ANALYSIS OF HIGHER EDUCATION MANAGEMENT SYSTEMS THROUGH THE USE OF DYNAMIC MODELING CONCEPTS

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CHAPTER I

INTRODUCTION

The problems currently facing higher education are tremendous. Evidence is available from all quarters of increasing dissatisfaction with both the processes and products of the Country's colleges and universities.

In a recent special Saturday Review article, entitled "Who Runs the University?", prepared in cooperation with the Committee for Economic Development, a group of leaders representing various facets of higher education, pinpointed a number of the problems (1). President Meyerson, of the University of Buffalo, painted the bleak picture of a nation whose people still failed to give proper weight to the humanities, whose outstanding professors seemed to be leaning more toward research and less toward teaching, and whose legislators and private donors, angered by student unrest, were curtailing funds vitally needed to meet increasing enrollments and burgeoning costs. Robert Powell, President of the National Student Association, argued eloquently for increased student influence in matters of internal governance, including faculty selection, promotion and retention, grading policies, and curriculum determination. William Roth, a University of California regent, spoke out for greater power to enable top administration officials to cope with the vise-like pressures converging at that level - between students, parents, faculty, industry, regents, and government officials. Not only is greater power needed, the administrators must also be flexible, politically keen, and capable of optimizing the use of available funds. Logan Wilson, President of the American Council on Education, criticized the diffusion of decision-making and lack of clear-cut authority characterizing many of the institutions of higher learning. John Millett, Chancellor of the Ohio Board of Regents, felt that the great challenge for the 1970's involved the establishment of new forms of governance which can preserve autonomy, resolve conflict and result in improved management of resources. Franklin Patterson, President of Hampshire College, sharply criticized most institutions for their failure to develop new patterns of association and cooperation between similar organizations. He felt that they tended to duplicate capital, instructional, and managerial costs, and that to survive, many schools must learn to pool their resources.

The broad-guage Saturday Review article, encompassing many forms of university problems, is only one of hundreds which have been written recently in varied publications. Similar views of university and outside groups were expressed in a special issue of the Oklahoma State University O'Collegian newspaper (2), a special report of the trustees of Editorial Projects for Education (3), a report on higher education of the Department of Health, Education, and Welfare (HEW) (4), a panel on State Planning and Coordination of Higher Education (5), a study by The Fund for the Advancement of Education (6), and many others.

While student unrest, campus governance, administrative power, educational objectives, and other vital topics are discussed with increasing frequency, the problem of spiraling costs and their management is apparently of universal concern. The sheer magnitude of present educational expenditures and the rapid rate of increase provide ample cause for concern. A recent U. S. Office of Education report estimated an increase in college and university enrollment from 6.9 million in 1967 to 9.4 million in 1977 (7). Costs were estimated to rise from $16.6 billion to $27.8 billion during the same period. During the 1960-1970 decade, enrollment in higher education doubled while costs quadrupled.

Arnold Reisman (8), Editor of the new _Educational Science Section Newsletter_ of the Operations Research Society of America, recently noted that the United States has 2,269,000 teachers in elementary and secondary schools and 833,000 faculty members in colleges and universities. It is estimated that 3,315,000 professions are directly or indirectly connected with the Country's total educational program, and that 67,646,000 persons are enrolled as students. Future expenditure projections indicate that the 1969-70 operating budget of $63.4 billion dollars will reach $87.4 billion by 1980. Personnel needs in elementary and secondary schools should reach 2,928,000 by 1980, and in higher education, the Ph.D. requirement should reach 763,000, increases of 29% and 60%, respectively. The estimated replacement value of the current national educational plant is over $500 billion, making it one of the most important sectors of the economy in magnitude as well as impact.

Considering the current magnitude and rising cost of education, coupled with student unrest and the economic slowdown, one might expect the current pressure for more effective cost control to be natural. Suggestions for attaining accountability are being received from all quarters. A recent sample of the potpourri of proposals includes: a _Forbes_ article, entitle "Wake Up, Cut Down or Die" (9); Amitai

Etzioni's (10) editorial, entitled "On the Art of University Pruning" in Science magazine; a Wall Street Journal discussion of the desirability of changing tenure provisions to cut costs (11); Frederick Terman's (12) interesting paper on the minimum economic size of undergraduate and graduate engineering programs; Business Week's description of the university consortiums formed in various regions to share faculty, audio classroom facilities, libraries, and other expensive components (13); and the provocative theories of George Pake (14), in his article, entitled "Wither United States Universities?".

While several proposals for change are made in the article by Pake, its major thrust involves the problem of effective management and cost control. Currently Vice-President of Xerox Corporation, the author acquired considerable university expertise through his experience as a student in university-run classes from the elementary level through the Ph.D., as a teacher at two universities, and in subsequent assignments as provost, then trustee of a major institution. In his opinion, the major management challenge concerns the inability of educational institutions to increase the teaching productivity of individual faculty members. In the face of rising salaries, decreasing teaching loads, escalating library and computer expenses, and faculty and student comments and demonstrations which threaten to reduce appropriations and donations, there are few direct incentives for administration, faculty, or students to reduce costs. Course and departmental proliferation, as well as actions causing negative public reactions, would be controlled more effectively, he feels, under a type of group incentive plan similar to a well-known college teacher retirement system. Under the plan, each person would obtain a specific number of shares, the value of each being a function of the total university appropriation. If course loads or class sizes are significantly reduced, or course proliferation occurs, the value of each share would drop. His thesis is that such a device would have a significant "damping" effect on spiraling costs and would improve the understanding of administrative problems by faculty and students.

While the myriad published solutions to the problems of higher education may or may not "fit" a particular institution's needs, a vital by-product of such thrusts is heightened interest in and pressure for management improvement. Education administration has long been a program area in colleges of education, and much work has been done in the development of organization theory and other subject matter, particularly as applied to administration of public elementary and secondary schools. During the past decade, however, a number of other groups have sought to apply the theories and practices of quantitative management to educational problems. In 1961, at the first joint meeting of the Operations Research Society of America and the Institute of Management Science, Platt (15) suggested that quantitative management tools be applied to education. Subsequent progress in their application has been rapid. Taft and Reisman (16) considered the utility of using systems analysis procedures to show how the various subsystems in a university are interrelated. They viewed the structure as a complex grouping of entwined dynamic subunits, rather than as a series of independent parts. Many other systems studies (to be discussed in the next chapter) have also been proposed. One group of investigators has utilized control theory to develop state-space models, while a sizable number have approached the problem from the viewpoint of decision-making through

Planning, Programming, Budgeting Systems concepts (PPBS), and smaller groups have recommended other approaches.

To date, none of the major systems approaches enjoy the status of being fully operational, tested and widely accepted. The mathematically based state-space models have been criticized as being unrealistically simplified to fit mathematical restrictions; Planning, Programming, Budgeting Systems have met with varying degrees of success; Leontieff Input-Output models have been denounced as inflexible and representative of past data; programming, inventory control, and other operations research tools have been condemned for possibly suboptimizing at the expense of over-all optimization, and management information systems have come under heavy fire because of the difficulties and expense connected with data acquisition.

Research Objectives

The tools listed above have been applied to total institutional analysis as well as to such areas as student enrollment prediction, student flow registration procedures, faculty, student and classroom scheduling, curriculum planning, institutional investment policy, maintenance resource allocation, personnel management, student services, academic productivity, analysis of university year-round operations, student attendance patterns, faculty distribution in a college, and other similar subsystems. The criticisms mentioned above have been most severe where attempts have been made to apply the concepts to total university units. Unrealistic simplification to fit mathematical limitations, data acquisition expense and difficulty, inflexibility, old or incomplete data, and other condemnations increased as the scope of educational systems studies expanded. Other difficulties, which will be discussed later, include the human relations problems involved in gaining the vital understanding and support of operating managers who control organizational data, the need for new types of data aimed toward control of operations rather than mere recording of past events, and a better understanding of educational organization problems by quantitative management analysts.

A formidable obstacle to effective educational system analysis is that of understanding the interrelationships involved at all levels, including subsystems of universities such as departmental units. Complications include the existence and impact of both formal and informal lines of communication, the relative effect of internal and environmental changes, difficulties involved in defining objectives and determining educational quality, and many other intangibles which combine to complicate the job of system improvement.

While no panacea exists which circumvents all of the difficulties involved, the objective of this research is to determine the applicability to and efficacy of the dynamic systems concepts developed by Forrester (17). It is felt that the equations and diagrams involved may engender a better understanding of educational systems than other analytical approaches, and the simulation procedures which play a key role in the procedure should pinpoint the critical planning and control areas. The concepts emphasize the information-feedback characteristics of organized activities and provide a procedure to study the means by which structure, amplification (through policies) and time delays (in decisions and actions) interact to influence the success of any enterprise. They permit an analysis of the flows of people, funds, materials, orders, and capital equipment, as well as the information flows and decision-making networks which tie them together. The two types of variables recognized are level and rate. Using an analogy taken from accounting, level variables are somewhat like balance sheets. They represent the system accumulations, which might include faculty, existing buildings and laboratories, funds, and such intangibles as faculty attitudes and reputation. Profit and loss statements are similar to the rate variables. They represent activity, and establish the rates at which the level variables are changing. They are the policies or decision-functions which cause the system to evolve. Also analogous would be a system of interconnected fluid storage tanks whose levels are controlled by a series of valves. Since such general basic concepts should be applicable to any type of organization, from the simplest unit organization to one as complex as a large university, this research has been conducted to demonstrate first the feasibility of using the concepts to model the structure of higher educational units, and then to utilize the models for sensitivity analyses designed to improve their organization and operation.

Plan of the Dissertation

An introduction to systems concepts and a history of their development will comprise the first section of the second chapter. Attention will then be given to current applications of the concepts to educational institutions. The chapter will close with an introduction to and evaluation of the major educational simulation models developed to date.

Following an introductory explanation of system dynamics principles in the opening section of Chapter III, a brief comparative analysis will be made of the compilers which can be used to simulate the models.

The first model will be constructed in Chapter IV. It will consist of an aggregative, broad-gauge model of a university structure. Because of the complexities involved in such a complex of unit organizations, the model will be restricted to only a few of the major interacting loops which are common to most institutions of higher learning. For example, the interactions of auxiliary enterprises such as food service, housing, parking, and others will not be considered because the loop interactions and resulting complexity would be prohibitive. The latter part of the chapter will comprise an introduction to the International Business Machines Corporation compiler - Continuous Systems Modeling Program (System/360 CSMP) - and its use as an analytical tool in conjunction with system dynamics models. Its efficacy will be tested by first running an analysis on the initial model, then checking it for sensitivity to specific variables.

To test the effectiveness of system dynamics in a unit organization, a university department will be modeled in Chapter V. While a number of intangibles are present, as in the university model, a more microscopic view will be obtained. The divisions considered include the student, staff, research, and quality sectors. The model will then be analyzed by CSMP.

The final chapter will consist of conclusions derived from the research and recommendations for further study.

CHAPTER II

DEVELOPMENT OF SYSTEMS CONCEPTS

Definition

During the past fifteen years, the term "systems" has gained such widespread use that it is now a part of almost every American's vocabulary. Unfortunately, the term has been used in different ways and applied to countless activities, resulting virtually in semantic chaos. For example, many managers and analysts use the terms "systems analysis", "operations analysis", "management analysis", "operations research", and others synonymously. Compounding the difficulty currently encountered is the fact that the term has been used in different ways for many years. Man has always tried to discover relationships between things and has long established procedures or systems to explain the relationships. For example, Plato and other philosophers contemplated and wrote about a system of society (18) (19); early astronomers wrote of the stellar system and the cosmos; and early Egyptian architects used an ingenious system of measurements to construct the pyramids (20) (21). Modern examples are also commonplace. Subway systems, school systems, and air defense systems are but a few of an almost infinite number (22)-(26).

Challenging even to many engineers whose work is closely allied with systems is the role of control and communication theory. The information theory developed by Claude Shannon (27), an eminent electrical engineer, and the communication and control theories of Norbert Wiener (28), an outstanding mathematician, are so abstruse that only a small fraction of those interested in systems analysis have studied them in detail, yet they are often referred to as basic to the systems field. For example, the work in cybernetics of Wiener and the electrical engineering control theory research of Forrester at the Massachusetts Institute of Technology formed the background for Industrial Dynamics, the interesting new approach to systems analysis utilized in this dissertation for modeling. Based on feedback systems, simple concepts can be used to explain the rudiments of the approach (29). Ordinary concepts like a thermostat controlling a home furnace, a person driving an automobile, or a manufacturing company seem to have little in common. On closer review, however, they do have one single identifying similarity. Each represents an information feedback system in which a stimulus - the temperature, another car, a change in orders - causes a reaction. The reaction, in turn, affects the stimulus. The change in the stimulus then creates a further reaction. The process is one of continual interplay and adjustment, as information flows back and forth within the system.

Each of the three examples cited is a closed loop information system, in which one action creates a reaction which modifies the first action. The thermostat, when the temperature drops below a certain level, switches on a furnace. When the furnace brings the temperature up to the desired level, the thermostat turns the furnace off. The man driving down the street "automatically" reacts when his car deviates from the speed or direction he desires, and his reaction corrects the deviation.

Manufacturing companies and other organizations follow much the same pattern, except that their reaction time is much slower. A rise in orders will call forth a reaction within a business, for example, but it may take weeks to occur because so many factors and so many people are involved. The necessary information needed by each actor to make correct decisions about the action to be taken has a time lag factor much longer than that present in the case of the man driving down the street. The man can react almost instantaneously; the corporate enterprise will take much longer. Yet, both are dynamic; both do react to stimuli which they, in turn, modify. Study of the modification and interaction process through System Dynamics principles represents a unique and hopefully valuable tool in all systems studies.

Another major area involved in the semantics morass surrounding systems concepts is that of management principles or organization theory. Even those familiar with the field have difficulty defining the lines of demarcation between traditional and systems concepts. Many writers have attempted to develop general theories concerning the relationships involved in organized human activity. Among classical or traditional theorists were Weber (30) and his work on bureaucracy, Fayol (31) and his general management theory, Emerson (32) and his principles of efficiency, Mooney and Reiley (33) and their work on the division of authority and responsibility, and Taylor's (34) theory of shop management. Later, a human relations school of organizational behavior developed following the pioneering effort of Roethlisberger and Dickson (35).

The views of the traditionalists and humanists were brought together by Chester I. Barnard (36), one of the most respected (and quoted) authors in the organization theory field. Writing in the 1930's after thirty years of top-level management experience, he welded the structural concepts of the past to the human relations view which recognized the organization as a system whose efficacy depended greatly on formal, informal, and intergroup relationships.

Rensis Likert (38) later associated the human relations model with systems concepts. Herbert Simon (39) and James March (40) stressed the importance of the decision-making process within an organization, Talcott Parsons (41) and William Scott (42) helped to usher in the modern interlinking of organization and systems concepts, and Van Court Hare (43), Richard Johnson (44), and Stanford Optner (45) efficiently combined theory with contemporary practice.

Although some difference of opinion still exists concerning the exact nature and meaning of systems and their relationship with the areas listed, a pattern of understanding is currently emerging. One of the best publications available for a composite current view of definitions in the field is the paper entitled "The Future of Systems and Industrial Engineering," by Croft and Eldin (46). They state that a system is an array of components designed to accomplish a particular objective according to plan.

Another systems area currently involved in some confusion is that called "total systems". Numerous authors have discussed the concept, usually defining it only in a broad sense or merely citing examples of military and airline installations where a series of subsystems have been interlocked for effective over-all coordination (47)-(50). A more precise definition is given by Eldin (51):

> The complete monitoring of an enterprise by groups of interconnected computers; the automatic control by the machine of inventories, production scheduling, shipping, payroll and other operations that can be reduced to mathematical

> representation and the limiting of direct human control to such functions as setting over-all objectives and reacting to totally unexpected situations.

While many organizations may never achieve a total system under the above definition, a number of writers consider the objective to be a desirable one (52)-(56).

Educational Applications

While semantic difficulties have plagued the systems concept and severe technical problems have hampered its implementation, the desirability of utilizing modern quantitative tools to thoroughly analyze all facets of a problem is gaining widespread recognition. The high costs concomitant with computer operations, the difficulties sometimes involved in fitting mathematical equations to specific realistic problems, the stochastic nature of some events which precludes precise solutions, and many other difficulties have presented impediments to systems analysis but have not appreciably slowed their application to the myriad problems of modern education. An effective catalyst for such efforts was provided at a 1961 joint meeting of the Operations Research Society of America and the Institute of Management Science, when Platt (15) recommended that quantitative tools be applied to education.

Aided by progress in control theory, computer hardware and software, operations research, simulation and industrial experimentation, and spurred by the magnitude and urgency of the problems facing education, an ever-increasing number of systems analysts are attempting to improve the operations of educational systems. Representing a large number of disciplines and employed by a variety of organizations including universities, consulting firms, and various levels of government, they have studied problems ranging from departmental unit organizations to complete universities and their environmental interactions. Strong institutional support has also been extended by many organizations. Several of the more prominent include the U. S. Office of Education, the American Council on Education (representing the National Association of State Universities and Land-Grand Colleges, The American Association of State Colleges and Universities, The Association of American Colleges, The Association of American Universities, and The American Association of Junior Colleges), The National Science Foundation, The Ford Foundation, The Operations Research Society of America, the Institute of Management Science, The Western Interstate Commission for Higher Education, The American Association of School Administrators, and the recently formed International Society of Educational Planners.

Educational institutions have also been vitally interested. For example, The University of California, operating as an active member of the Western Interstate Commission for Higher Education (WICHE), has contributed significantly to current research concerned with the management of university systems and effective resource allocation. Under University and Ford sponsorship, the Office of the Vice President - Planning and Analysis - has sponsored far-ranging investigations (56)-(80).

While California and the WICHE group have already achieved a position of eminence in university systems analysis, many other institutions are becoming active. One is the Systems Research Group at the University of Toronto. Under the leadership of Judy and Levine (81) (82), they developed the flexible and well-known comprehensive simulation model called "Comprehensive Analytic Methods for Planning in University Systems" (CAMPUS), which is already being adapted to community colleges, state systems, colleges with completely individualized instruction, and to elementary and secondary school systems. Further work there has resulted in a newer version, CONNECT/CAMPUS, which is the most detailed of the straightforward resource-costing models currently available, and other advances (83)-(84).

Significant progress in the analysis of educational systems has also been made at a number of other universities. Those most active include The University of Pittsburgh (85)-(92), Pennsylvania State University (93)-(98), Iowa State (99)-(102), Michigan State (103)-(105), Ohio State (106)-(116), Florida State (117), The University of Texas at Austin (118), Rennsselear (119) (120), Virginia Polytechnic Institute (121)-(124), The University of Minnesota (125) (127), Stanford (128), Louisiana State (129), Carnegie Tech (130), and Purdue (131).

