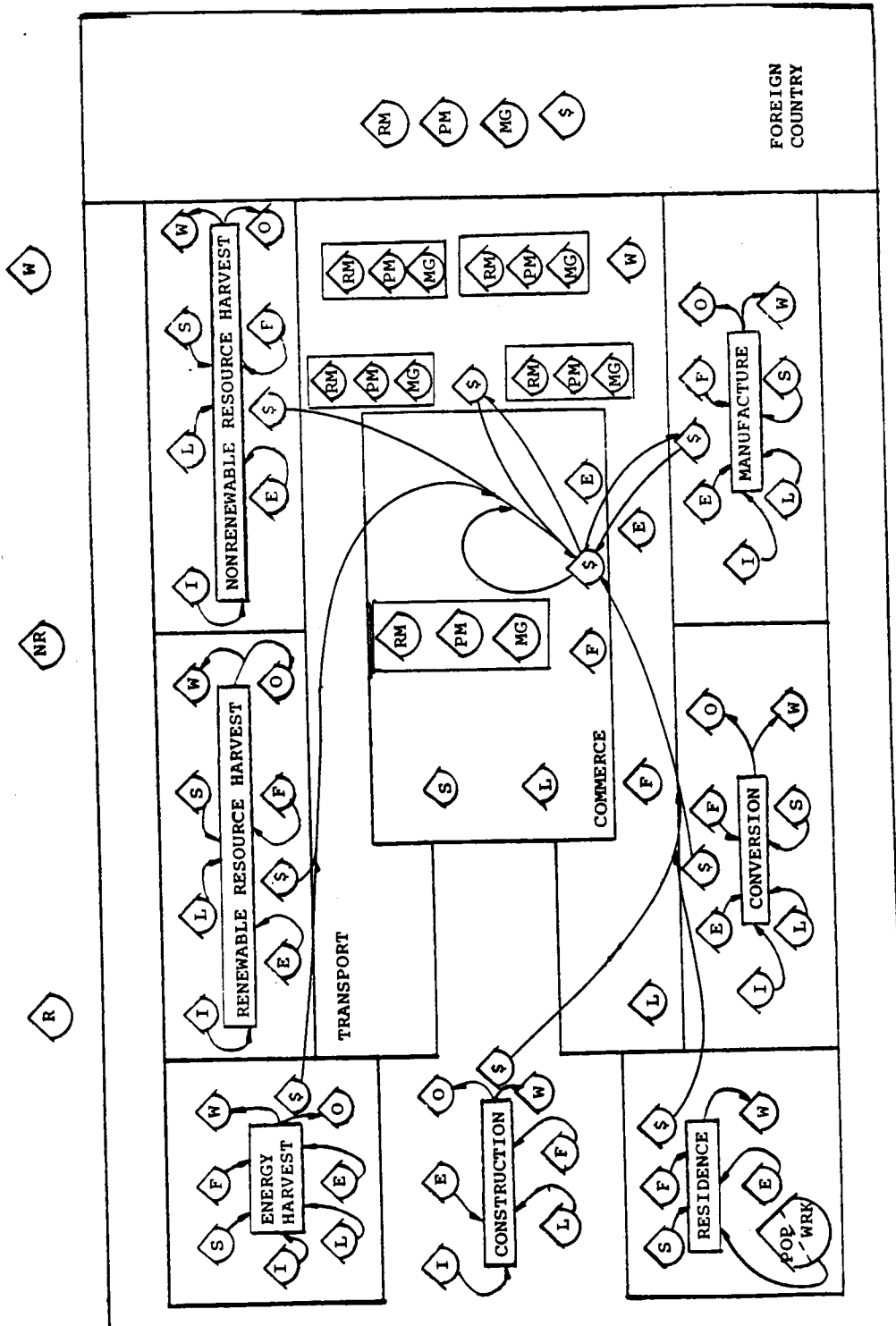


Figure 11. Manufactured Goods Payments

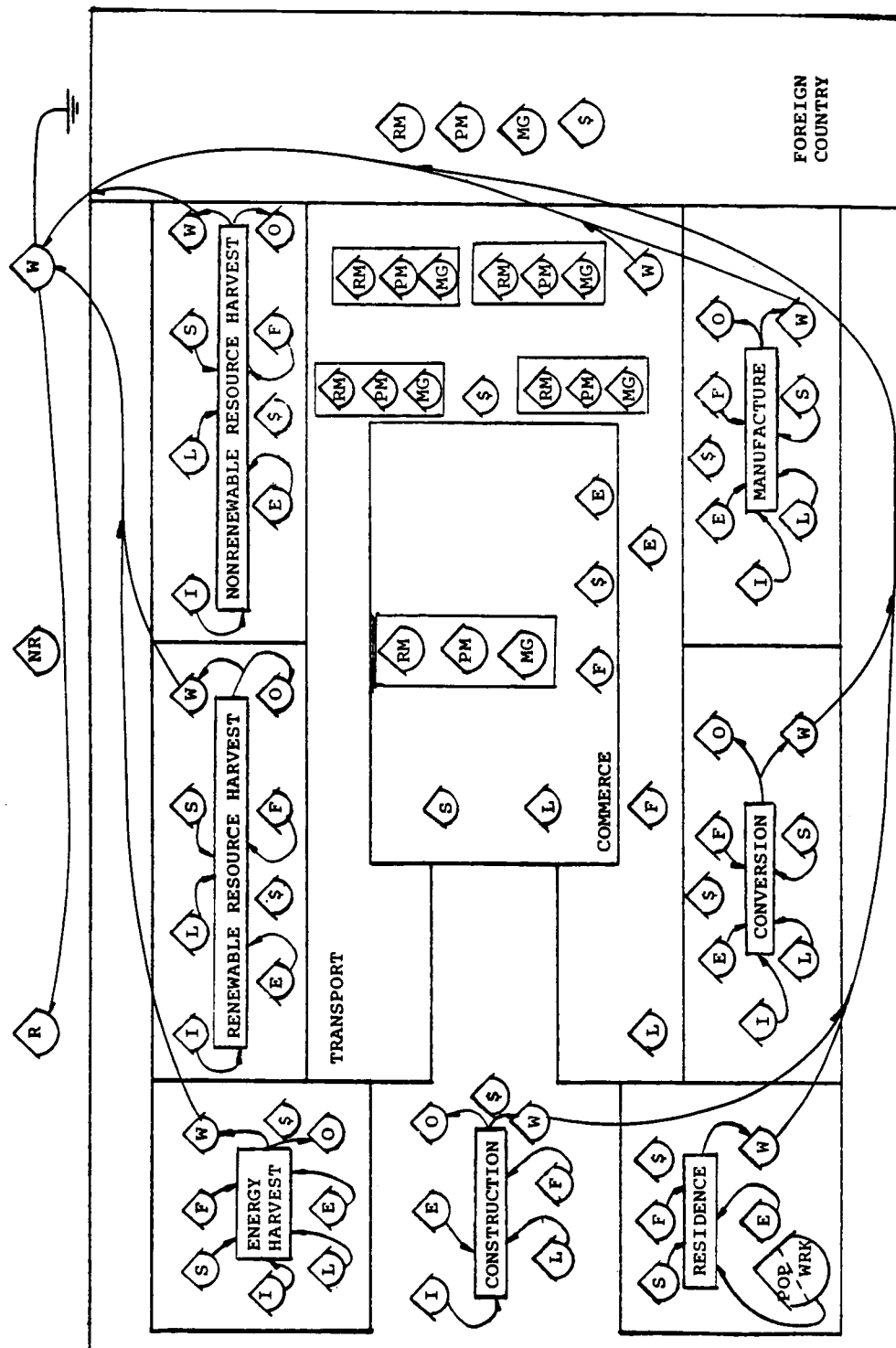


Figure 12. Waste Materials

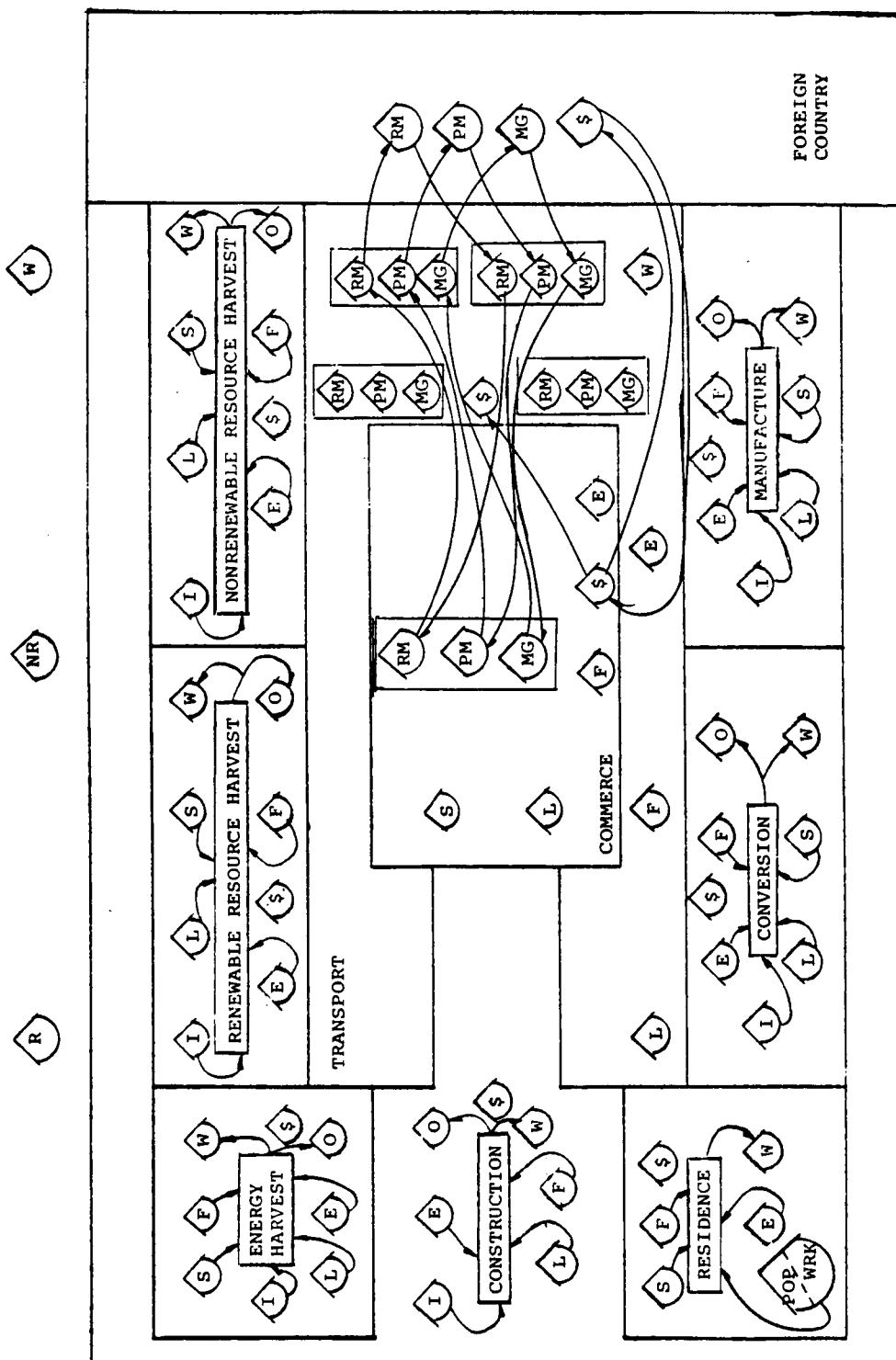


Figure 13. Import-Export

APPENDIX D

FORMAL LUMPED MODEL DESCRIPTION

The model is represented by the sequential machine

$$\langle \text{INPUTS}, \text{STATES}, \text{OUTPUTS}, \delta_h, \lambda \rangle$$

where

$$\begin{aligned} \text{INPUTS} &\subseteq X && (\text{RANGE } \alpha) \\ &\alpha \in \text{inputvariables} \\ \text{STATES} &\subseteq X && (\text{RANGE } \beta) \\ &\beta \in \text{statevariables} \\ \text{OUTPUTS} &\subseteq X && (\text{RANGE } \gamma) \\ &\gamma \in \text{outputvariables} \end{aligned}$$

$$X(\text{RANGEa}) = (\text{RANGEa})_1 X(\text{RANGEa})_2 X \dots X(\text{RANGEa})_i \dots$$

$$\text{inputvariables} \subseteq \text{descriptivevariables}$$

$$\text{statevariables} \subseteq \text{descriptivevariables}$$

$$\text{outputvariables} \subseteq \text{descriptivevariables}$$

$$\text{Transition Function : } \delta_h : \text{STATES} \times \text{INPUTS} \rightarrow \text{STATES}$$