Other groups are also making significant contributions. One very important organization previously referred to is the Western Interstate Commission for Higher Education (WICHE). Consisting of thirteen western states, with headquarters at Boulder, Colorado, the group has focused on such objectives as: to increase educational opportunities for westerners, to expand the supply of specialized manpower in the West, to help universities and colleges improve both their programs and their management, and to inform the public about the needs of higher education. The organization has already had considerable impact on educational efforts through its sponsorship of conferences and clinics, its cooperation and joint sponsorship of studies with the American Council on Education and various government agencies, the dissemination of useful information among its members, the publication of numerous proceedings and special papers on a variety of topics, including management information systems to aid budget and facilities officers (132), and a classification structure to aid the exchange of information between educational institutions (133).

Not previously mentioned are other major non-profit organizations interested in the area; they include: The Department of Health, Education, and Welfare (HEW) (134), the Organization for Economic Cooperation and Development (OECD) (135), The Western Association of College and University Officers (136), The American Association of Collegiate Registrars and Admission Officers (AACRAO) (137) (138), and the Rand Corporation (139).

A number of profit-oriented organizations have also invested significant time and manpower in an effort to improve the management of educational institutions. Among the most active are the Systems Research Group of Toronto (140), Peat, Marwick, Mitchell and Company of New York (141)-(145), Cresap, Moore, and Padgett of New York, Isaacs-Dobbs Systems Incorporated of Los Angeles, and Management-Computer Interlock, Incorporated of Houston.

As was mentioned earlier, the efficacy of extensive efforts by management scientists in all areas is a function of the understanding and support accorded by the college and university administrators. Time and training, coupled with exogenous pressures, will gradually secure their support. Implementation of the concepts in the administration of elementary and secondary education also needs the support of teachers and administrators. The speed with which such support is acquired depends somewhat on the understanding and acceptance of the concepts by education college faculties and the authors of their textbooks. Fortunately, their current texts and individual pronouncements indicate a heightened interest. Revisions of established texts are now including sections on the subject and a number of new books are entirely devoted to one or more facets of systems science (146)-(153).

Systems concepts are also being included in many of the textbooks devoted to other phases of educational administration. For example, it is mentioned in several sections of the new two-volume _Handbook on Administration_, edited by Knowles (152), in a new text by Neagley, Evans, and Lynn (153), and in the second edition of the Morphet, Johns (148) text on educational organization and administration.

In summary, it appears that modern systems concepts will be applied to the problems of educational administration at a rapidly increasing rate in the future. New advances are being made by those trained in the sciences and those responsible for implementation are apparently adopting the concepts with alacrity. While considerable energy and wisdom will be required to overcome the many physical and human obstacles involved, administrative practices at all levels of education should undergo a remarkable transformation during the 1970's.

Systems Simulation

A number of the tools of management science already have been applied to educational systems. Some, like PPBS, PERT-CPM and decision theory, have been mentioned. A more complete list would include control theory, inventory theory, linear, quadratic and dynamic programming, engineering economic analysis, organization theory, applied statistics, methods analysis and standards, queueing principles, Markov chains, matrix theory, Leontieff input-output analysis, computer technology, and facilities design. The procedures have been applied to different segments of the systems and have met with varying degrees of success. PPBS, for example, has been praised by some as an aid to planning and condemned by others as unduly complicated. PERT-CPM has enjoyed success for project management activities, but does not fit many of the on-going day-to-day problems faced by administrators. Linear and other mathematical programming tools have been criticized for not fitting realistic problems. Queueing, inventory theory, and other methods have been accused of suboptimizing or being too narrow in scope. To avoid some of the criticism and to permit more accurate broad-gauge analyses, systems simulation has become increasingly popular in educational administration. A number of small-scale models have been developed to handle specific fragments of an institution, but the number of effective comprehensive models is small. One of the earliest and best known is CAMPUS which was developed at the University of Toronto by Judy and Levine (82). Another is CSM (Cost Simulation Model) developed at the University of California by Weathersby. Based on the CSM model, Mathematica later developed RRPM (Resource Requirements Prediction Model) for WICHE. Also well-known is the model developed at Michigan State University by Koenig (103), called the "Systems Model for Management, Planning, and Resource Allocation in Institutions of Higher Education." More limited in scope, but also well-known are CAP:SC (Computer Assisted Planning for Small Colleges), developed by the consulting firm of Peat, Marwick, Livingston, and Company, and the Tulane University Model.

The CAMPUS model was developed at a cost of over a million dollars, and its successor, CONNECT/CAMPUS is one of the most flexible and widely used systems. Work has been done to utilize it not only in larger universities, but also in small community colleges and elementary and secondary schools. While such a complete system tends to require considerable quantities of expensive data, the problem has been reduced somewhat through the utilization of data normally available in most institutions. The RRPM contains less detail than CAMPUS and is directed more toward institutional finances and costs. Like CAMPUS, it is currently being tested in a number of institutions. It is also designed to use data which are generally available. The Koenig model is less flexible than CAMPUS or RRPM and does not quantify measures of output other than costs and the number of student degrees completed. Designed to operate for a nine year planning period, the Tulane model is most useful for resource costing purposes, particularly in the area of faculty costs based on student enrollment. It is not good for decisions concerning optimal resource allocation, however, because it contains no structure to evaluate the interrelationship of its variables and the impact of exogenous inputs. CAP:SC also has no structure to evaluate variable interrelationships, hence, a larger number of expensive computer runs must be made for the decision-making process. It is also relatively inflexible, but contains a sufficient level of aggregation to make it a potentially useful long-range planning tool for small colleges.

Unfortunately, none of the models consider the major outputs of educational institutions and none seem to combine such features as flexibility, suitability for both over-all and subunit analysis, ability to evaluate the interrelationship of endogenous and exogenous variables, and moderate cost. While such a perfect instrument may not exist, it is felt that the principles of system dynamics, coupled with the use of the IBM continuous system modeling program, System 360/CSMP, may provide a new and potentially valuable tool for the analysis of educational systems. In the next chapter, the basic principles of system dynamics will be explained, followed by a brief discussion of applicable compilers which are available for simulation. In the following chapter, an attempt will be made to utilize those concepts to prepare an aggregate model of a university. The feasibility of using CSMP for its evaluation via sensitivity analysis will then be attempted. Finally, a similar analysis will be applied to a university department subunit.

CHAPTER III

SYSTEM DYNAMICS MODELING AND SIMULATION

Basic Theory

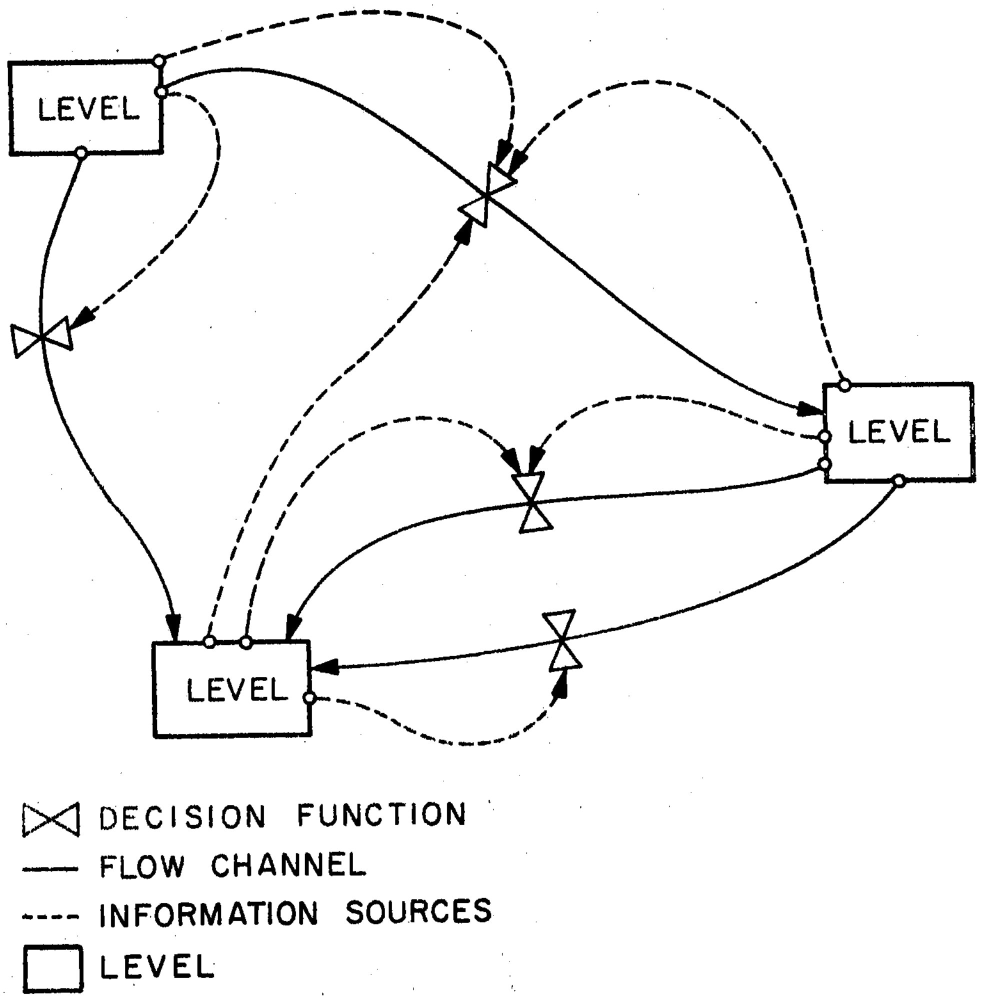
While a thorough working knowledge of system dynamics theory can be achieved only through experience and a careful study of the literature, its basic elements are easily grasped (17) (29) (154).

The system dynamics concept, formerly called Industrial Dynamics, was developed by J. W. Forrester (17), Professor of Industrial Management at the MIT Sloan School of Management, who felt that management education needed a central skeleton around which the art of management could be organized. He and his group consequently developed the systems philosophy which they believe can integrate the traditional functional management subjects (marketing, finance, production, etc.), with the human aspects, the technical considerations and environmental conditions. Their viewpoint is, they feel, fundamental and common to all systems, providing a framework which should be both conceptual and theoretical, and at the same time practical and useful. The management systems philosophy is based on the belief that the central problems of management arise from the characteristics of closed, goal seeking systems. These are extensions of the feedback systems studied in engineering servo-mechanism which imply that, at all points within a system, conditions lead to decisions that cause actions that change conditions and, thereby, alter future decisions. In such mechanisms, the vital importance of the communications network is obvious, putting Forrester in strong agreement with other students of organization theory such as Chester I. Barnard (36) and Melvin R. Lohmann (37). They also are in agreement that organizations are living, viable organisms which must be viewed as dynamic rather than static.

As modern society grows increasingly complex, the task of management has developed into much more than an art; conceptual skill is playing an increasing role in the success of all organizational effort. Management has fast become an exciting, dynamic, and intellectually demanding field. Formerly, because society felt that it was an art more than a profession, both education and practice were highly fragmented. The student was taught individual skills such as organization, manufacturing, marketing, and finance. This produced graduates who as specialists in a particular area were not fully aware of how the subsets of the discipline interacted to form the unified system required for the successful operation of an organization. In highly competitive business, for example, the relationships between the flows of information, materials, money, manpower and capital equipment must be considered, along with goals and values. They interlock to amplify each other, causing fluctuations which might require changes in decisions, policies, organizational forms, and investment choices, to name a few. System dynamics was developed to provide an analytic tool to handle such requirements. As mentioned above, it views the organization as a complex system of interlocking information channels merging at various points for the control of the physical process. Within the system, there are individual points whose information sources travel into other areas of the organization and the surrounding environment. At each decision-making point, a decision-information loop is established. Through the use of information as an input to the loop, decisions are developed causing action, which in turn adds new information to the loop. Thus, decision-making is a continuous process in which information is converted into rates of flow to the system. New information is used as it becomes available in order to provide the exact amount of action needed to adjust the system to its desired goals.

In the development of a decision, the state of the system is described by the condition of the levels as shown in Figure 1. Some examples of levels are laboratory inventories, the number of faculty and staff employees, and the degree of optimism about the economic future. The output developed from the decision point affects the rate at which the system level will change. Flow rates between the levels are changed by the decisions.

In the organization structure, policy is the formulation of a statement which defines the relationships between information sources and resulting decision flows. Two types of policies exist: formal and informal. Formal policy exists for guidance of the decision maker while informal policy depends on habit, conformity, social pressure, ingrained concepts of goals, awareness of power centers within the organization, and upon personal interests. The dynamic model is used to study the influence of policies on the system behavior. In the model, all decisions come under the control of policy, and policy controls the flow at all points in the actual system. At each decision point it is important that consideration be given to those variables available at the time the decision process occurs. It is essential that both those values which



The basis system dynamics model is based on levels and flow rates. As the contents of one level flow to another level, information about the flow is relayed to decision functions that control the rates of flow.

Figure 1. A Basic System Dynamics Model

are "true" values and those associated variables representing measured or conceived values be included so that the model is portrayed realistically.

The first step in developing the decision function for a decision point is to list those factors that influence the decision. Not only must their direct effect on the decision be evaluated but consideration must be given to the degree of feedback of the decision developed on the factor and the timing of the feedback. The short- and long-term influences of the factor must be considered because they can be in opposite directions. The interaction between the variables is very important in determining the behavior of the information-feedback system. Upon completion of the individual decision point functions, they are combined to produce the decision model.

Basically, system dynamics involves the construction of verbal, graphical, and then mathematical models of the closed loop feedback characteristics of the most important activities of a system, which Forrester defines as a grouping of parts that operate together for a common purpose. Every model has four basic features:

(1) Levels represent the accumulations at various points in the system at any given point in time. As mentioned before, examples would include such things as the number of students, laboratory equipment, operating funds, and others. Looking at them another way, one may say that levels exist wherever there are delays in flow rates.

(2) Flow rates are the present movements between levels. They indicate activity; levels measure the state to which the system has been brought by activity.

An educational example would be a university department. Its total educational capacity would be a level; the demands made upon that capacity would be a flow. If demands exceed capacity, additional capacity would have to be developed. So flow rates determine levels - as levels do flow rates.

As an industrial example, consider inventory reorders. When stock in inventory (a level) goes below a certain predetermined point, additional stock is ordered from the factory. Movement of goods (a flow rate) from factory (a level) to inventory (a level) will change both factory and inventory levels.

(3) Decision functions or rate equations determine how the information received about levels leads to the decision whether to lower or increase a flow rate. Thus, in the industrial example just given, an automatic reorder point for inventory would initiate an increase in the flow rate from factory to inventory whenever that point was passed.

(4) Information channels are the media connecting decision functions to levels.

It is the system dynamics thesis that this basic structure can be used to describe the simple networks that, when put together, form the organization model. The number of networks required depends on the organization studied and on the degree of aggregation feasible. The departmental model studied in Chapter V, for example, has four networks - student, staff, research, and quality. According to Forrester (17), six or fewer networks generally provide a meaningful model of an industrial situation. Such a model might include the following:

(1) The materials network, which represents all flow rates and levels of physical goods.

(2) The orders network, which includes orders for materials, requisitions for new employees, purchase of new plant, or office space.

(3) The money network. Here money is used only in the sense of actual cash, with money flow and movement of payments between money levels. The bank balance is a money level under this concept; accounts receivable and price are not included; they are part of the over-all information network which interconnects all the others.

(4) The personnel network, which outlines the company's position in terms of available manpower and utilization of manpower. Obvious levels here would be the labor pool, men in training, men working at the factory. Flow rates would be the rates at which workers were moving from one level to another.

(5) The capital equipment network, which includes factory and storage space, tools and equipment. Flow rates would include the installation of new equipment and production space, and the discard rate of old machines.

(6) Finally, and most important of all, there is the interconnecting information network. Obviously none of the five subsidiary networks can exist in a vacuum; decisions in each are influenced by information flowing in from other networks. So the information network is the coordinating system for all the

> others, transferring information about any level to decision points using that information in any network. For example, a radical change in the orders network will invariably affect the materials network, and could affect the personnel and capital equipment networks as well. It should certainly be communicated to the money network. Thus, the information network has the job of tying together the entire company into a cohesive whole able to make a coordinated response, just as the nerves in the human body make possible a logical and controlled response to some outside stimulus.

The foregoing comments were designed to provide an understanding of the basic objectives of system dynamics and its over-all operation. As mentioned previously, the method involves the construction of verbal, graphical, and then mathematical models of the closed loop feedback characteristics of the most important activities of a system. Since feedback concepts can be quite abstruse, it is helpful to construct a flow diagram of the loop structure for better comprehension of the relationships between the various elements. While verbal descriptions provide the information required to construct specific parts of a diagram, and the equations precisely describe the composition of each level and rate, a flow diagram is vital to an understanding of how level and rates are interconnected to generate feedback loops, and how the loops are interrelated to form the system.

To provide a better understanding of the flow diagram used to describe the university and departmental models in Chapters IV and V, it is appropriate that a brief description be given of the factors involved in model construction. First, sketches of the basic elements and the corresponding equations (where appropriate), are shown in Figures 2 and 3. Following a brief discussion of each element, several of the feedback building blocks will be illustrated. Then the process of formulating the mathematical equations, the last step in the initial model construction, will also be abstracted from the Forrester text (29). Finally, the chapter will close with an overview of the continuous simulation compilers which are available for analysis and improvement of the model.

Flow Diagram Symbols

In Figure 2, levels are first shown. It is recommended that all level equations and special functions involving integration be represented by a rectangle. The symbol identifies the accompanying equation, shows the rates in and out which are being integrated, the symbols representing the variable, the full variable name, and the equation number as a cross reference to the model in the equation set. Rates or policies are shown next. Valve-shaped, since they act as a valve in the analysis, they receive only information as their input. Rate equations are the policy statements that define the flow streams in a system. The symbol shows the letter group representing the variable and its full name, the equation number, and the information inputs on which the rate depends. The auxiliary variables lie in the information flow between the rates and the levels. Although they are parts of the rate equations, they are subdivided and separated because they express concepts with independent meaning. A circle is used to identify the equation, its abbreviation and number, and the input and output information flows.