In all sectors:

$$\text{Assets}_{t+1} := \text{Assets}_t + \text{Income}_t - \text{Payments}_t$$

In Commerce sector:

$$\begin{aligned} \text{Raw Materials}_{t+1} &:= \text{Raw Materials}_t \\ &\quad + \text{Transport.to commercial.RM}_t \\ &\quad + \text{Transport.from foreign.RM}_t \\ &\quad - \text{Transport.from commercial.RM}_t \\ &\quad - \text{Transport.to foreign.RM}_t ; \\ \text{Processed Materials}_{t+1} &:= \text{Processed Materials}_t \\ &\quad + \text{Transport.to commercial.PM}_t \end{aligned}$$

$$\begin{aligned}
 & + \text{Transport.fromforeign.PM}_t \\
 & - \text{Transport.fromcommercial.PM}_t \\
 & - \text{Transport.toforeign.PM}_t ; \\
 \text{Manufactured Goods}_{t+1} & := \text{Manufactured Goods}_t \\
 & + \text{Transport.tocommercial.MG}_t \\
 & + \text{Transport.fromforeign.MG}_t \\
 & - \text{Transport.fromcommercial.MG}_t \\
 & - \text{Transport.toforeign.MG}_t ;
 \end{aligned}$$

In Residence sector:

$$\begin{aligned}
 \text{Population}_{t+1} & := \text{Population}_t \\
 & * (1 + \text{birthrate}_t - \text{deathrate}_t) ;
 \end{aligned}$$

In Foreign Country:

$$\begin{aligned}
 \text{Raw Materials}_{t+1} & := \text{Raw Materials}_t \\
 & + \text{Foreign.import.RM}_t \\
 & - \text{Foreign.export.RM}_t ; \\
 \text{Processed Materials}_{t+1} & := \text{Processed Materials}_t \\
 & + \text{Foreign.import.PM}_t \\
 & - \text{Foreign.export.PM}_t ; \\
 \text{Manufactured Goods}_{t+1} & := \text{Manufactured Goods}_t \\
 & + \text{Foreign.import.MG}_t \\
 & - \text{Foreign.export.MG}_t ;
 \end{aligned}$$

In General System Parameters:

$$\begin{aligned}
 \text{Nonrenewable Resources}_{t+1} & := \text{Nonrenewable Resources}_t \\
 & - \text{Nonrenewables.Input}_t \\
 & - \text{Energy.Input}_t ;
 \end{aligned}$$

$$\begin{aligned} \text{Renewable Resources}_{t+1} &:= \text{Renewable Resources}_t \\ &\quad + \text{Recyclerate} \\ &\quad \quad * \text{Waste materials}_t \\ &\quad - \text{Renewables.Input}_t \\ &\quad - \text{Energy.Input}_t \end{aligned}$$

$$\begin{aligned} \text{Waste materials}_{t+1} &:= \text{Waste materials}_t \\ &\quad - \text{Recyclerate} * \text{Waste materials}_t \\ &\quad + \text{SUM}_{\text{sectors}} (\text{Waste materials}_t); \end{aligned}$$

Output Function : λ : STATES X INPUTS $\rightarrow$ OUTPUTS

In all sectors:

(sector $\langle \rangle$ Transport, Commerce,
Residence, Foreign Country)

$$\begin{aligned} \text{Area}_t &:= \text{Sites}_t * (\text{Area per site}); \\ \text{Output}_t &:= (\text{Output per site}) * \text{Sites}_t; \\ \text{Input}_t &:= \text{Output}_t * (\text{Input per output}); \\ \text{Labor}_t &:= \text{Output}_t * (\text{Labor per output}); \\ \text{Equipment}_t &:= \text{Output}_t * (\text{Equipment per output}); \\ \text{Fuel}_t &:= \text{Equipment}_t * (\text{Fuel per equipment}); \\ \text{Structures}_t &:= \text{Sites}_t * (\text{Structures per site}); \\ \text{Waste materials}_t &:= \text{Fuel}_t * (\text{Waste per fuel}) \\ &\quad + \text{Input}_t * (\text{Waste per input}); \\ \text{Income}_t &:= \text{Output}_t * (\text{Money per output}); \\ \text{Payments}_t &:= \text{Input}_t * (\text{Money per input}) \\ &\quad + \text{Labor}_t * (\text{Money per labor}) \\ &\quad + \text{Equipment}_t * (\text{Money per equipment}) \\ &\quad + \text{Fuel}_t * (\text{Money per fuel}) \end{aligned}$$

+ Structures * (Money per structure);
t

In Transport sector:

to commercial:

Raw Materials := Renewables.Output
t t
+ Nonrenewables.Output ;
t
Processed Materials := Energy.Output
t t
+ Conversion.Output ;
t
Manufactured Goods := Manufacture.Output ;
t t

Output := Raw Materials
t t
+ Processed Materials
t
+ Manufactured Goods ;
t
Input := Output ;
t t

from commercial:

Raw Materials := Conversion.Input ;
t t
Processed Materials := Manufacture.Input
t t
+ SUM (Fuel) ;
sectors t
Manufactured Goods := SUM (Equipment) ;
t sectors t

Output := Raw Materials
t t
+ Processed Materials
t
+ Manufactured Goods ;
t
Input := Output ;
t t

to foreign:

Raw Materials := Foreign.import.RM ;
t t
Processed Materials := Foreign.import.PM ;
t t
Manufactured Goods := Foreign.import.MG ;
t t

$$\begin{aligned} \text{Output} &:= \text{Raw Materials} \\ &\quad + \text{Processed Materials} \\ &\quad + \text{Manufactured Goods} \end{aligned}$$

$$\text{Input} := \text{Output}$$

fromforeign:

$$\begin{aligned} \text{Raw Materials} &:= \text{Foreign.export.RM} \\ \text{Processed Materials} &:= \text{Foreign.export.PM} \\ \text{Manufactured Goods} &:= \text{Foreign.export.MG} \end{aligned}$$

$$\begin{aligned} \text{Output} &:= \text{Raw Materials} \\ &\quad + \text{Processed Materials} \\ &\quad + \text{Manufactured Goods} \end{aligned}$$

$$\text{Input} := \text{Output}$$

In all Transport:

$$\begin{aligned} \text{Output} &:= \text{tocommercial.Output} \\ &\quad + \text{fromcommercial.Output} \\ &\quad + \text{toforeign.Output} \\ &\quad + \text{fromforeign.Output} \end{aligned}$$

$$\text{Input} := \text{Output}$$

$$\text{Labor} := \text{Output} * (\text{Labor per output});$$

$$\text{Equipment} := \text{Output} * (\text{Equipment per output});$$

$$\text{Fuel} := \text{Equipment} * (\text{Fuel per equipment});$$

$$\begin{aligned} \text{Waste materials} &:= \text{Fuel} * (\text{Waste per fuel}) \\ &\quad + \text{Input} * (\text{Waste per input}); \end{aligned}$$

$$\text{Income} := \text{Output} * (\text{Money per output});$$

$$\begin{aligned} \text{Payments} &:= \text{Input} * (\text{Money per input}) \\ &\quad + \text{Labor} * (\text{Money per labor}) \end{aligned}$$

$$+ \text{Equipment} * (\text{Money per equipment})$$

$$+ \text{Fuel} * (\text{Money per fuel});$$

In Commerce sector:

$$\text{Area} := \text{Sites} * (\text{Area per site});$$

$$\text{Output} := \text{Transport.fromcommercial.Output} + \text{Transport.toforeign.Output};$$

$$\text{Input} := \text{Transport.tocommercial.Output} + \text{Transport.fromforeign.Output};$$

$$\text{Labor} := \text{Output} * (\text{Labor per output});$$

$$\text{Equipment} := \text{Output} * (\text{Equipment per output});$$

$$\text{Fuel} := \text{Equipment} * (\text{Fuel per equipment});$$

$$\text{Structures} := \text{Sites} * (\text{Structures per site});$$

$$\text{Waste materials} := \text{Fuel} * (\text{Waste per fuel}) + \text{Input} * (\text{Waste per input});$$

$$\text{Income} := \text{Output} * (\text{Money per output});$$

$$\text{Payments} := \text{Input} * (\text{Money per input}) + \text{Labor} * (\text{Money per labor}) + \text{Equipment} * (\text{Money per equipment}) + \text{Fuel} * (\text{Money per fuel}) + \text{Structures} * (\text{Money per structure});$$