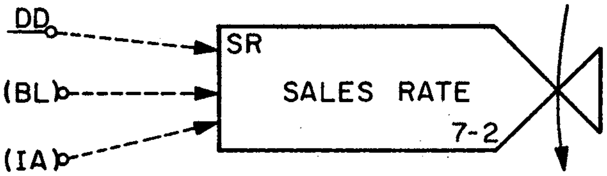
$$I.K. = I.J + (DT)(RR.JK - SR.JK) \qquad \text{Eq. 7-1, L}$$

Inventory at time K = Inventory at time J + (Solution interval)
(Reorder rate, period J to K - Sales Rate, period J to K)

Level Equation

$$SR.KL = \frac{BL.K}{DD}(IA.K) \qquad \text{Eq. 7-2, R}$$

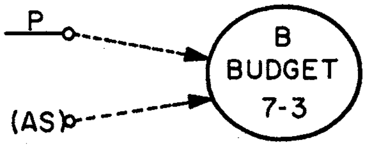
$$\text{Sales rate, period K to L} = \frac{\text{Backlog at time K}}{\text{Delivery delay}}\text{(Inventory Adjustment).}$$



Rate Equation

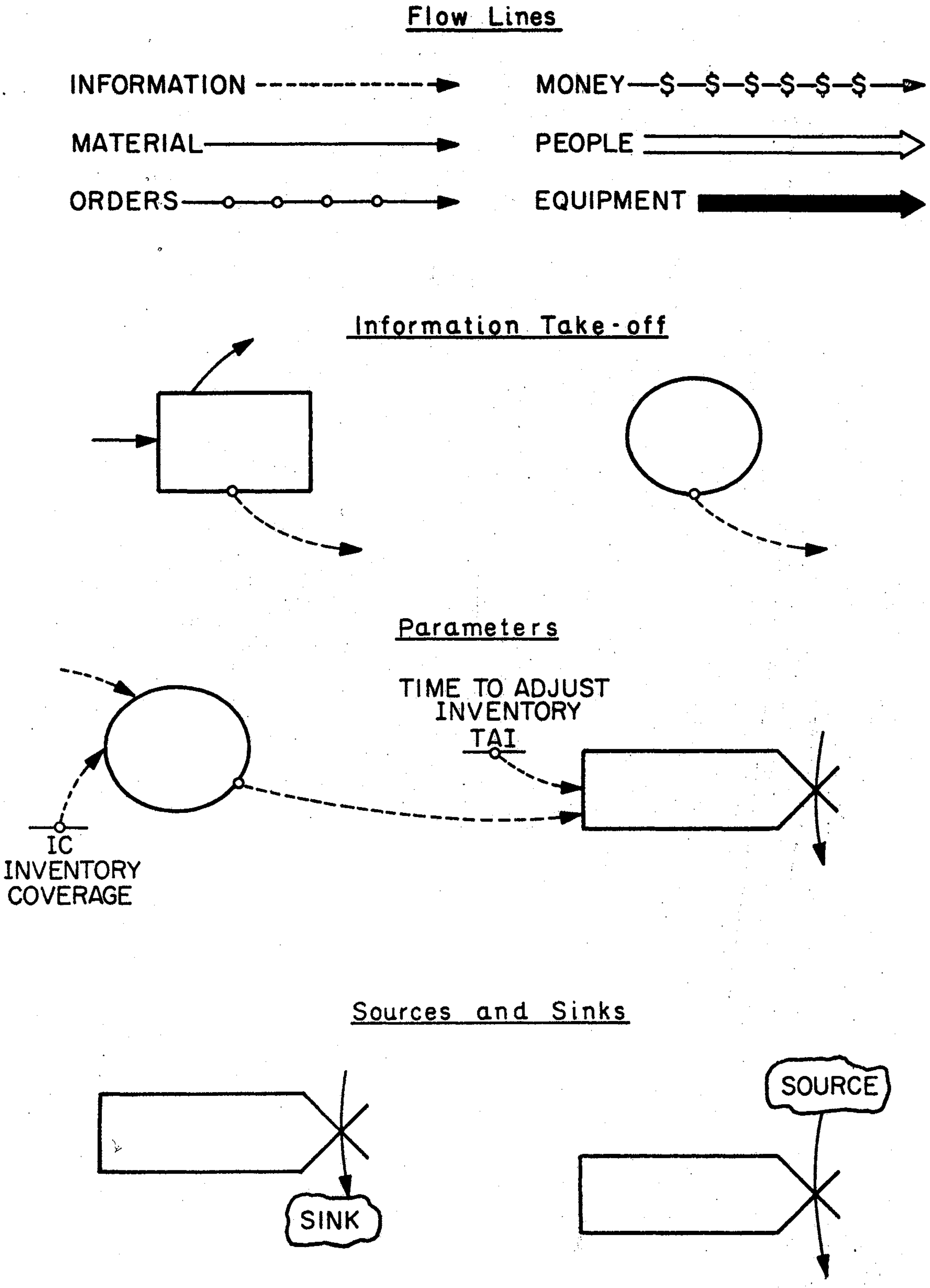
$$B.K. = (AS.K)(P) \qquad \text{Eq. 7-3, A}$$

Budget, at time K = (Average sales at time K) (Price per unit)



Auxiliary Equation

Figure 2. Symbols for Level, Rate, and Auxiliary Equations



Flow Lines

Information Take-off

Parameters

Sources and Sinks

Figure 3. Flow Lines, Information Take-off, Sources and Sinks, and Parameters

The flow lines in Figure 3 improve diagram clarity by identifying the different variables. Information connections occur in a "nonconserved" subsystem where information can be used without depleting the source. The other variables are "conserved" in that they show quantities that are moved from place to place in the system. While the information network is used in all models, the others are frequently used but will often need redefinition depending on the system involved.

Information about a variable can be taken without reducing that variable, the small circle represents only the transfer of information about the magnitude of the content. When leaving a level, only take-off is possible, unless the level itself is information, in which case flow would occur. When leaving a rate or auxiliary, only take-off is possible.

Parameters are the values which remain constant during a simulation run, although they can be changed between simulations. They are used as inputs to rates, either directly or indirectly through auxiliary equations. As is shown, their information take-off is either underlined or overlined.

Sources and Sinks are used to indicate flows which exert no direct influence on the system after they leave the model boundary. Source results from an outside or infinite source and sinks are used to terminate flow lines after they leave the system.

Feedback Loops

Feedback loops are the basic "building blocks" of system dynamics, for they are interlinked to form the flow diagrams used to model the system under study. Since a feedback, or "closed" system is modified by its past action a knowledge of loop characteristics is important to analysts. The loops may involve either positive or negative feedback. Positive feedback generates growth processes, for in it action builds on past results, as in the growth of a herd of cattle, a grove of trees, as well as in most other life processes. Negative feedback is characterized as goal-seeking. It sets an objective and adjusts until it is achieved, as in the case of a heating system seeking a correct temperature, or a university department waxing or waning in response to fluctuating student enrollment.

Figure 4 illustrates two of the simplest loops: first-order negative feedback, and positive feedback. In the first-order negative loop, it will be noted that a single decision rate regulates the input to one system level, the inventory. It is called "first-order" because the inventory represents the only level variable involved. Also, no complications are included such as delays or distortions in the information channel traveling from inventory to order rate, or delays between orders for goods and their receipt. If the latter problem did exist, the loop would require a second level, goods on order, which would make the loop a second-order negative feedback. It would also use a second rate variable called receiving rate.

The positive loop, as previously mentioned, represents a growth process rather than a goal-adjusting one. It does not have the reversal of sign in traveling around the loop. Positive loop action increases the difference between the system level and the "goal" or reference point, as the growth process continues through time.

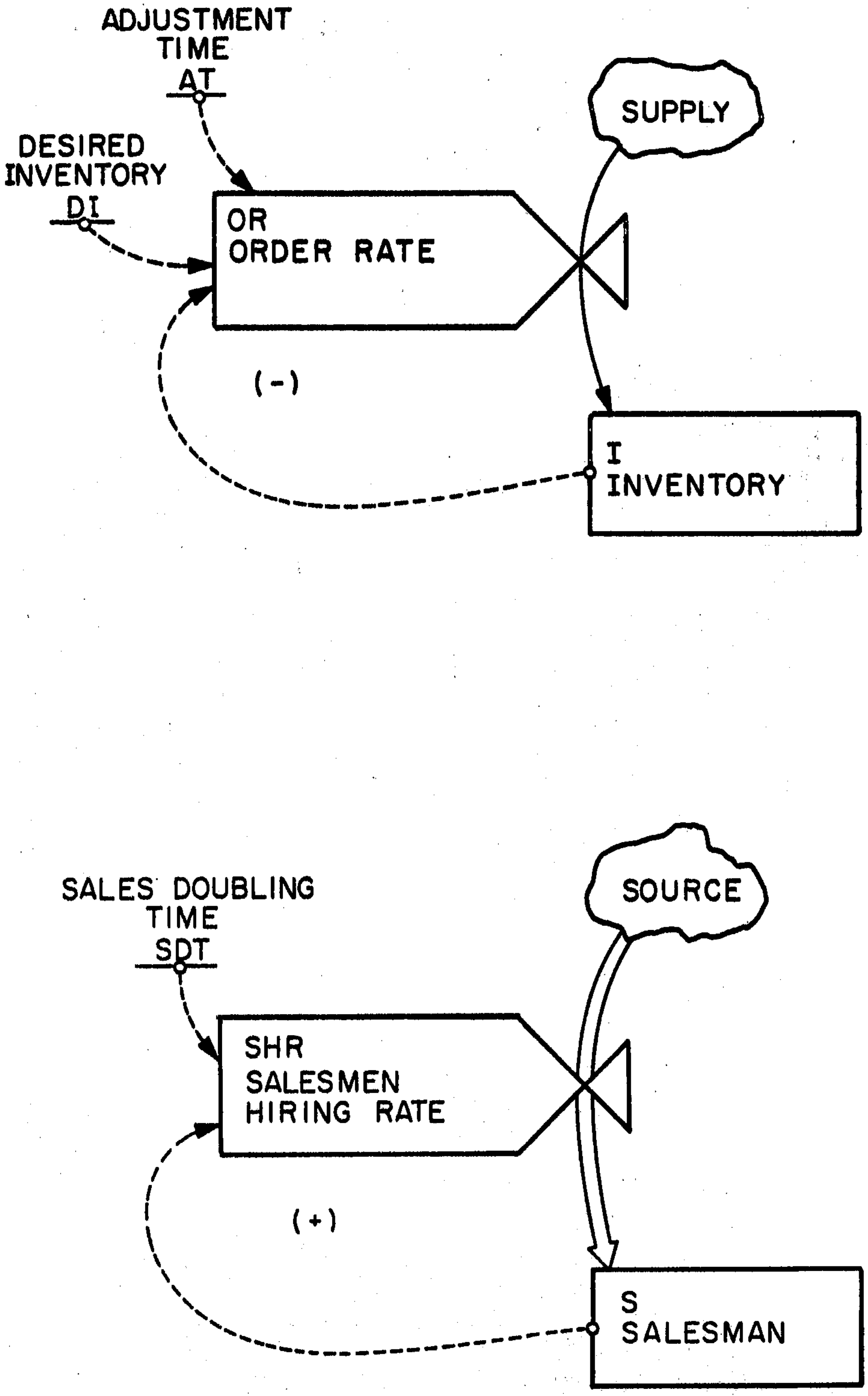


Figure 4. First-Order Negative, and Positive Feedback Loops

Equations

Since verbal descriptions of model components are much less precise and more lengthy than equations, the latter are used as soon as possible to describe the system under study. To simplify the construction of equations, a number of conventions have been adopted by the developers of system dynamics. One is the use of "J" to indicate the immediately preceding period, "K" for the time in which the current computation applies, and "L" for the next time period. Thus, when computation starts at time K, previous computations have made available the levels at time J, and the rates of flow over the interval JK. If no previous computations have been performed, the level equations must be given initial values to define the condition of the system. Based on these values, the rates of flow between the levels can be determined immediately, and the new levels at the end of the computation period are also obtained.

Equation symbols also have a standard format. Since computer printing machines do not have subscript or superscript notation, only line level characters and numbers are used. Constants and variables are represented by six or less characters, the first of which is alphabetic. Variables are closed with a period and time postscript, levels using J or K, and rates JK or KL, indicating the preceding or following interval. Constants have no postscripts.

Equation symbols can best be illustrated by writing a level and a rate equation. A level equation could be compared to a storage tank which rises or falls depending on the input and output flow rates over time. It can be represented as follows:

L.K = L.J + (DT)(RA.JK - RS.JK)

L--Level (units)
L.K--New value of level being computed at time K (units)
L.J--Value of level from from previous time J (units)
DT--The length of the solution interval between time J and time K (time measure)
RA--Rate being added to level L (units/time measure)
RA.JK--The value of the rate added during the JK time interval (units/time measure)
RS--Rate being subtracted from level L (units/time measure)
RS.JK--The value of the rate subtracted during the JK time interval (units/time measure)

The solution interval DT is a parameter, not of the system but of the computing process. It converts the flow rate over time into an added or reduced amount in the level, enabling the level equation to perform the process of integration. The level equation above is also known as a first-order difference equation in the branch of mathematics involving step-by-step integration.

Since rate equations indicate the flow controls in a system, their inputs are system levels and constants and their outputs control the flow to, between, or from levels. When computing at time K, using level information at K, to obtain the KL flow rates, a rate equation would take the following form: R•KL = f(levels and constants). In general, since they are really policy or decision statements which tell how the system controls itself, they are broader, more subtle, and take many more forms than level equations.

Auxiliary equations are subdivisions of the rates and must be evaluated following the level equations on which they depend, and before the rate equations of which they are a part. Thus, the computation sequence when they are used is first levels, then auxiliaries, and finally rates. These and initial value equations both may take many forms (29).

The preceding introduction to system dynamics concepts was necessarily sketchy, for the subject is somewhat similar to accounting in one sense. It involves considerable detail and requires experience before modeling proficiency can be achieved. Additional skill is then required to analyze the initial model with the assistance of the compilers described next. For additional mastery of the modeling and simulation details, the previous references (17) (29) (154) are suggested, along with several specialized treatises written by members of the MIT dynamics group (155) (156) (157).

Continuous Systems Simulation

A continuous system is one in which the predominant activities cause smooth changes in the attributes of the system entities. When such a system is modeled mathematically, the variables of the model representing the attributes are controlled by continuous functions. Most generally, in continuous systems, relationships among the attributes describe the rates at which attributes change, so that the model consists of differential equations (158).

Discrete systems, on the other hand, are systems in which changes are predominantly discontinuous. A description of a discrete system is concerned with the events producing changes in the state of a system. A description of a continuous system is usually in the form of continuous equations showing how system attributes change with time. However, the type of description does not necessarily coincide with the type of system.

> The study of continuous systems will sometimes be simplified by considering the changes to occur as a series of discrete steps.... In addition, the description of discrete systems is often simplified by considering the changes to occur continuously (158).

Dynamic modeling is the modeling of continuous systems, describable by differential equations, or mixed systems, describable in terms of differential equations and logical equations (158). Those continuous dynamic systems that are of usual concern to scientists and engineers have traditionally been simulated on analog computers. As systems under investigation have become increasingly complex, however, the need for speed, flexibility, and accuracy has increased. Digital simulation of continuous systems dates back only to 1955 with the work of Selfridge (158). Although special compilers were prepared earlier, the first commonly used digital simulation program, MIDAS, did not appear until 1963.

A number of continuous system simulation languages have been developed since that time which offer the user greater freedom in describing a system. They make use of a FORTRAN-like statement language, allowing a problem to be programmed directly from the equations of a mathematical model, rather than requiring the equations to be broken into functional elements. They extend the range of continuous system simulation by removing the orientation toward linear differential equations which characterizes analog methods (158).

Several compilers are now available to provide continuous simulation for organizations modeled by system dynamics methods. One, called DYNAMO, was developed especially for the concepts by Pugh, a member of the MIT group (160). DYNAMO (DYNAmic MOdels) was a 1959 successor to SIMPLE (Simulation of Industrial Management Problems with Lots of

Equations) which was prepared in 1958 for the IBM 704 computer. DYNAMO was later improved and modified for the IBM 709, 7090, and 9094 computers and now exists as Dynamo II, version 4, which is available from Pugh-Roberts Associates, Inc.[1] Version 4 can now be used effectively on the IBM 360 and other modern units.

Since DYNAMO is a special purpose compiler designed for the digital simulation of industrial dynamics models, which are constructed essentially in terms of algebraic and first-order difference equations, its programs are written in terms of rate and level equations. As was mentioned previously, rate equations can have any appropriate algebraic form. They represent the decision functions in the system. Level equations, on the other hand, represent accumulations (of information, materials, capital equipment, etc.) within the system, and have the JK and KL intervals described earlier in the chapter. The main purpose of the time notation is to facilitate the construction of equations in such a way that they are compatible with the procedure followed by the computer in calculating all equations at each iteration. Thus, during the simulation runs, levels are computed at each point in time, for example time K, based on the previous values of the levels at time J and the values of the rates during the interval JK.

In addition to rate and level equations, DYNAMO programs include auxiliary, supplementary, constant, and initial-value equations. These are convenient for programming purposes, but otherwise have no impact on the logic of the model. At each iteration, then, the order of computation is first levels, then auxiliaries, and finally rates.

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[1] Pugh-Roberts Associates, Inc., 179 Fifth Street, Cambridge, Mass., 12141.

Another compiler designed especially for Systems Dynamics is FORDYN (FORtran simulator for industrial DYNamics), published in 1965 by Llewellyn (161) to aid investigators who did not have access to an IBM 7090 or 7094 computer. Written for the IBM 1410 computer, Fordyn is a system of Fortran IV FUNCTIONS AND SUBROUTINES, plus a framework which fits the system dynamics models. While Fordyn is said to lack some of the diagnostic properties of DYNAMO, it has been used effectively by a number of investigators.

The compiler used to simulate the educational models described in the next two chapters is the System/360 Continuous System Modeling program (S/360CSMP). It is intended to help satisfy the need for a problem-oriented language by allowing problems to be prepared directly from either a block-diagram or a set of ordinary differential equations. The program provides a basic set of functional blocks with which the components of a continuous system may be represented, and it accepts application-oriented statements by defining the connections between these functional blocks. CSMP also accepts FORTRAN statements, thereby allowing the user to more easily handle nonlinear and time-variant problems of considerable complexity. Through these features, S/360 CSMP strives to allow the user to concentrate on the phenomena being simulated rather than the mechanism for producing the simulation (162) (163).

CSMP and DYNAMO both have the advantage of being non-procedural (automatic sorting) and application-oriented, but CSMP has the additional advantage of a no-sort option. Since it automatically accepts statements in Fortran, a user may program in Fortran IV and use the simulation capabilities of CSMP. This makes the language easy to use, since most analysts are already familiar with FORTRAN.

Three types of statements are used in order to write a simulation problem in CSMP:

1. Structure statements. These correspond to the level and rate equations in DYNAMO; i.e., they include both functional and algebraic relationships. The structure statements form the network to be simulated.
2. Data statements. These take care of all numerical values necessary for the simulation; i.e., parameters, initial conditions, constants, and table entries associated with the problem.
3. Control statements. These refer to matters concerning compilation and output specifications; i.e., run time, solution interval, and output variables to be printed and/or plotted.

These statements are composed of constants, variables, and operators, as in FORTRAN, plus CSMP functions. In essence, CSMP has most of the special functions available in DYNAMO, plus others not provided by the earlier compiler. Also, those functions available in DYNAMO and not in CSMP (i.e., exponential delays) can be easily obtained through the use of either MACRO functions or subroutines written in FORTRAN. Finally, while CSMP does not provide simultaneous (superimposed) plotouts of several variables, that feature can be provided through the use of the Calcomp Plotter.

DYNAMO simulation models treat system accumulation as first-order difference equations, as indicated previously. The continuous formulation of such levels could be written as follows:

$$\text{LEVEL} = \text{LEVEL}_{t=0} + \int_0^t \text{INR}(t) - \text{OURT}(t) \quad dt$$

This would be the theoretical formulation of levels in industrial dynamic models using a differential equation formulation. An equivalent statement, written in CSMP notation, would be as follows:

LEVEL = INTGRL (ICLEV, INR-OUTR)

where

LEVEL = Value of the accumulation at any time

INTGRL = Functional notation

ICLEV = Initial condition of LEVEL

INR = Variable input rate

OUTR = Variable output rate

CHAPTER IV

A UNIVERSITY ANALYSIS

Model Development

This chapter is designed to demonstrate the applicability of system dynamics and continuous simulation concepts to an educational system. Since the system selected is that of a complex state university, the model will be simplified to facilitate concentration on the methodology employed. Verbal description, equations, and a flow diagram will all be utilized to demonstrate their respective roles and aggregative procedures will be used to reduce complexity.

When a system involves a number of interacting variables its model usually requires some estimation and experimentation. Initial values of the constants and parameters are often difficult to predict and the interactions of the variables compound the problems involved. Although many of the values utilized in the university model are taken from an actual example, others represent data which required estimation.

The areas selected for the aggregated model include undergraduate and graduate students, faculty, physical facilities, and the budget. As shown in Figure 5, undergraduate and graduate student sources were selected as the starting points for the analysis. They were estimated initially at 9000 and 4500, respectively, based on past records of high school and college graduation in the area surrounding the subject university.

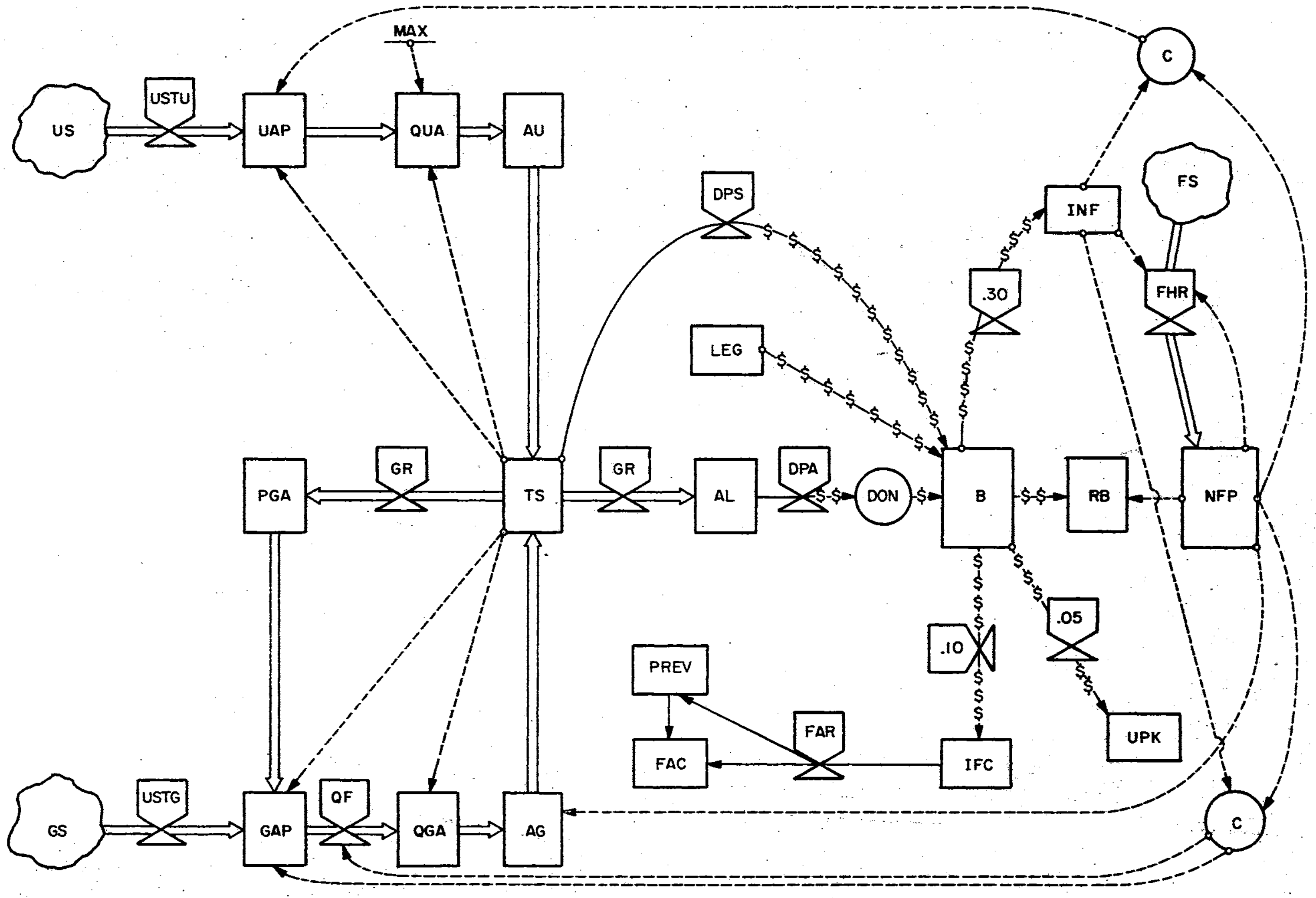

Figure 5. University Composite Model

The fraction of source groups who apply for admittance to a particular institution depend on a number of factors, some quite intangible. Current draft laws, family occupations, job availabilities and university standards, reputation and capacity represent only a small sample. One of the intangible factors selected for inclusion in the model is the ratio of actual faculty to the number indicated as desirable by a perusal of course offerings, comparison with other college catalogs, or discussions with students previously enrolled. If the employed number of faculty is less than the indicated number needed, applications should be adversely affected.

C = NFP/INF

C = Faculty influenced variable affecting student applications received.

NFP = Number of faculty in the university pool.

INF = Indicated number of faculty for the university.

University standards will also have an impact on applications submitted. For this model, they are initially assumed to eliminate seventy-two per cent of the potential undergraduate source and sixty-five per cent of the graduate. Both factors are designed to vary with time and as a function of the student-faculty ratio, arbitrarily set near eighteen for each. The equations are designed to relax standards by 1% per one year simulation period until the ratio restriction is encountered, then they are tightened by 1% annually.

TS2NFP = TS/NFP

TS2NFP = Ratio of total students to the number of faculty in the pool.

TS = Total number of students in the university.

NFP = Previously defined.

USTU = USTU + 0.01

IF(TS2NFP .GT. 18.5)   USTU = USTU - 0.02

USTU = University standards for undergraduate applications.

TS2NFP = Previously defined.

USTG = USTG + 0.01   USTG = USTG - 0.02

USTG = University standards for graduate applications.

TS2NFP = Previously defined.

The number of undergraduate applications received by the university is found by combining the above factors.

UAP = (USTU) (C) (US)

UAP = Number of undergraduate applications.

USTU = Previously defined.

C = Previously defined

US = Undergraduate source.

The number of graduate applications received, as well as being a function of some external source is also dependent on the number of students graduating from the same university and possibly reapplying for graduate school.

GAP = (USTG) (PGA + GS) (C)

GAP = Number of applications for graduate school.

USTG = Previously defined.

PGA = Potential graduate applications from university graduates.

GS = External graduate source.

C = Previously defined.

One of the critical assumptions made in writing the model is that as the source of students becomes larger and the size of the university increases additional schools will be established in the state to absorb some of the increase. Thus, some of the qualified students in the source will enroll at other universities.

Another assumption is that the university model has some enrollment limit beyond which it can expand no further. The upper limit may be the result of several reasons - facility limitation, land limitation, arbitrary action of the administration, the practical limits of teaching loads, etc.

Initially, most applicants are qualified for admittance. As the number of total students approaches the maximum university size, however, increased standards will cause a smaller percentage of applicants to be declared qualified. Since the current enrollment is ten thousand, and forty thousand is considered close to the maximum possible number, a damping factor is employed to slow future growth.

QUA = (UAP/4.0) (MAX/TS)

QUA = Number of qualified undergraduate applications.

UAP = Previously defined.

MAX = Maximum enrollment considered feasible, as approached standards become increasingly stiff.

TS = Previously defined.

The number of qualified graduate applications was considered to be dependent on the ratio of students to faculty.

QF = QF + 0.02

IF (TS2NFP .GT. 18.5) QF = QF - 0.03

IF (QF .GT. 1.0) QF = 1.0

QGA = (GAP) (QF)

QGA = Number of qualified graduate applications.

GAP = Previously defined.

QF = Qualification factor.

Since the model assumes a public, state-supported university, all qualified undergraduate applicants are admitted.

AU = QUA

AU = Number of admitted undergraduates.

QUA = Previously defined.

Graduate students are admitted at a rate of three per faculty member if that many applicants are qualified.

AG = 3.0 NFP

IF (AG .GT. QGA) AG = QGA

AG = Number of admitted graduate students.

NFP = Previously defined.

QGA = Previously defined.

The amount of alumni contributions to the university is based on a simple average donation per alumnus.

DON = (AL) (DPA)

DON = Donations to the university.

AL = Number of university alumni.

DPA = Average contribution per alumnus per year.

The graduation rate of the university was assumed to be twenty per cent of the student body per year.

GR = (TS·0.20)/DELTAT

GR = Graduation rate.

TS = Previously defined.

DELTAT = Time period for the simulation (in this model, one year).

The number of alumni accumulates as more students graduate.

AL = AL + (GR) (DELTAT)

AL = Number of university alumni.

GR = Previously defined.

DELTAT = Previously defined.

The total number of students in the university is computed by taking those students enrolled previously plus the number of newly admitted undergraduates and graduates less those that graduated less those that dropped. It was assumed that 12% of the previous year's student body did not return, or "dropped out".

TS = TS + AU + AG - (GR•DELTAT) - (TS•0.12)

TS = Number of students in the university.

AU = Previously defined.

AG = Previously defined.

GR = Previously defined.

The number of potential graduate school applications from the graduating class was assumed to be one-fourth.

PGA = (GR) (DELTAT) (0.25)

PGA = Number of potential graduate applications from the current period graduating class.

GR = Previously defined.

The rate of legislative support for the university was assumed to increase by 2% per year.

LEG = 1.02•LEG

LEG = Legislative appropriation.

The hub of the university, the budget, is computed from the legislative appropriation, alumni contributions, and student fees.

B = (TS) (DPS) + DON + LEG

B = Budget.

TS = Previously defined.

DPS = Fees in dollars per student.

DON = Previously defined.

LEG = Previously defined.

The indicated number of faculty that should be employed at the university is computed as a function of the budget and average faculty salary. Thirty per cent of the university budget was devoted to faculty salaries.

INF = (0.30•B)/FS

INF = Indicated number of faculty that should be employed.

B = Previously defined.

FS = Average salary per faculty member.

The number of faculty in the university pool of instructors at the current time period is a function of those faculty members employed during the previous period and those newly employed.

NFP = NFP + (FHR) (DELTAT)

NFP = Number of faculty in the university pool.

FHR = Faculty hiring rate.

DELTAT = Previously defined.

The rate at which faculty members are hired is determined by the number of new instructors needed and the average faculty hiring time. It is possible for the hiring rate to become a negative value and, thus, staff would be reduced.

FHR = (INF - NFP)/FHT

FHR = Faculty hiring rate.

INF = Previously defined.

NFP = Previously defined.

FHT = Average faculty hiring time.

The amount of facilities available to a university plays an important role in its functioning. Three factors are a part of this section - the indicated facilities needed, the facility acquisition rate, and the actual facilities available.

The indicated facility increase needed is estimated as 10% of the budget.

$IFC = 0.10 \cdot B$

IFC = Indicated facility increase.

B = Previously defined.

The facility acquisition rate is influenced by the average facility building time. For this model, the building time was assumed to be two years. In other words, one-half of the new facilities are ready in one year, the other one-half are completed the following year.

$FAR = IFC/FBT$

FAR = Facility acquisition rate.

IFC = Previously defined.

FBT = Facility building time.

$FAC = FAC + (FAR \cdot DELTAT) + PREV$

FAC = Total facility increase since time 0.

FAR = Previously defined.

DELTAT = Previously defined.

PREV = Facilities budgeted the previous time period but not acquired until the current time.

PREV = IFC - FAR

PREV = Facilities budgeted the previous period but not acquired until the current time.

IFC = Previously defined.

FAR = Previously defined.

The budget for faculty research is computed as a fixed amount per faculty member up to one-fourth of the total university budget.

RB = 1200 • NFP

IF (RB .GT. 0.25•B)   RB = 0.25•B

RB = Research Budget.

NFP = Previously defined.

The budget for maintenance and physical plant is a percentage of the over-all university budget.

UPK = 0.05•B

UPK = Maintenance and physical plant upkeep budget.

B = Previously defined.

The CSMP Simulation

A number of simulation runs were made to test the model and to evaluate its sensitivity to changes in several of its variables. The constants and parameters employed are as follows:

CONST DELTAT = 1	time/run (1 year)
CONST DPA = 2.00	dollars/alumnus
CONST DPS = 1500	dollars/student
CONST FS = 12000	average faculty salary
CONST FHT = 1	faculty hiring time
CONST T = 1	initial exponent for student source growth

CONST FBT = 2.0	facility building time, in years
CONST MAX = 40000	maximum number of students
PARAM US = 9000	initial undergraduate student source
PARAM GS = 4500	initial graduate student source
PARAM X = 10000	undergraduate student source factor
PARAM Y = 1.15	undergraduate student growth factor
PARAM P = 5000	graduate student source factor
PARAM Q = 1.1	graduate student growth factor
PARAM USTU = .28	university standards--undergraduate
PARAM USTG = .35	university standards--graduate
PARAM UAP = 2500	undergraduate applications
PARAM GAP = 1400	graduate applications
PARAM QF = 0.75	graduate qualification factor
PARAM QUA = 2000	qualified undergraduate applications
PARAM QGA = 1000	qualified graduate applications
PARAM AU = 2000	number admitted undergraduates
PARAM AG = 1000	number admitted graduates
PARAM GR = 2000	graduation rate
PARAM TS = 10000	total students initially enrolled
PARAM DON = 175000	dollars donated by alumni
PARAM AL = 87500	number of alumni
PARAM LEG = 9500000	dollars legislative appropriation
PARAM B = 25000000	annual university budget
PARAM INF = 625	indicated number in faculty pool
PARAM NFP = 625	number in faculty pool
PARAM FHR = 10	faculty hiring rate, initial
PARAM IFC = 2500000	indicated facility increase/year

PARAM FAR = 1250000	facility acquisition rate
PARAM FAC = 22500000	existent facilities
PARAM PREV = 1250000	facilities acquired in previous year
PARAM RB = 750000	annual research budget
PARAM UPK = 1250000	annual maintenance and physical plant budget

The rate of university growth appears to be one of the most critical factors in the model. It is governed by the graduate and undergraduate student sources, GS and US. Three different student source functions were used in separate simulation runs to test the model. The percentage of the budget allocated to faculty salaries was also altered slightly. In addition, one of the apparently delicate factors in the model, the faculty to student ratio, was changed slightly to determine its effect. Each simulation run was for a period of twenty-five years.

A sample copy of the program and several of the curves generated for one of the university model runs are included as Appendix A.

After some initial adjustment to the interacting variables, the first simulation model to yield reasonable results used exponentially shaped source curves (XY^t and PQ^t) to generate undergraduate and graduate applications, 30% of the budget for faculty salaries and student-faculty ratios of 18½ for undergraduate and 17½ for graduate students.

Since currently available CSMP facilities do not permit multiple plots, the outputs from the simulation runs were plotted on a Calcomp printer to facilitate analysis. Figures 6 and 7 show the results of the initial run. Admitted undergraduates and graduates, total students, university budget, and number in the faculty pool were plotted in Figure 6, and undergraduate and graduate applications, indicated number of faculty, faculty hiring rate and research budget are shown in