In Residence sector:

$$\text{Workforce} := \text{Population} * \text{laborforce};$$

$$\text{Area} := \text{Sites} * (\text{Area per site});$$

$$\text{Equipment} := \text{Sites} * (\text{Equipment per site});$$

$$\text{Fuel} := \text{Equipment} * (\text{Fuel per equipment});$$

```

Structures := Sites * (Structures per site);
Waste materials :=  $\sum_t$  Fuel * (Waste per fuel)
                  +  $\sum_t$  Input * (Waste per input);
Income :=  $\sum_t$  sectors (Money per labor);
Payments :=  $\sum_t$  Equipment * (Money per equipment)
            +  $\sum_t$  Fuel * (Money per fuel)
            +  $\sum_t$  Structures * (Money per structure);

```

In Foreign Country:

```

Output :=  $\sum_t$  (Foerign.export );
Input :=  $\sum_t$  RM,PM,MG (Foreign.import );
Income :=  $\sum_t$  Output * (Money per output);
Payments :=  $\sum_t$  Input * (Money per input);

```

For readability, the following abbreviations are used:

RM	Raw Materials
PM	Processed Materials
MG	Manufactured Goods
SUM	Summation function

APPENDIX E

DATA STRUCTURES

Data structures are described in declaration statements of the Pascal programming language.

Data Types

TYPE

charset=SET OF CHAR;

(* State Record Types *)

```
totalrecord=RECORD
    sites, input, output, wastematerials,
    labor, equipment, fuel,
    structures, assets,
    income, payments : REAL
END; (* totalrecord RECORD *)
```

```
pricerecord=RECORD
    input, output,
    labor, equipment, fuel,
    structures : REAL
END; (* pricerecord RECORD *)
```

```
traderecord=RECORD
    rawmaterials,
    procmaterials,
    mangoods : REAL
END; (* traderecord RECORD *)
```

```
sectorrecord=RECORD
    (* Descriptive Variables*)
    total : totalrecord;

    (* Internal Flow Parameters *)
    price : pricerecord;

    lifetime : RECORD
        equipment, structures : REAL
    END;

    areapersite, strucpersite,
    outputpersite, inputperoutput,
    laborperoutput, equipmentperoutput,
    fuelperequipment,
    fuelwaste, inputwaste : REAL
```

```

        END; (* sectorrecord RECORD *)

quanta=RECORD
    resources : RECORD
        renewable, nonrenewable : REAL
    END;
    landarea, waterarea : RECORD
        used, unused : REAL
    END;
    atmosphere, wastematerials,
    renewalrate, entropyfactor,
    laborforce : REAL
END; (* quanta RECORD *)

staterecord=RECORD
    harvrenew, harvnonrenew,
    harvenerg, conversion,
    manufacture, construction : sectorrecord;

    transport:RECORD
        (* Descriptive Variables *)
        tocommercial,
        fromcommercial,
        toforeign,
        fromforeign : traderecord;

        total: totalrecord;

        (* Internal Flow Parameters *)
        price : pricerecord;

        lifetime:RECORD
            equipment:REAL
        END;

        outputpersite,
        laborperoutput,
        equipmentperoutput,
        fuelperequipment,
        fuelwaste:REAL
    END;

    commerce:RECORD
        (* Descriptive Variables *)
        stocks:traderecord;

        total: totalrecord;

        (* Internal Flow Parameters *)
        price: pricerecord;

        lifetime:RECORD

```

```

        equipment,
        structures:REAL
    END;

    areapersite, strucpersite,
    laborperoutput,
    equipmentperoutput,
    fuelperequipment,
    fuelwaste, inputwaste:REAL
END;

residence:RECORD
    (* Descriptive Variables *)
    total:RECORD
        sites, wastematerials,
        equipment, fuel,
        structures, assets,
        income, payments : REAL
    END;

    population, workforce:REAL;

    (* Internal Flow Parameters *)
    price:RECORD
        equipment, fuel,
        structures:REAL
    END;

    lifetime:RECORD
        equipment,
        structures,
        people:REAL
    END;

    areapersite, strucpersite,
    equipmentpersite,
    fuelperequipment,
    fuelwaste,
    birthrate, deathrate:REAL
END;

foreigncountry:RECORD
    (* Descriptive Variables *)
    import,
    export,
    stocks:traderecord;

    total:RECORD
        input, output,
        wastematerials,
        assets,
        income,