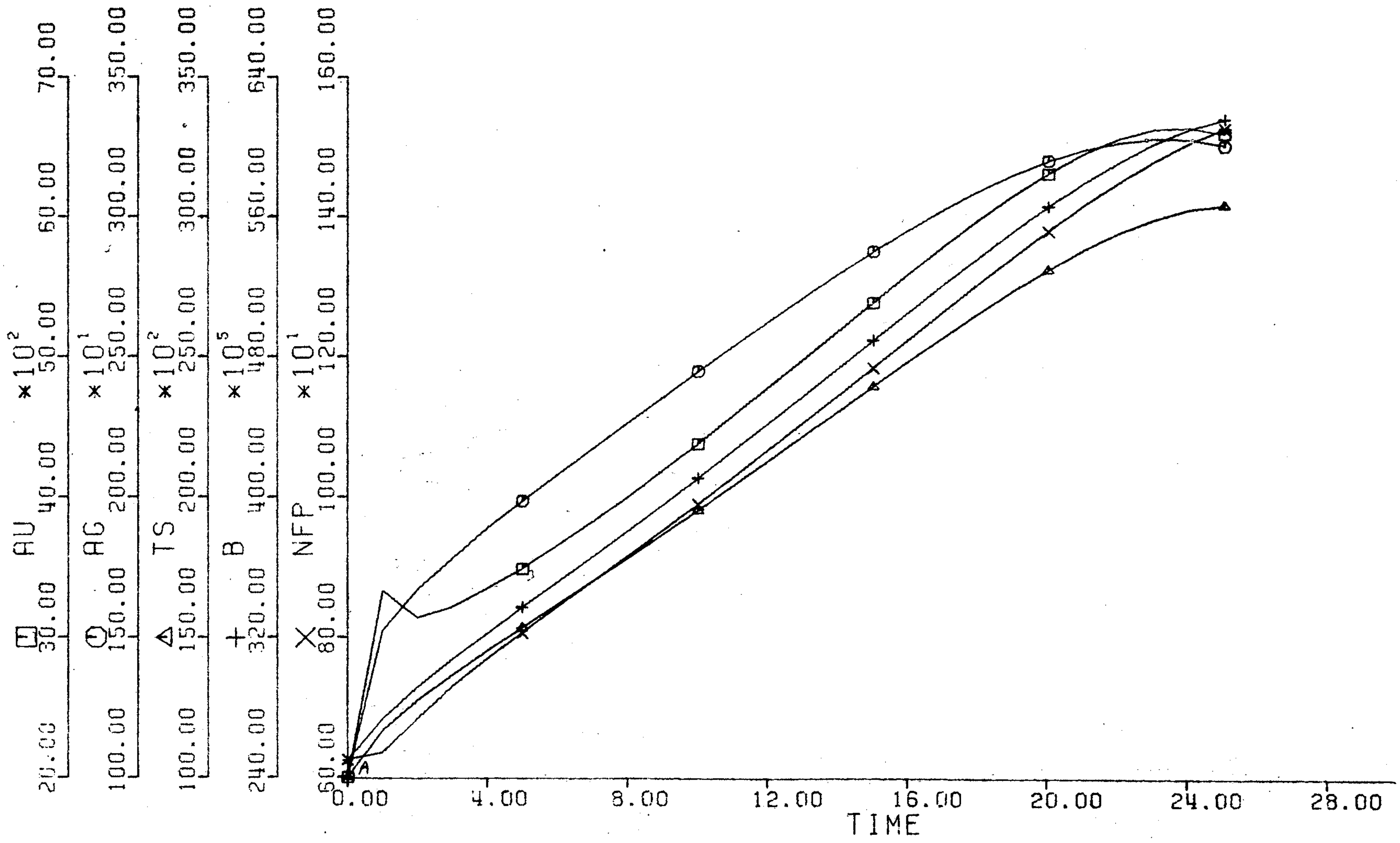

Figure 6. University Model - First Simulation - Exponential Growth

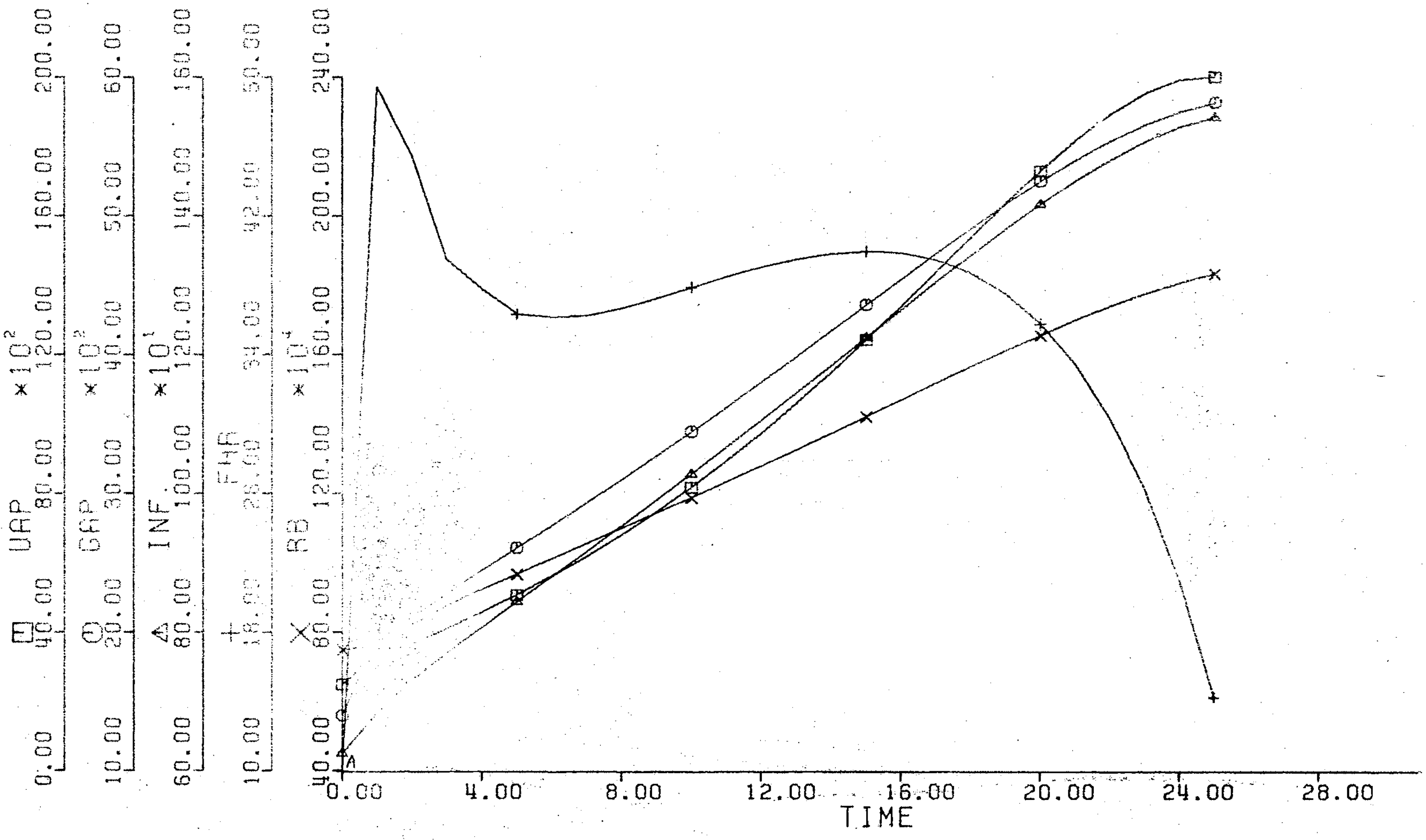

Figure 7. University Model - First Simulation - Exponential Growth

Figure 7. It is clear that the number of admitted students begins to level off after about twenty years as the student-faculty ratio gets above the set standards and the student body size approaches 40,000, the ceiling imposed. As the rate of student body growth declines, the faculty hiring rate also drops rapidly.

The second simulation run used the same student faculty ratios as the first, but the faculty budget was increased from 30% to 35% of the total budget, and the student source curves were changed from exponential to linear growth. The same ten values, shown in Figures 8 and 9, were plotted as in Figures 6 and 7. The rate of student body growth, particularly undergraduate, increased more rapidly during the early years but dropped off sharply during the middle of the simulation period as the student-faculty ratio exceeded the limit and forced stricter standards for admission. This caused a similar wide fluctuation in the faculty hiring rate, both curves showing a second rise as the ratio fell back to the proper level around the twentieth year. Several of the curves, including undergraduate applications and admissions, and the faculty hiring rate, all fluctuated more than they did during the first run.

Since the linear growth rate of the student sources was rather high, the final values of the curves in the second simulation were substantially greater than the first. Undergraduate applications were 32,000 compared to 20,000; graduate applications rose from 5,800 to 18,000; admitted undergraduates were up from 6,500 to 7,500; admitted graduates went from 3,000 to 6,800; total students 39,000 to 43,000; faculty 1,500 to 2,300; research budget \$1.8 to \$2.7 million, and total budget \$61 million to \$80 million.

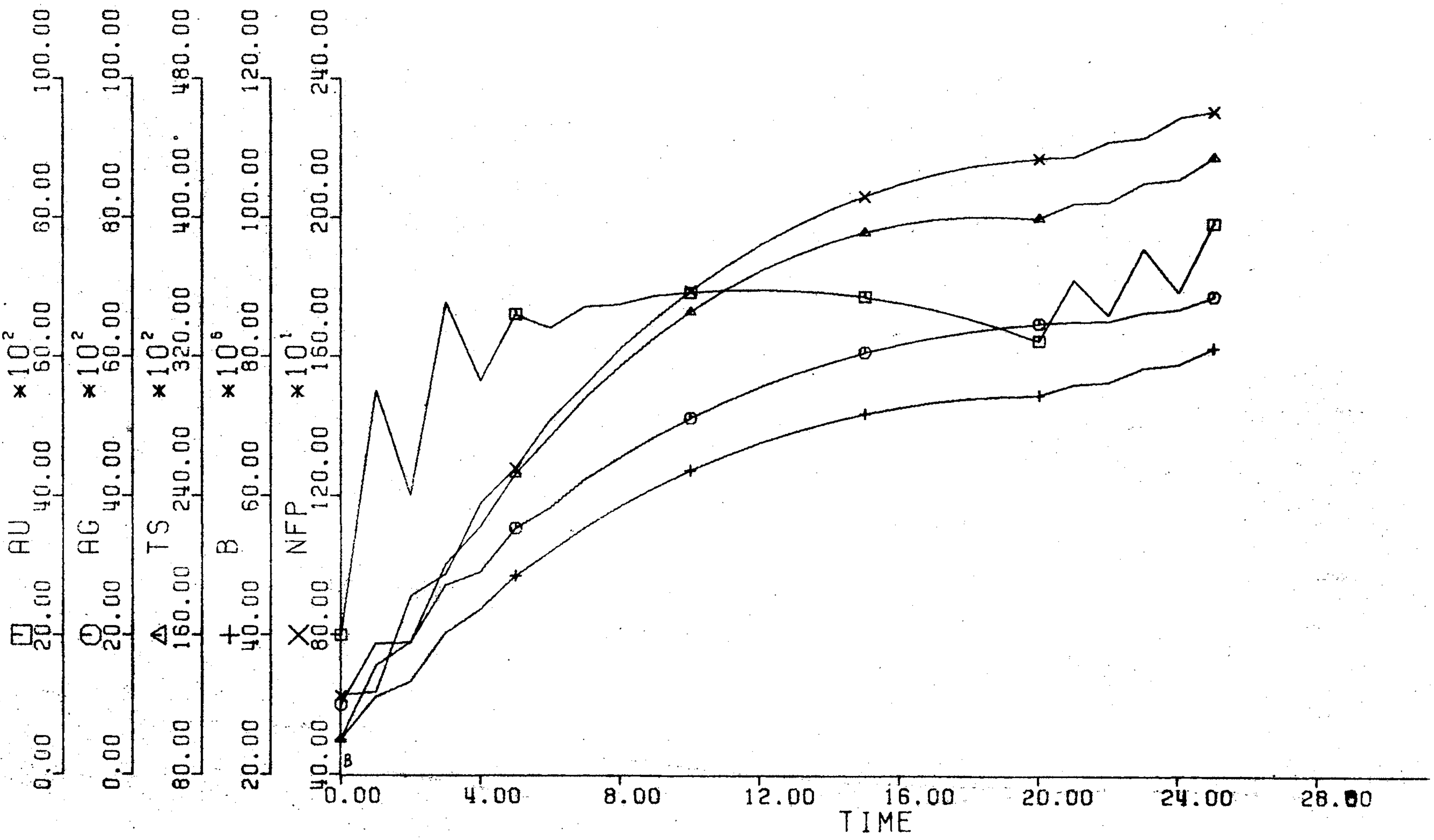

Figure 8. University Model - Second Simulation - Linear Growth

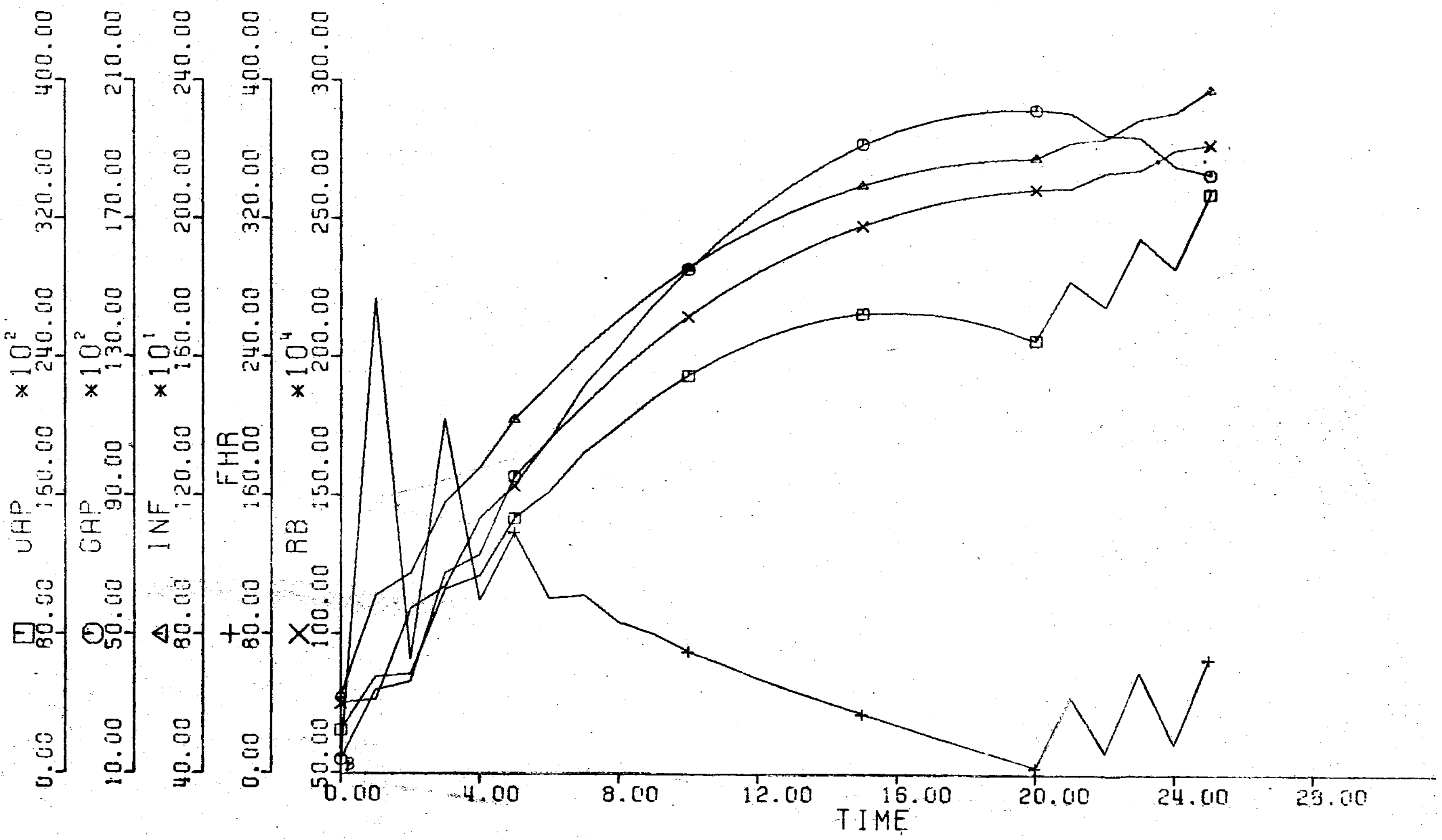

Figure 9. University Model - Second Simulation - Linear Growth

The third simulation used the same student-faculty ratio and faculty budget, but the student source growth rate was changed from linear to a diminishing returns type. Specifically, the Van Bertalanffy curve $y = A(1-e^{-kt})$ was used. While the plotted curves for the third run, as shown in Figures 10 and 11, initially appear similar to those of Figures 8 and 9, significant differences resulted from the change to the Van Bertalanffy source curve. After twenty-five years, undergraduate and graduate student applications were somewhat lower at 12,000 and 8,000, respectively (in consonance with smaller sources); acceptances numbered less than 5,000 each; total enrollment was approximately 28,000; the faculty pool was slightly less than 1,700; and the research and university budgets were \$2,000,000 and \$58,000,000, respectively. It was felt that the diminishing returns source curve gave a more realistic student source than those of the first two runs, for other schools are assumed to be able to handle a part of the anticipated student population growth in the region.

The fourth run again used the Van Bertalanffy source curve and approximately the same student-faculty ratio, but used only 30% of the budget for faculty rather than 35%. By the end of the twenty-five year run, significant differences had occurred. While the sources remained the same as the third run, the applications from undergraduates and graduates dropped to 9,200 and 2,700, and the acceptances to 4,500 and 2,600. Total enrollment also dropped to 21,000, faculty to 1,160, and the research and total budgets to \$1.4 and \$47 million. The results are shown in Figures 12 and 13.

In the next chapter, a university department will be modeled in more detail. In addition, an attempt will be made to obtain a

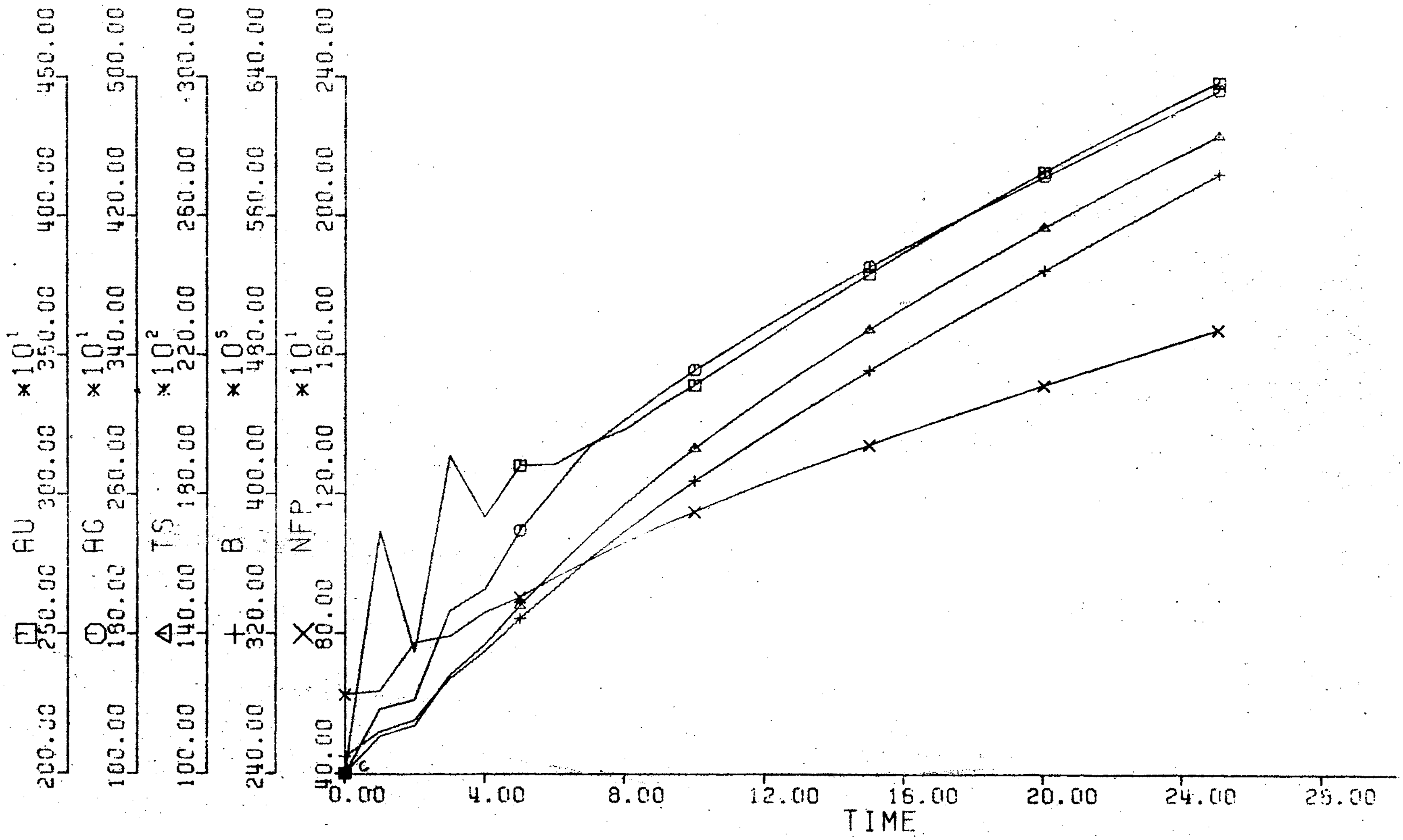

Figure 10. University Model - Third Simulation - Van Bertalanffy Growth

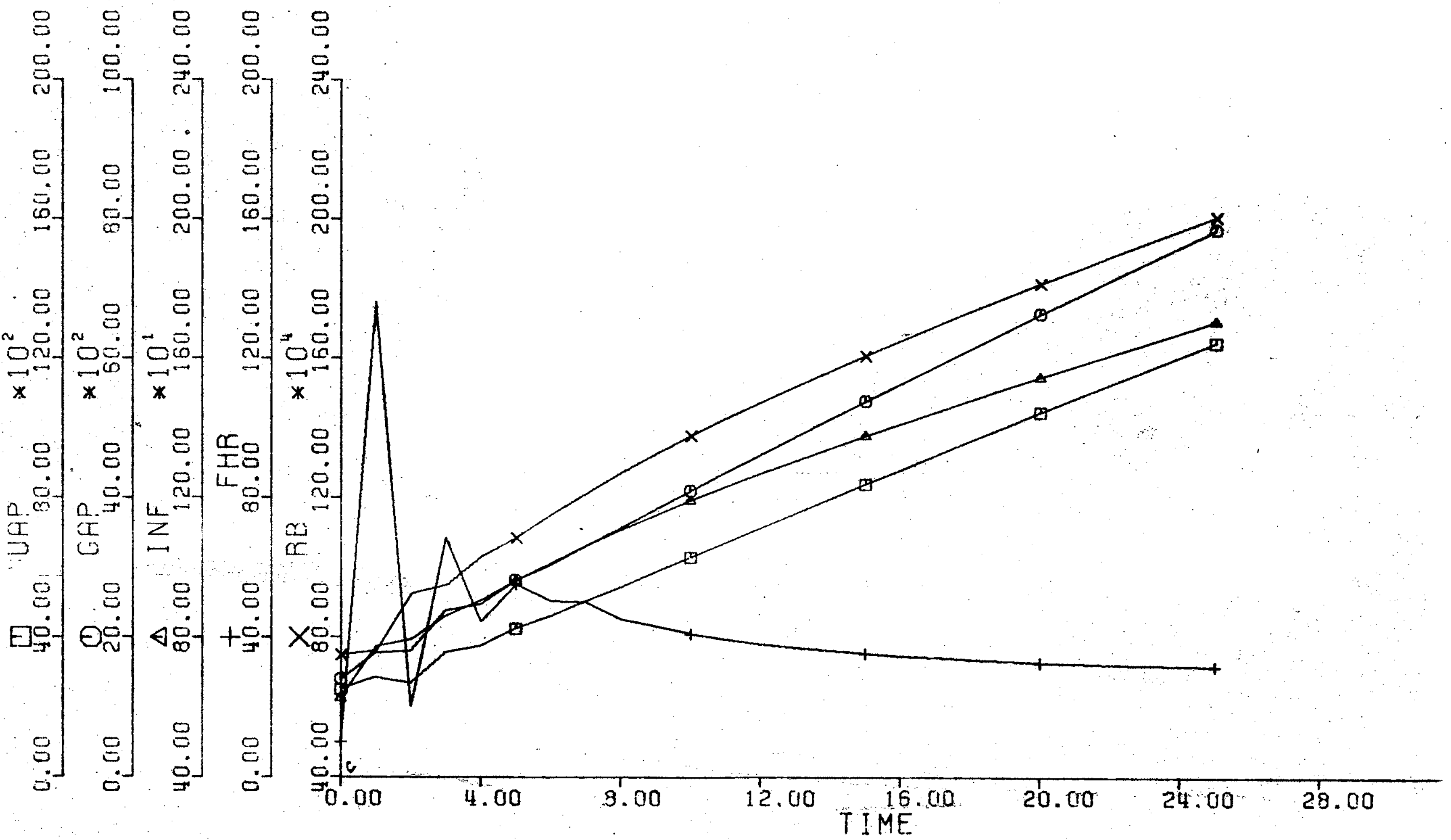

Figure 11. University Model - Third Simulation - Van Bertalanffy Growth

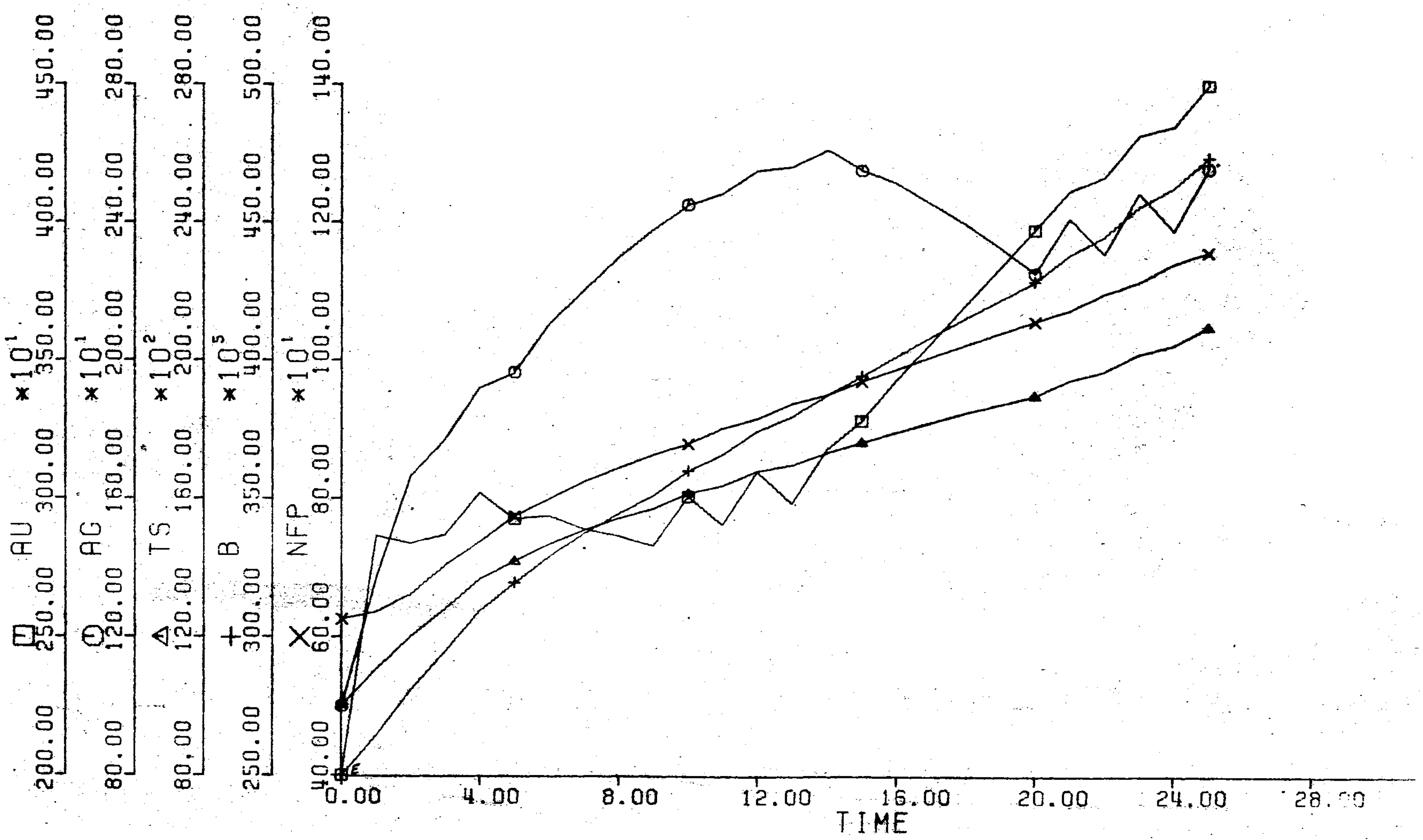

Figure 12. University Model - Fourth Simulation - Van Bertalanffy Growth - Lower Faculty Support

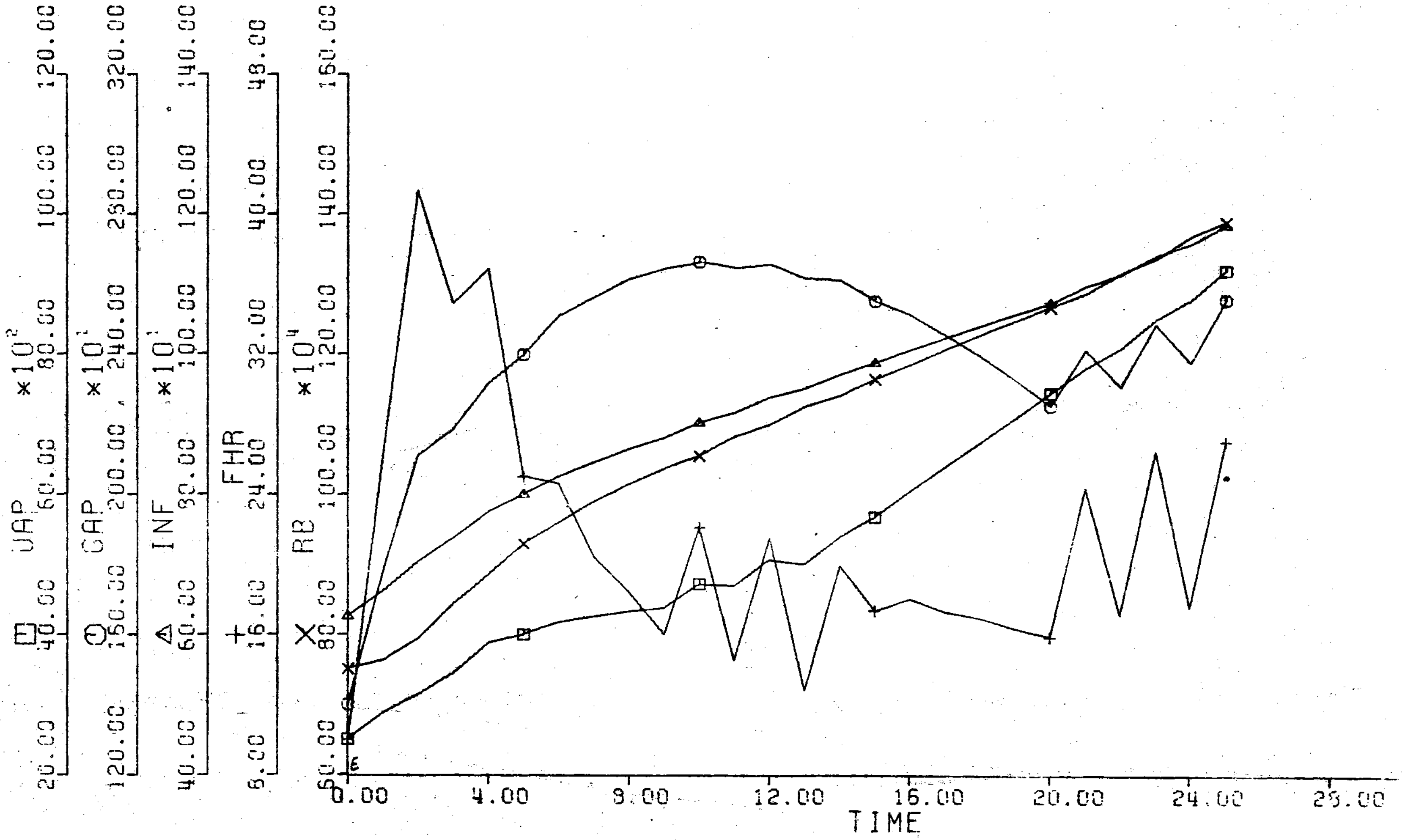

Figure 13. University Model - Fourth Simulation - Van Bertalanffy Growth - Lower Faculty Support

reasonable approximation to the past performance and growth characteristics of the unit under consideration in order to improve the model's effectiveness for future prediction.

CHAPTER V

A DEPARTMENTAL ANALYSIS

Model Development

The preceding model demonstrated the applicability of system dynamics concepts to an aggregated model. A broad gauge view was obtained, using equation symbols similar to those explained in Chapter III but without the time notation. The notation is useful as an aid to memory, but is not required when CSMP is substituted for Dynamo in the simulation process. The purpose of this chapter is to model a university sub-unit in a more detailed fashion. In addition, time notation will be added and the CALCOMP 563 plotter will again be utilized to provide a clearer summary of simulation results.

Student Section

The base of this model is student enrollment in the College of Engineering. Therefore, a type of predictive technique for future enrollment is first established.

ENROL.K = ENGR ST-1,L

ENROL.K = Enrollment in the College of Engineering for the current year.

ENGR = Variable whose value was assigned by some predictive technique for the model.

The enrollment rate in the Master of Science programs in Industrial Engineering and Operations Research was assumed to be a fraction of those students graduating from the undergraduate Industrial Engineering program each year plus others from outside sources. It was also assumed that the quality of the department was a factor in influencing the number in each group. Since some doubt existed over the linearity of the relationship between quality and enrollment, a logarithmic relationship was selected.

RRMS.JK = (MSFRAC) (XLOG(QUAL.J,QUALO,FMS1)) (IEBS.J)
+ (MSQ) (XLOG(QUAL.J,QUALO,FMS2)) ST-2,R

RRMS.JK = Enrollment rate in M.S. programs.

MSFRAC = Fraction of B.S.I.E. students enrolling in the M.S.I.E. or M.S.O.R. programs at year 0 per quality point.

MSQ = Number of other enrollments in M. S. programs at year 0 per quality point.

XLOG(QUAL.J,QUALO,F) = Function relating the value of quality in the following manner:

XLOG(QUAL.J,QUALO,F) = F·ln(QUAL.J/QUALO)
+ QUALO

QUAL.J = Current value for departmental quality.

QUALO = Initial value of department quality at year 0.

FMS1 and FMS2 = Constant scale factors.

IEBS.J = Number of undergraduates enrolled in Industrial Engineering during time period J.

Since students drop out of the M.S. programs at varying rates over a period of two years, the following equations were established.

DRMS.JK = (MSDR1) (CARMS(2)) + (MSDR2) (CARMS(1)) ST-3,R

DRMS.JK = Dropout rate in M.S. programs.

MSDRi = Fraction of M.S. students who drop out during the ith year of graduate study.

CARMS(2) = Number of M.S. students enrolling at time J.

CARMS(1) = Number of students enrolling in M.S. programs at time J - 1.

Graduation from the Master of Science programs generally takes place in either one or two years.

GRMS.JK = (MSGR1) (CARMS(2)) + (MSGR2) (CARMS(1)) ST-4,R

GRMS.JK = Rate of graduation from the M.S. programs.

MSGRi = Fraction of M.S. students that graduate during the ith year of graduate study.

CARMS(2) = Previously defined.

CARMS(1) = Previously defined.

The Ph.D. enrollment rate is approximately the same form as the M.S. rate. M.S.I.E. students who continue into the Ph.D. program and other students from outside the system compose the source of enrollment. Again, a logarithmic relationship between students and quality of the I.E. department yielded reasonable results.

RRPHD.JK = (PHDFRA) (XLOG(QUAL.J,QUALO,FPHD1)) (IEMS.J)
+ (PHDQ) (XLOG(QUAL.J,QUALO,FPHD2)) ST-5,R

RRPHD.JK = Enrollment rate in Ph.D. program.

PHDFRA = Fraction of M.S.I.E. graduates enrolling in the Ph.D. program at year 0 per quality point.

PHDQ = Number of other enrollments in Ph.D. program at year 0 per quality point.

XLOG(QUAL.J,QUALO,F) = Previously defined.

FPHD1 and FPHD2 = Constant scale factors.

IEMS.J = Number of M.S.I.E. students during time J.

Students drop out of the Ph.D. program at varying rates over a four year period, as reflected in the following equations.

DRPHD.JK = (PHDDR1) (CARPHD(4)) + (PHDDR2) (CARPHD(3))
+ (PHDDR3) (CARPHD(2)) + (PHDDR4) (CARPHD(1)) ST-6,R

DRPHD.JK = Dropout rate in Ph.D. program.

PHDDRi = Fraction of Ph.D. students that drop out during their ith year in the program.

CARPHD(5 - i) = Number of students enrolling in the Ph.D. program at time 5 - i.

Students graduate from the Ph.D. program at varying rates over four periods of one year each.

GRPHD.JK = (PHDGR1) (CARPHD(4)) + (PHDGR2) (CARPHD(3)) + (PHDGR3) (CARPHD(2)) + (PHDGR4) (CARPHD(1)) ST-7,R

PHDGRi = Fraction of Ph.D. candidates in I.E. who graduate during their ith year in the program.

CARPHD(5 - i) = Previously defined.

Based on past experience, the number of B.S.I.E. students was assumed to be some percentage of the over-all enrollment in the College of Engineering. This percentage varies according to departmental quality. A logarithmic relationship was used.

IEBS.K = (BSFRAC) (XLOG(QUAL.J,QUALO,FBS)) (ENROL.K) ST-8,L

IEBS.K = Number of undergraduates enrolled in the B.S.I.E. program during time K.

BSFRAC = Fraction of undergraduate students in the College of Engineering enrolled in I.E. at year 0/quality point.

XLOG(QUAL.J,QUALO,F) = Previously defined.

FBS = Constant scale factor.

ENROL.K = Previously defined.

The total number of M.S.I.E. candidates during the current time period is the number enrolled during the previous period plus the newly enrolled students less the graduates and dropouts.

IEMS.K = IEMS.J + (RRMS.JK - GRMS.JK - DRMS.JK) (DT) ST-9,L

IEMS.K = Number of graduate students enrolled in the M.S.I.E. program at time K (current time).

IEMS.J = Number of graduate students enrolled in the M.S.I.E. program at time J (previous time period).

RRMS.JK = Previously defined.

GRMS.JK = Previously defined.

DRMS.JK = Previously defined.

DT = One time period. (In this model, DT = 1 year).

The total number of Ph.D. candidates during the present time period is the number enrolled during the previous period plus those who enrolled since that time less the number who graduated or dropped out since the previous period.

$$\text{IEPHD.K} = \text{IEPHD.J} + (\text{RRPHD.JK} - \text{GRPHD.JK} - \text{DRPHD.JK})\ (\text{DT}) \qquad \text{ST-10,L}$$

IEPHD.K = Number of students enrolled in the Ph.D. program at time K (current time).

IEPHD.J = Number of students enrolled in the Ph.D. program at time J (previous time period).

RRPHD.JK = Previously defined.

GRPHD.JK = Previously defined.

DRPHD.JK = Previously defined.

DT = Previously defined.

Research Section

In the research section of the model, the number of active research projects in the department was the basic variable. There are essentially two types of research projects in the Industrial Engineering department. One type consists of projects sponsored by university in-house grants. The other type is that which is sponsored by some group external to the university, which will be called out-house projects.

The acquisition of university sponsored research projects bears a strong relationship to the number of graduate faculty in the department.

$$\mathrm{IHRESR.JK} = (\mathrm{IHFAC})\ (\mathrm{FACGR.J}) \qquad \text{RS-1,R}$$

IHRESR.JK = Rate representing the number of in-house projects generated from time J to time K (in this case one year).

IHFAC = Constant representing the number of in-house projects received per year per graduate faculty member.