```

```

                                payments:REAL
                                END;

                                (* Internal Flow Parameters *)
                                price:RECORD
                                    input,
                                    output:REAL
                                END
                                END;

                                total : quanta;

                                time : INTEGER
                                END; (* staterecord RECORD *)

                                statepointer=^staterecord;

                                (* Model Selection Types *)
                                names=(rharv,nharv,eharv,
                                    conv,manf,cons,
                                    tran,comm,resi,forc);

                                valptr=RECORD
                                    CASE BOOLEAN OF
                                    TRUE:(val:INTEGER);
                                    FALSE:(ptr:statepointer);
                                END;

                                padlrec=RECORD
                                    offset:INTEGER;
                                    val,maxval:REAL;
                                    titl:STRING[25]
                                END;

                                (* Graphic Output Types *)
                                syms=(firstsym,
                                    boardnode,
                                    tank,warehouse,
                                    locusts,linegraph,
                                    scatternode,
                                    lastsym);

                                nodelink=^node;

                                node=RECORD
                                    next:nodelink;
                                    CASE item:syms OF

                                        tank,
                                        boardnode: (bcolr:COLOR;
                                                    fcolr:COLOR;
                                                    maxval:REAL);

```

```

warehouse: (bricks:INTEGER;
            nextx:INTEGER;
            nexty:INTEGER);

linegraph: (nextp:INTEGER);

locusts: (points:INTEGER);

scatternode: (xval:INTEGER;
              yval:INTEGER)
END; (* node *)

```

Variables

VAR

```

(* State-related Variables *)
  pixmode:BOOLEAN;
  quitime:BOOLEAN;
  singlestep:BOOLEAN;
  scrnchange:BOOLEAN;
  nowstate:statepointer;
  newstate:statepointer;
  startstate:statepointer;
  zerostate:statepointer;

(* Model Selection Variables *)
  scrnsec:names;
  runsteps:INTEGER;
  numpaddls:INTEGER;
  highpaddl:INTEGER;
  padltab1:ARRAY[0..toppadl] OF padlrec;

(* Graphics-related Variables *)
  avail:nodelink;
  board:ARRAY[0..maxcols,0..maxrows]
    OF nodelink;
  cols,sqrwid:INTEGER;
  rows,sqrht:INTEGER;
  scale:INTEGER;
  scalefactor:INTEGER;

```

APPENDIX F

ALGORITHMS

Algorithms are described as pseudo-Pascal language procedures.

Initialization

```
PROCEDURE bootup;
BEGIN
  Get new staterecord nodes for
    nowstate, newstate, startstate, zerostate;
  Create figures;
  Set graphics game board scale to 2;
  Clear all staterecord variables;
  Clear game board;
  Clear global variables for
    available graphics node list,
    output mode (pixmode, singlestep),
    padltabl array;
  Clear text and graphics screens;
END; (* bootup *)

PROCEDURE setup(VAR state: statepointer);
BEGIN
  CASE user input OF
    Change setup:
      Allow user to select, through menu hierarchy,
      the initial values of variables, or to specify
      input devices for desired input variables;
    Save state:
      Save the current model state on disk;
    Get state:
      Retrieve model state from disk (query user for
      file name);
    Run this setup:
      End setup and execute simulation;
  END; (* CASE *)
END; (* setup *)
```

State Transition

```
PROCEDURE transfn(VAR now,next: statepointer);
VAR
  last: statepointer;
```

```

BEGIN
  REPEAT
    next^.variable:=transition function(now^.variables)
  UNTIL (all desired time t+1 variables
        have been accounted for);
  last:=now; now:=next; next:=last;
END; (* transfn *)

```

Input Device Primitives

```

FUNCTION seekpad1(start:INTEGER):INTEGER;
(*
  Returns value of first button found pressed
*)
BEGIN
  Begin with button "start";
  REPEAT
    IF (button is pressed)
      THEN RETURN seekpad1:=(button pressed)
      ELSE scan next button MOD (no. of paddles attached)
  UNTIL found
END; (* FUNCTION seekpad1 *)

FUNCTION setoff(startrec:statepointer;
                VAR location:REAL):INTEGER;
(*
  Finds the address of "location" as an
  offset from the start of record "startrec"
*)
VAR
  result1,result2:INTEGER;
BEGIN (* setoff *)
  Set scan length:=length of startrec record;
  Set starting point:=first byte of startrec;
  Save contents of "location";
  REPEAT
    (* Put-look a '#' *)
    Put a '#' in the first byte of "location";
    result1:=(scan from starting point, counting bytes,
              until a '#' is found);
    (* Put-look a '%' *)
    Put a '%' in the first byte of "location";
    result2:=(scan from starting point, counting bytes,
              until a '%' is found);
  IF (result1=result2)
    THEN the scan has found "location"
    ELSE IF (scan length exceeded)
      THEN cancel search and print error message
      ELSE add the larger of (result1,result2)
           to starting point

```

```

UNTIL (result1=result2) or scan length exceeded;
Restore contents of "location";
IF found THEN RETURN setoff:=(total bytes counted)
      ELSE RETURN setoff:= -1
END; (* PROCEDURE setoff *)

```

Input Device Selection

```

PROCEDURE setpaddl;
(*
  Associates an input device (game paddle)
  with a program variable
*)
BEGIN
  Ask user to press button of paddle desired;
  paddl:=seekpadl(0);
  IF (offset of desired location) >= 0
  THEN BEGIN
    padltabl[paddl].offset:=
      (offset of desired location);
    padltabl[paddl].titl:=
      (string "title" of location);
    padltabl[paddl].maxval:=
      Query user for maximum value of location;
    Set location:=maximum value
      using padltabl[paddl].offset
    END
  ELSE WRITELN('Failed to set paddle')
END; (* setpaddl *)

```

Input Variable Selection

```

PROCEDURE inptfn(state:statepointer);
  VAR
    percent:REAL;
  BEGIN
    IF (there are paddles connected) THEN
      FOR (each paddle) DO
        IF (paddle is associated with a location) THEN
          BEGIN
            percent:=(paddle value)/(largest device value);
                                  (* usually 255 *)
            padltabl[paddle].val:=
              percent * padltabl[paddle].maxval;
            Set location:=padltabl[paddle].val
              using padltabl[paddle].offset
          END
        END
      END
    END; (* inptfn *)

```

Screen Graphics Primitives

```

PROCEDURE scaleboard(s:INTEGER);
BEGIN
  IF s IN [minscale..maxscale] THEN
    BEGIN
      scale:=s;
      scale
      scalefactor:=(2      );
      width of screen square:=
        (pixels per column) * scalefactor;
      height of screen square:=
        (pixels per row) * scalefactor;
      (* Calculate number of columns and rows of squares
         possible at this scale *)
      columns of squares:=
        (pixels across screen) / (width of square);
      rows of squares:=
        (pixels up screen) / (height of square)
    END
  (*
  Scaling Table:
                                minscale
  maxcols+1 = (scrnwid+1)/colunit*(2      )

                                minscale
  maxrows+1 = (scrnht +1)/rowunit*(2      )

  SO: minscale maxcols maxrows sqrwid sqrht
        0         39      31       7       5
        1         19      15      14      10
        2          9       7      28      20
        3          4       3      56      40
        4          1       1     112      80
        5          0       0     224     160

  *)
END; (* scaleboard *)

PROCEDURE initsquare(kind:syms;
                    c,r:INTEGER;
                    mx:REAL;
                    fc,bc:COLOR);
BEGIN
  (*
  Initializes board square (c,r) to be type "kind"
  --attaches node containing
    :maximum value
    :foreground color
    :background color
  *)

```

Get a boardnode;

(* Now get what lower node is required *)

CASE kind OF

tank: Change board node to tank node;

(* No lower node required *);

warehouse: BEGIN

Get a warehouse node and

point board node to it;

bricks:=0;

nextx:=c*sqrwid; nexty:=r*sqrht

END;

locusts: BEGIN

Get a locusts node and

point board node to it;

points:=0

END;

linegraph: BEGIN

Get a linegraph node and

point board node to it;

nextp:=c*sqrwid

END;

scatternode,

boardnode: (* No lower node required *);

END; (* CASE *)

Fill node square with background color
END; (* initsquare *)

Screen Graphics Routines

PROCEDURE pour(c,r:INTEGER;
value:REAL);

(*

Procedure to adjust type "tank" screen square
*)

VAR

ratio:REAL;

mid:INTEGER;

BEGIN

ratio:=value / node.maxval;

mid:=(Height of the square)*ratio;

CASE

(tank is full):

fill whole square with foreground color;

(tank is empty):

fill whole square with backbround color;

```

(anything else): BEGIN (* Adjust tank level *)
    Fill from mid to top
    with background color;
    Fill from bottom to mid
    with foreground color
END

END (* CASE *)
END; (* pour *)

PROCEDURE stackbricks(c,r:INTEGER;
    value:REAL);

(*
    Procedure to adjust type "warehouse" screen square
*)
VAR
    ratio:REAL;
    mid:INTEGER;

PROCEDURE addabrick; (* local *)
BEGIN
    Set the brick color to the foreground color;
    Paint a brick at (node.nextx,node.nexty);
    node.bricks:=node.bricks+1;

    (* Save where next brick will go *)
    IF (node.bricks < maximum)
    THEN BEGIN
        node.nextx:=node.nextx + (1 brick width);
        IF (No more room on this row)
        THEN BEGIN
            node.nextx:=
                (leftmost square position);
            node.nexty:=
                node.nexty + (1 brick height)
        END
    END
    ELSE node.bricks:=maximum
END; (* addabrick *)

PROCEDURE takabrick; (* local *)
BEGIN
    IF (node.bricks > 0)
    THEN BEGIN
        (* Save where next brick will go *)
        node.nextx:=node.nextx - (1 brick width);
        IF (No more room on this row) THEN
        BEGIN
            node.nextx:=(rightmost square position);
            node.nexty:=node.nexty - (1 brick height)
        END;

        Set the brick color to the background color;