FACGR.J = Number of graduate faculty members in the I.E. department at time J.

The number of externally funded research projects is assumed to be a function of the quality of the department.

$$\mathrm{OHRESR.JK} = (\mathrm{OHQ})\ (\ln(\mathrm{QUAL.J}/\mathrm{QUALO}) + \mathrm{QUALO}) \qquad \text{RS-2,R}$$

OHRESR.JK = Rate representing the number of out-house research projects generated per time period (from J to K).

OHQ = Constant representing the number of out-house research projects received each year as a function of quality.

The termination rate of research projects is based on the total number of active projects in the department.

$$\mathrm{RESTR.JK} = (\mathrm{RESTF})\ (\mathrm{RESF.J}) \qquad \text{RS-3,R}$$

RESTR.JK = Research termination rate in projects per time period.

RESTF = Fraction of the total research projects that are terminated during the year.

RESF.J = Number of active research projects during time period J.

The number of current research projects can be computed by using the three previous rates.

$$\mathrm{RESF.K} = \mathrm{RESF.J} + (\mathrm{IHRESF.JK} + \mathrm{OHRESR.JK} - \mathrm{RESTR.JK})\ (\mathrm{DT}) \qquad \text{RS-4,L}$$

RESF.K = Number of research projects active during the current time period K.

RESF.J = Previously defined.

IHRESR.JK = Previously defined.

OHRESR.JK = Previously defined.

RESTR.JK = Previously defined.

DT = Previously defined.

Staff Section

There are basically three types of staff members in the I.E. department - graduate faculty, undergraduate faculty, and graduate assistants. This model is designed to calculate only the number of positions in each of these three categories which is justified to cover teaching and available research.

The teaching load of the department was determined in average total hours per semester for undergraduate courses, graduate courses, and thesis and dissertation work. The following three equations are designed to measure these three separate areas.

HUNGR.K = (HBSIE) (IEBS.K) + (HBSNIE) (ENROL.K - IEBS.K) SF-1,L

HUNGR.K = Hours of undergraduate courses to be taught in the I.E. department each semester.

HBSIE = Average number of hours of I.E. courses required per B.S.I.E. student.

IEBS.K = Previously defined.

HBSNIE = Average number of I.E. courses required per non-I.E. engineering student.

ENROL.K = Number of students in the College of Engineering.

HGRAD.K = (HMSIE) (IEMS.K) + (HPHDIE) (IEPHD.K) SF-2,L

HGRAD.K = Hours of graduate courses to be taught in I.E. department each semester.

HMSIE = Average number of hours of I.E. courses required per M.S.I.E. student.

IEMS.K = Previously defined.

HPHDIE = Average number of hours of I.E. courses required per Ph.D. candidate.

IEPHD.K = Previously defined.

HTHES.K = (THMS) (IEMS.K) + (THPHD) (IEPHD.K) SF-3,L

HTHES.K = Total thesis hours per semester required by graduate students.

THMS = Average number of thesis hours per M.S.I.E. student.

IEMS.K = Previously defined.

THPHD = Average number of thesis hours per Ph.D. candidate enrolled.

IEPHD.K = Previously defined.

The number of research projects determine the research load in the department. It was assumed that research projects funded positions for graduate faculty and graduate assistants only. The number of such positions calculated is the number of full-time equivalent positions.

FACRES.K = (FACRP) (RESF.K) SF-4,L

FACRES.K = Number of graduate faculty positions paid by research funds.

FACRP = Average number of graduate faculty positions supported per research project.

RESF.K = Previously defined.

GARES.K = (GARP) (RESF.K) SF-5,L

GARES.K = Number of graduate assistant positions paid by research funds.

GARP = Average number of graduate assistants supported per research project.

RESF.K = Previously defined.

The justified number of graduate I.E. faculty is given by the sum of the number required for research, the number required for teaching graduate courses and directing thesis research, and the number required to teach advanced undergraduate courses.

FACGR.K = FACRES.K + (POSGR) (HGRAD.K + HTHES.K)
+ (POSGR) (UNFRGF) (HUNGR.K) SF-6,L

FACGR.K = Number of justified graduate faculty positions.

FACRES.K = Previously defined.

POSGR = Constant representing positions per graduate hour.

HGRAD.K = Previously defined.

HTHES.K = Previously defined.

UNFRGF = Fraction of undergraduate courses taught by graduate faculty.

HUNGR.K = Previously defined.

The justified number of undergraduate faculty is based on the fraction of the undergraduate teaching load carried by the undergraduate faculty and on the load per faculty member.

FACUGR.K = (POSUGR) (UNFRUF) (HUNGR.K) SF-7,L

FACUGR.K = Number of justified undergraduate faculty positions.

POSUGR = Constant representing positions per undergraduate hour.

UNFRUF = Fraction of undergraduate courses taught by undergraduate faculty.

HUNGR.K = Previously defined.

Graduate assistant positions may be supported by either teaching or research. The number of full-time equivalent graduate assistant positions is given, therefore, by the sum of the teaching positions for undergraduate courses not taught by faculty and the research positions.

GA.K = GARES.K + (POSUGR) (UNFRGA) (HUNGR.K) SF-8,L

GA.K = Number of justified graduate assistant positions.

GARES.K = Previously defined.

POSUGR = Previously defined.

UNFRGA = Fraction of undergraduate courses taught by graduate assistants.

HUNGR.K = Previously defined.

Quality Section

The quality section is one of the more important facets of the model. Each of the three sections discussed previously impinge on the quality of the Industrial Engineering department.

The number of published papers are assumed to be one of the factors related to quality. They come from the work of graduate faculty, M.S.I.E. students, Ph.D. candidates, and funded research projects.

PAPERS.K = (PAPGF) (FACGR.K) + (PAPMS) (IEMS.K)
+ (PAPPHD) (IEPHD.K) + (PAPRES) (RESF.K) QU-1,L

PAPERS.K = Number of papers published per time period by the I.E. department.

PAPGF = Constant representing the number of papers published per graduate faculty member not doing funded research per year.

FACGR.K = Previously defined.

PAPMS = Constant representing the number of papers published per M.S. student per year.

IEMS.K = Previously defined.

PAPPHD = Constant representing the number of papers published per Ph.D. candidate per year.

IEPHD.K = Previously defined.

PAPRES = Constant representing the number of papers published per research project each year.

RESF.K = Previously defined.

The quality of the Industrial Engineering department is assumed to be a function of the following six factors: graduate faculty, undergraduate faculty, published papers, M.S. students, Ph.D. candidates, and research projects. A logarithmic relationship between these factors and quality seems to yield reasonable values.

$$\text{QUAL.K} = (100.0)\cdot\ln(((\text{QPGF})\ (\text{FACGR.K}) + (\text{QPUGF})\ (\text{FACUGR.K}) + (\text{QPPAP})\ (\text{PAPERS.K}) + (\text{QPPHD})\ (\text{IEPHD.K}) + (\text{QPMS})\ (\text{IEMS.K}) + (\text{QPRP})\ (\text{RESF.K}))/\text{QUALO}) + 1.0) \qquad \text{QU-2,L}$$

QUAL.K = Quality of department.

QPGF = Relative value assigned per graduate faculty member.

FACGR.K = Number of justified graduate faculty positions.

QPUGF = Relative value assigned per undergraduate faculty member.

FACUGR.K = Number of justified undergraduate faculty positions.

QPPAP = Relative value assigned per published paper.

PAPERS.K = Number of papers published by department members per year.

QPPHD = Relative value assigned per Ph.D. candidate.

IEPHD.K = Number of Ph.D. candidates in the I.E. program.

QPMS = Relative value assigned per M.S. student.

IEMS.K = Number of M.S. students in the I.E. program.

QPRP = Relative value assigned per research project.

RESF.K = Total number of research projects.

QUALO = Quality of I.E. department at time 0.

The composite model illustrating the previous equations is shown on the following page as Figure 14.

Input Data Discussion

The number of equations required for the departmental model and the complexity of their interactions made it desirable to present them in the preceding summarized fashion. A more detailed explanation of the thought process involved, the assumptions required and the initial conditions utilized for the modeling process will now be provided. While the model is more detailed than that of the university outlined in the preceding chapter, numerous assumptions and some simplifications were nevertheless necessary.

The basic sectors considered included students, staff, research, and quality. In the student section the first equation (ST-1,L) was selected to emphasize the fact that college enrollment is considered to be the base of the model. The equation symbols were designed to provide rapid and accurate identification. For example, ST-1,L refers to the student section of the model, first equation, level type.

The second equation, ST-2,R, refers to the student section, second equation, rate type. As indicated, the enrollment rate in the masters programs depends on internal and external sources, both of which are affected by departmental quality based on the logarithmic relationship listed. The quality factors in the model were selected to provide an estimate of the relative worth of several departmental groups and activities, and to provide an initial total which was approximately 100 for the test department studied. With IEBS enrollment known, and on the basis of a logarithmic function initially approximating 100, MSFRAC

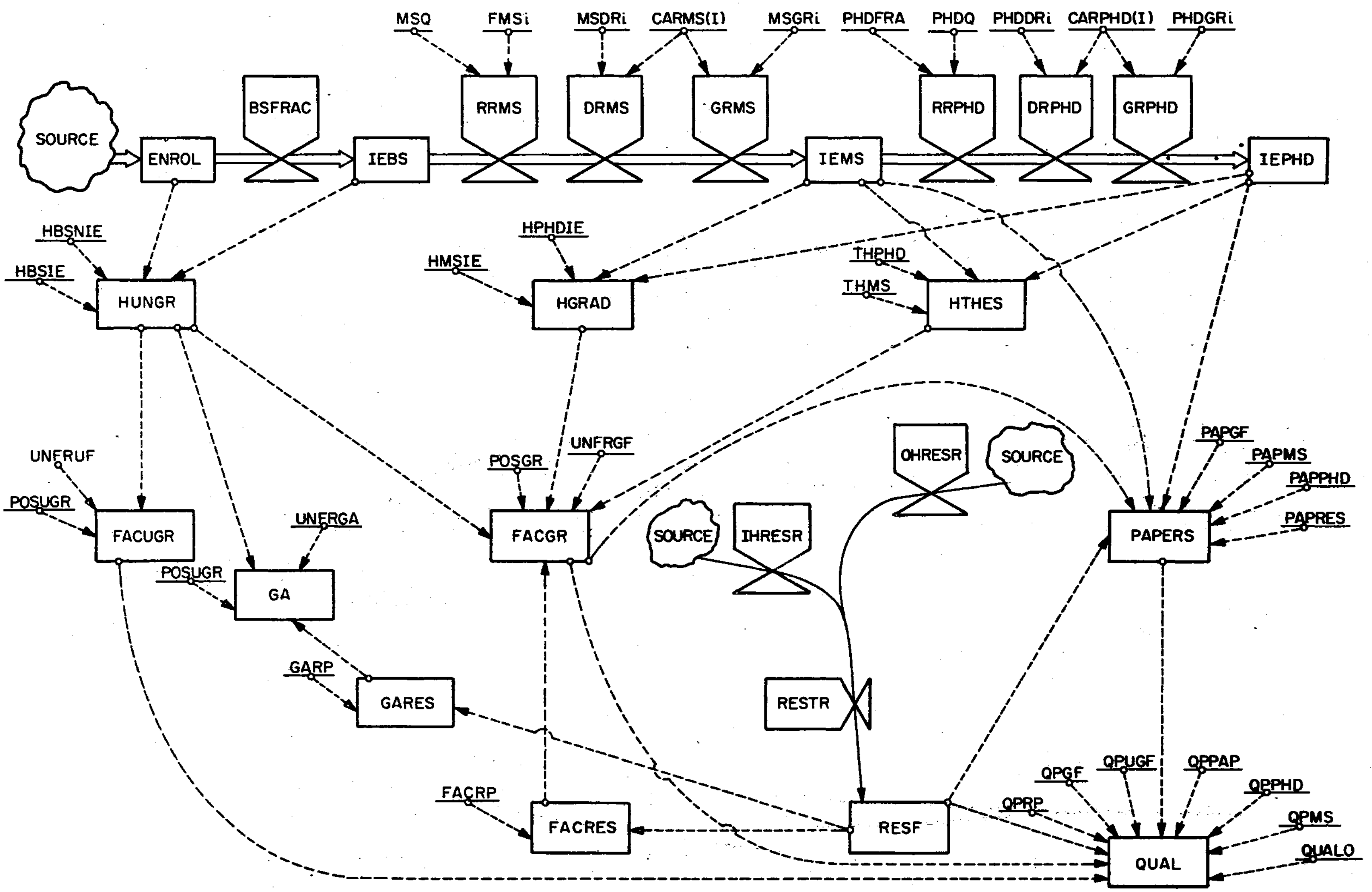

Figure 14. Composite Model University Department

and MSQ values were selected which yielded results close to past experience. The constant scale factors were included as part of the quality equation to provide additional flexibility for model manipulation if required to achieve realistic results.

The master's program dropout rate equation, ST-3,R, and the graduation rate, ST-4,R, were both based on past records of the department. Approximately 4% was used as the first year dropout rate, MSDRI, and 1% for the second year, MSDR2. Similarly, the graduation rates MSGR1 and MSGR2, 70%, and 25%, respectively, were based on experience, as were student enrollments, CARMS1 and 2.

Equations ST-5,R; ST-6,R; and ST-7,R considered enrollment, dropout, and graduation rates for doctoral students. Except for the longer time period involved, they were handled in the same manner as those involving the master of science students. The constant scale factors, FPhD1 and 2, were set at 100 each and initial dropout rates were estimated at 6% for PhDDR1, 1% for PhDDR2, and .05% for the third and fourth years. Graduation rates were estimated to average 0% at the end of one calendar year (PhDGR1), 38% after two years, 39% after three, and 15% after four. As with the master of science equations, the enrollment from within the department (PhDFRA) and from outside (PhDQ) were selected to yield results close to past experience.

The equations for the remainder of the student sector, B.S.I.E. student level (Equation ST-9,L), M.S. student level (ST-9,1), and Ph.D. student level (ST-10,L) were then based on the equations and concepts discussed. The constant scale factor (FBS) and BSFRAC were determined as before, and the last two equations represented accumulations of information determined from previous equations.

In the research sector, the first equation, RS-1,R, was designed to determine the number of in-house projects generated per year. The number of graduate faculty members (FACGR) was known, and the number of projects received per year per member was estimated from prior experience. Externally funded projects, determined from Equation RS-2,R, were made a function of quality. Since the initial value of the logarithmic term was close to 100, an OHQ constant was selected which yielded a realistic value. The termination rate of research projects, Equation RS-3,R, was determined from the product of known active projects and an estimated fraction of terminations per year (75%). The latter figure was obtained from existing departmental records. The fourth research sector equation, RS-4,L, designed to provide the number of current research projects (RESF), was determined by summarizing the results of the three research rate equations.

The staff sector equations were designed to calculate the number of graduate faculty, undergraduate faculty, and graduate assistants required to handle teaching and research requirements in the department. The first three equations were concerned with teaching load requirements for coursework (graduate and undergraduate) and thesis and dissertation activities. The first equation, SF-1,L, was used to determine the undergraduate course load required each semester for industrial and non-industrial engineering students. The average number of hours of industrial engineering courses required for each, HBSIE and HBSNIE, were estimated from past course load records. Graduate course load requirements for master and doctoral candidates were determined in a similar manner in SF-2,L. The total thesis load hours required each semester by graduate students were obtained through the use of Equation

SF-3,L. IEMS and IEPhD enrollments were readily available, and the figure for the average number of thesis load hours per M.S.I.E. and Ph.D. student (THMS and THPhD) were estimated from past departmental enrollment and staff load data. Parenthetically, in the department considered, each student engaged in masters thesis work generates one-half load hour for his adviser and each dissertation student provides one load hour.

The number of graduate faculty and graduate assistant positions paid by research funds was determined by Equations SF-4,L and SF-5,L. The average number of faculty (FACRP) and graduate assistant (GARP) positions supported per research project was subject to considerable variation but reasonable estimates were made from a perusal of departmental data over a ten-year period.

Justified graduate faculty, undergraduate faculty, and teaching assistant positions were calculated in SF-6,L, SF-7,L, and SF-8,L. Graduate faculty positions, as shown in SF-6,L, were determined from the sum of research support (FACRES), hours of graduate coursework and thesis load multiplied by POSGR (a constant representing positions per graduate hour, determined on the basis of a nine hour load), and the hours of undergraduate coursework handled. The last value was obtained as the product of POSGR, HUNGR (total undergraduate course hours taught per semester), and UNFRGF (fraction of undergraduate courses taught by graduate faculty). UNFRGF was estimated from past course schedules. Undergraduate faculty and graduate assistant positions were handled in a similar but less complicated manner since only undergraduate coursework was involved. Both used the constant POSUGR to represent positions per undergraduate hour (based on a twelve hour load).

Departmental quality was considered to be chiefly a function of the number of graduate and undergraduate faculty, published papers, research, and the number of graduate students. Equation QU-1,L was designed to calculate the number of papers published per year by the department. Several of its factors were estimated from past experience-PAPMS, a constant representing the number of papers published per M.S. student per year, PAPGF for graduate faculty members, PAPhD for Ph.D. candidates and PAPRES for research projects. The graduate faculty, research project and Ph.D. estimates were more readily obtained than that of the M.S. candidates. The second equation, QU-2,L, provided an over-all quantitative estimate of departmental quality. It was obtained as a function of the natural logarithm of the sum of the contributing factors, each of which was assigned a relative value. Other known contributing factors were omitted because they were considered to be even more intangible. Although a logarithmic relationship was selected for the equation, a straight ratio arrangement would also yield reasonable results.

The CSMP Simulation

A number of simulation runs were made to test the model and to evaluate its sensitivity to changes in several of its variables. The following constants and parameters in the departmental model CSMP simulation came from several sources. Some were based on departmental policy, others from known values over the past years, several resulted from experience, and the remainder were experimentally derived to yield results consistent with available operating data.