```

```

        Paint a brick at (node.nextx,node.nexty);
        node.bricks:=node.bricks - 1
    END
    ELSE node.bricks:=0
END; (* takabrick *)

BEGIN (* stackbricks *)
    Calculate maximum bricks the square
    will hold at this scale;
    ratio:=value / node.maxval;
    mid:=(maximum bricks)*ratio;
    CASE
        (warehouse is full):
            WHILE (node.bricks < maximum) DO addabrick;
        (warehouse is empty):
            WHILE (node.bricks > 0) DO takabrick
        (need more bricks):
            REPEAT addabrick UNTIL (node.bricks >= mid);
        (need less bricks):
            REPEAT takabrick UNTIL (node.bricks <= mid)
    END; (* CASE *)
END; (* stackbricks *)

PROCEDURE swarm(c,r:INTEGER;
                value:REAL);

(*
    Procedure to adjust type "locusts" screen square
*)
VAR
    ratio:REAL;
    mid:INTEGER;

PROCEDURE addapoint; (* local *)
BEGIN
    Get a scatternode;
    Choose a random point within the node square;
    Save point coordinates in scatternode;
    Link node to the top of the list
    pointed to by board node;
    Set the spot color to the foreground color;
    Paint a spot at the random point;
    node.points:=node.points + 1
END; (* addapoint *)

PROCEDURE takapoint; (* local *)
BEGIN
    IF (there are points to take)
    THEN BEGIN
        Locate scatternode at the top of the list
        pointed to by boardnode;
        Set the spot color to the background color;
        Paint a spot at the scatternode point;
    
```

```

        Delete scatternode from the top of the list
        pointed to by board node;
        node.points:=node.points - 1
    END
END; (* takapoint *)

BEGIN (* swarm *)
    Calculate maximum points the square
    will hold at this scale;
    ratio:=value / node.maxval;
    mid:=(maximum points)*ratio;
    CASE
        (scatternode is full):
            WHILE (node.points < maximum) DO addapoint;
        (scatternode is empty):
            WHILE (node.points > 0) DO takapoint
        (need more points):
            REPEAT addapoint UNTIL (node.points >= mid);
        (need less points):
            REPEAT takapoint UNTIL (node.points <= mid)
    END (* CASE *)
END; (* swarm *)

PROCEDURE lineplot(c,r:INTEGER;
                  value:REAL);

(*
    Procedure to adjust type "linegraph" screen square
*)
VAR
    ratio:REAL;
    mid:INTEGER;

BEGIN
    IF (first point)
    THEN fill the whole square with the background color;
    IF (there's room to plot)
    THEN BEGIN
        ratio:=value / node.maxval;
        mid:=(height of square)*ratio;
        CASE
            (mid is too high):
                BEGIN
                    Set the spot color
                    to the background color;
                    Paint the spot
                    at (node.nexttp , top of the square)
                END;

            (mid is too low):
                BEGIN
                    Set the spot color
                    to the background color;

```

```

        Paint the spot
        at (node.nextp , bottom of the square)
    END;

    (anything else):
    BEGIN
        Set the spot color
        to the foreground color;
        Paint the spot
        at (node.nextp , mid)
    END
END; (* CASE *)
node.nextp:=node.nextp + 1
END (* IF *)
END; (* lineplot *)

```

Complete State Transition Loop

```

WHILE NOT(quitime) DO
    BEGIN
        (* Read all input devices and assign
        values to input variables *)
        inptfn(nowstate);

        (* Compute all time t functions *)
        instantfn(nowstate);

        (* Show time t state *)
        outptfn(nowstate);

        (* Compute time t+1 values *)
        transfn(nowstate, newstate);

        quitime:= (time t >= stopping point) OR
        (user interrupt)
        IF singlestep THEN wait
    END;
END;

```

VITA

Carl Richeson Gregory was born in Tallahassee, Florida on February 25, 1950. His family moved shortly thereafter to Champaign-Urbana, Illinois, and to Santa Barbara, California in 1955. He attended elementary school there and in Austin, Texas beginning in 1959. In Texas he was active in Scouting, receiving his Eagle badge in March 1965 and was inducted into the Order of the Arrow later the same year. He was graduated from Stephen F. Austin High School in June 1966, and entered the University of Texas in September 1966 in the Plan II program, a Liberal Arts Honors degree plan.

After studying computer programming, Mr. Gregory worked as a programmer for several departments at the University of Texas while an undergraduate, principally for Dr. C. Victor Bunderson at the Computer Assisted Instruction (CAI) Laboratory. He co-authored several technical reports and presented his work on a proposed pseudo-language for CAI authoring to the Association for the Development of Instructional Systems in Alberta, Canada in August 1969. He received his Bachelor of Arts degree with Honors in June 1972 and was initiated Phi Beta Kappa the next year.

Following graduation, the author worked as a programmer for Dr. Neal Armstrong in the Environmental Health Engineering Department at UT-Austin and as a drummer in

various local Austin bands. In January 1973 he entered the Graduate School of the University of Texas in Community and Regional Planning (CRP). As a graduate student he worked for the Council for Advanced Transportation Studies, designing a model of group decision-making with Chang-Yi David Chang and Arthur Friedman.

After completing the courses required for a Master of CRP degree, Mr. Gregory moved to Knoxville, Tennessee in October 1976 to work for Dr. Reynell Parkins in the Housing Research and Development Center of the University of Tennessee. He spent the summer of 1977 as a guest lecturer in the Department of Geography of National Taiwan University in Taipei, Taiwan. He was not successful at the Housing Center and failed to complete his Master's degree in CRP. He entered the Graduate School of the University of Tennessee in January 1979 and began study toward a Master of Science degree in Computer Science. This degree was awarded in March 1983.

The author is a member of the Association for Computing Machinery. He is currently employed by Gentleware Corporation of Knoxville, Tennessee.