Student Section

CONST	BSFRAC = 0.00112	per cent of engineering students/quality point enrolled as B.S.I.E.'S at year 0
CONST	BSQ = 1.0	per cent of B.S. enrolled/quality point from outside sources at year 0
CONST	FBS = 20.0	constant scale factor for calculating B.S. enrollment
CONST	FMS1 = 10.0	constant scale factor for calculating M.S. enrollment
CONST	FMS2 = 10.0	constant scale factor for calculating M.S. enrollment
CONST	FPHD1 = 100.0	constant scale factor for calculating Ph.D. enrollment
CONST	FPHD2 = 100.0	constant scale factor for calculating Ph.D. enrollment
CONST	MSDR1 = 0.04	per cent of M.S. students dropping out in year 1
CONST	MSDR2 = 0.01	per cent of M.S. students dropping out in year 2
CONST	MSFRAC = 0.0010	per cent of B.S.I.E. students/quality point enrolling in M.S. at year 0
CONST	MSGR1 = 0.70	per cent of M.S. students graduating during year 1
CONST	MSGR2 = 0.25	per cent of M.S. students graduating during year 2
CONST	MSQ = 0.084	number of M.S. enrollees/quality point from other schools at year 0
CONST	PHDDR1 = 0.06	per cent of Ph.D. students dropping out in year 1
CONST	PHDDR2 = 0.01	per cent of Ph.D. students dropping out in year 2
CONST	PHDDR3 = 0.005	per cent of Ph.D. students dropping out in year 3
CONST	PHDDR4 = 0.005	per cent of Ph.D. students dropping out in year 4

CONST PHDFRA = 0.00175	per cent of M.S. graduates/quality point enrolling in Ph.D. at year 0
CONST PHDGR1 = 0.0	per cent of Ph.D. students graduating during year 1
CONST PHDGR2 = 0.38	per cent of Ph.D. students graduating during year 2
CONST PHDGR3 = 0.39	per cent of Ph.D. students graduating during year 3
CONST PHDGR4 = 0.15	per cent of Ph.D. students graduating during year 4
CONST PHDQ = 0.0095	number of other enrollees in Ph.D. program/quality point at year 0
CONST DT = 1.0	1 year time period
PARAM ENGR = 900	initial engineering college enrollment
PARAM IEBS = 90	I.E. department enrollment B.S. level
PARAM IEMS = 5	I.E. department enrollment M.S. level
PARAM IEPHD = 1	I.E. department enrollment Ph.D. level

Research Section

CONST IHFAC = 0.20 or 0.50	number of in-house research projects/year/graduate faculty member
CONST OHQ = 0.02 or 0.05	number of out-house research projects/year as function of quality
CONST RESTF = 0.75	per cent of total research projects terminated in 1 year
PARAM RESF = 2.0	number of active research projects

Staff Section

CONST FACRP = 0.25	average number of graduate faculty positions supported/research project

CONST	GARP = 0.125	average number of graduate assistant positions supported/research project
CONST	HBSIE = 0.4	average number of hours load in I.E. courses required/B.S.I.E. student
CONST	HBSNIE = 0.039	average number of hours load in I.E. courses required/non-B.S.I.E. student
CONST	HMSIE = 0.6	average number of hours load in I.E. courses required/M.S.I.E. student
CONST	HPHDIE = 0.8	average number of hours load in I.E. courses required/Ph.D. student
CONST	POSGR = 0.111	number of graduate faculty positions required/course load hour
CONST	POSUGR = 0.083	number of undergraduate faculty positions required/course load hour
CONST	THMS = 0.25	average number of thesis hrs/M.S. student
CONST	THPHD = 0.67	average number of thesis hrs/Ph.D. student
CONST	UNFRGA = 0.29	undergraduate per cent of courses taught by graduate assistants
CONST	UNFRGF = 0.20	undergraduate per cent of courses taught by graduate faculty
CONST	UNFRUF = 0.51	undergraduate per cent of courses taught by undergraduate faculty
PARAM	HUNGR = 105.0	hours of undergraduate courses taught in I.E. dept./sem.
PARAM	HGRAD = 17.0	hours of graduate courses taught in I.E. dept./sem.
PARAM	HTHES = 10.0	hours of thesis courses taught in I.E. dept./sem.
PARAM	FACRES = 0.5	number of graduate faculty jobs paid by research funds
PARAM	GARES = 0.0	number of graduate assistant jobs paid by research funds
PARAM	FACGR = 2.5	number of justified graduate faculty jobs

PARAM	FACUGR = 6.0	number of justified undergraduate faculty jobs
PARAM	GA = 1.0	number of justified graduate assistant jobs

Quality Section

CONST	PAPGF = 1.0	number of papers/yr/graduate faculty member (not on research)
CONST	PAPMS = 0.1	number of papers/yr/M.S. student
CONST	PAPPHD = 0.2	number of papers/yr/Ph.D. student
CONST	PAPRES = 1.0	number of papers/yr/research project
CONST	QPGF = 3.5	quality points/graduate faculty member
CONST	QPMS = 1.2	quality points/M.S. student
CONST	QPPAP = 3.5	quality points/published paper
CONST	QPPHD = 2.5	quality points/Ph.D. student
CONST	QPRP = 4.0	quality points/research project
CONST	QPUGF = 2.0	quality points/undergraduate faculty member
PARAM	PAPERS = 10.0	number of papers published/period by I.E. department
PARAM	QUAL = 100.0	quality of department
PARAM	QUALO = 95.0	quality of department at time 0

Simulation Results

The initial simulation runs were designed to get the model in running order without detailed commitment to a match with actual conditions. After a working model was obtained, simulation runs were made to test its sensitivity to several factors, as was done with the university model. While the results were interesting, they were not considered useful for prediction purposes since the model had not been checked against actual departmental operations. Consequently, the actual constants and parameters involved in the departmental operations in 1961 were inserted as a starting point, and an attempt was made to adjust the interacting factors to produce actual departmental conditions in 1971. The simulation results shown in Figure 15 provide an excellent approximation. Undergraduate faculty decreased from approximately 6.0 (equivalent) to four, graduate faculty rose from 2.5 to 7, graduate assistants from 1(2 half-time people) to 2 3/4 (5½ half-time), B.S. enrollment from approximately 90 to 150, M.S. from 5 to 21, Ph.D. from 1 to 10, and over-all college enrollment from 900 to 1287. The results are also tabulated as row 1 of Table I. Parenthetically, the table also lists Research Projects and Quality, taken from the computer printout but not included in the graphs.

To further study the efficacy of the model, a twenty year simulation was run from 1961 to 1981, to observe the predicted results if departmental operations continued as before, using the Van Bertalanffy growth curve (moderate rate, diminishing returns) for enrollment and the lower constant value for research support included in the preceding list (IHFAC = 0.2, OHQ = 0.2). The results of the simulation are shown in Figure 16. The 1981 estimates are also included as row two in Table I. Total engineering enrollment increased from 1287 in 1971 to 1621 in 1981, a growth of 334 versus 387 for the preceding decade. The results fit expectations, for the Van Bertalanffy curve involves a diminishing growth rate. Based on current engineering enrollment trends, however, the actual rate of increase should flatten still more during the next

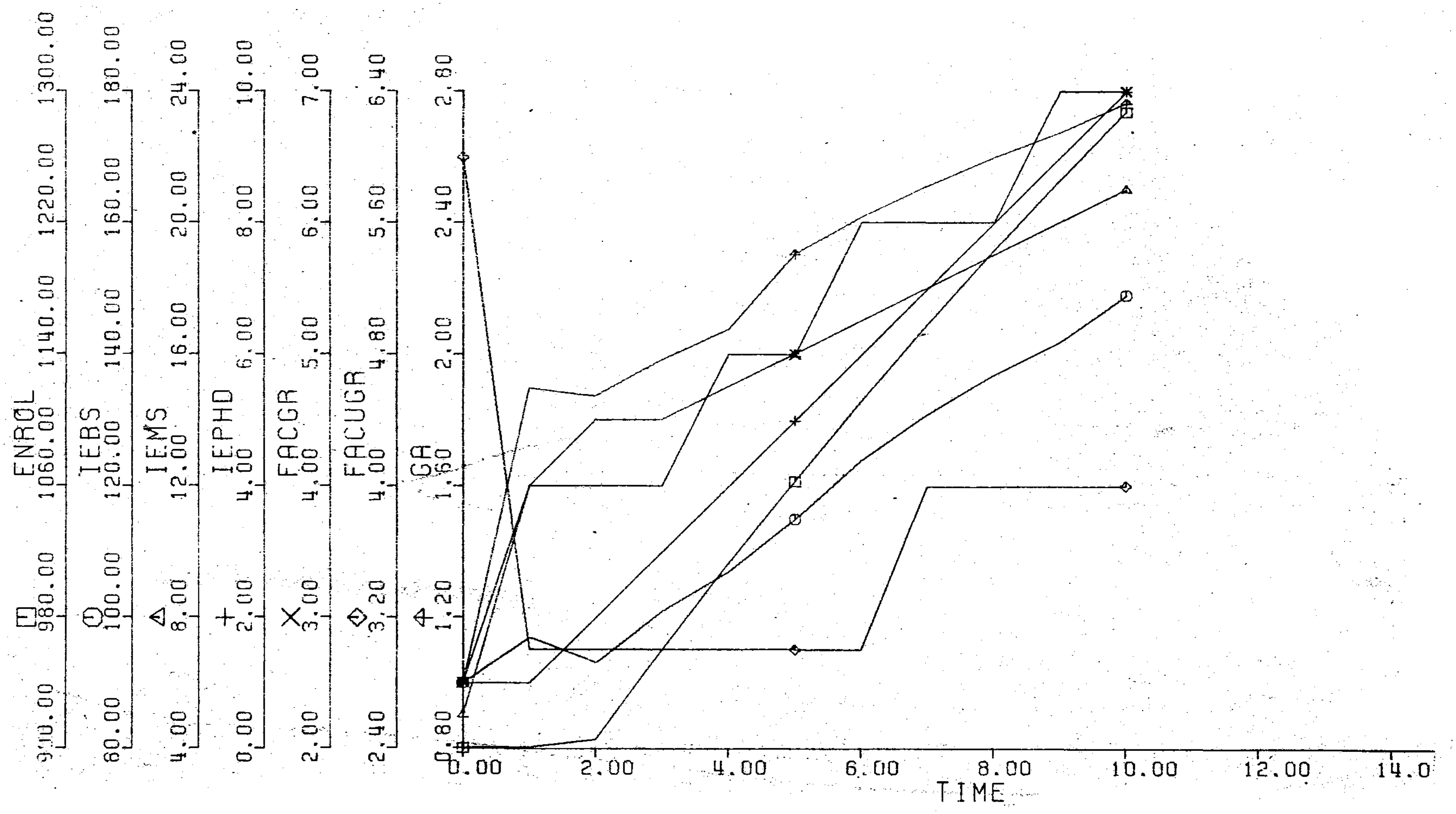

Figure 15. Departmental Model - Initial Fit - 1961-1971

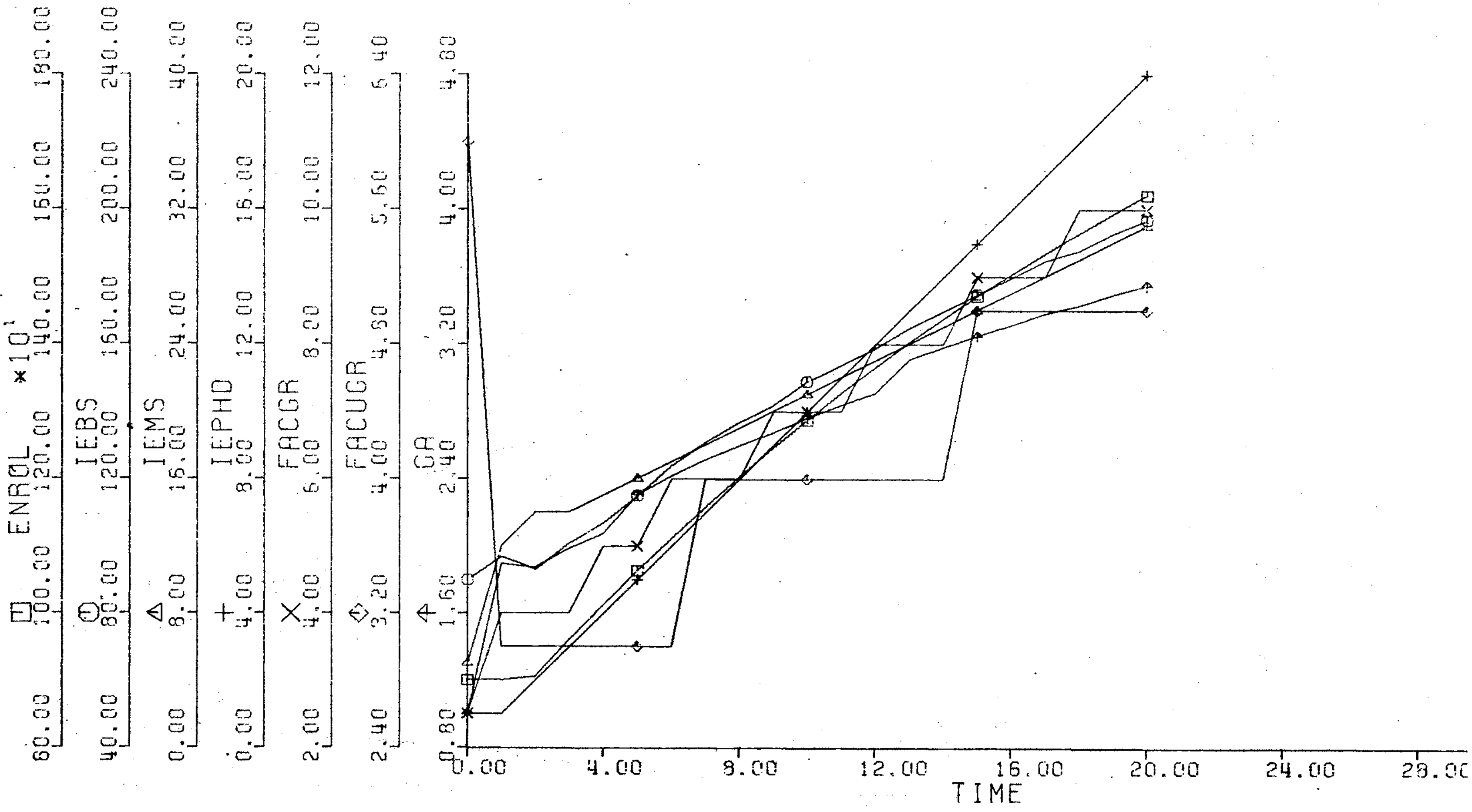

Figure 16. Departmental Model - Slow Growth - 1961-1981

ten years, hence all of the simulated results shown in row two are probably high for 1981.

The next simulation run, shown in Figure 17, continued to use the slow Van Bertalanffy enrollment growth curve, but with more research support (IHFAC = 0.05, OHQ = 0.05). In addition, the growth curve was increased from the .5 value of the 1961 run to the more realistic .9 value of 1971 for initial conditions. The results are shown in Figure 17 and the 1981 values are summarized in row 3. Note that while total engineering enrollment stayed the same as the preceding row, departmental B.S., M.S., and Ph.D. numbers all increased slightly. The number of undergraduate faculty members remained constant at five, still up only one from the 1971 figure. As expected, the number of graduate faculty members increased from 17 to 21, for the quality and number of research projects rose substantially as a result of the additional research impact. The period covered was from 1971 to 1991.

The next change in the model involved the use of a fast Van Bertalanffy growth curve for engineering enrollment and covered the period 1971-1981. The results are shown in Figure 18 and the 1981 values are tabulated in row four of the table. The substantial engineering college enrollment increase over the preceding row indicates that the 1971-1981 slow Van Bertalanffy results of the two preceding rows were calculated over the early, consistently rising portion of the curve rather than a later stage when flattening had occurred. The 30% college increase was matched by the bachelor's enrollment in industrial engineering, but not by the graduate sector, where only a 17% rise was achieved at both the M.S. and Ph.D. levels. The lower rate of graduate enrollment growth appeared, however, to be in consonance with the

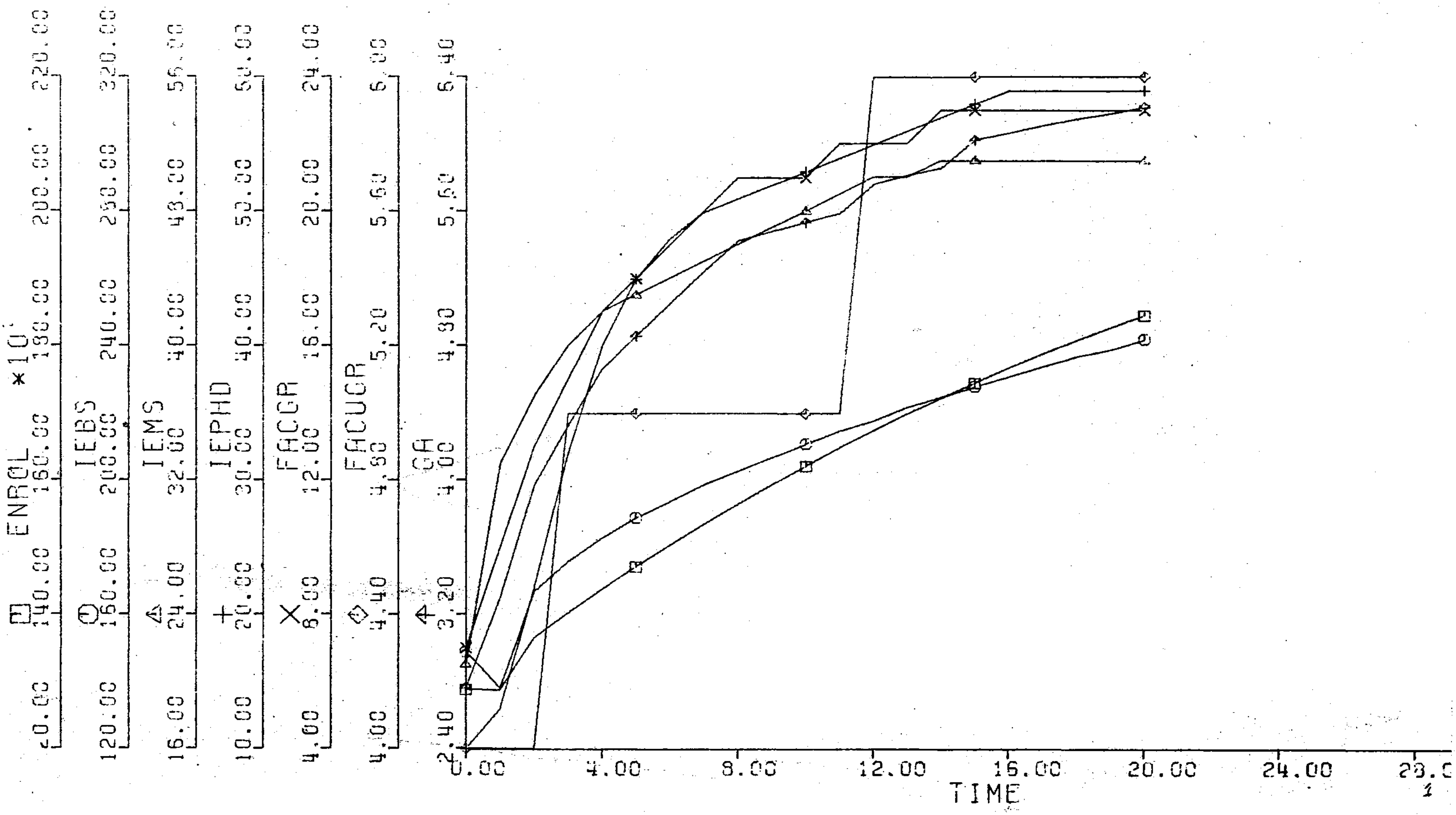

Figure 17. Departmental Model - Slow Growth - 1971-1991, Added Research

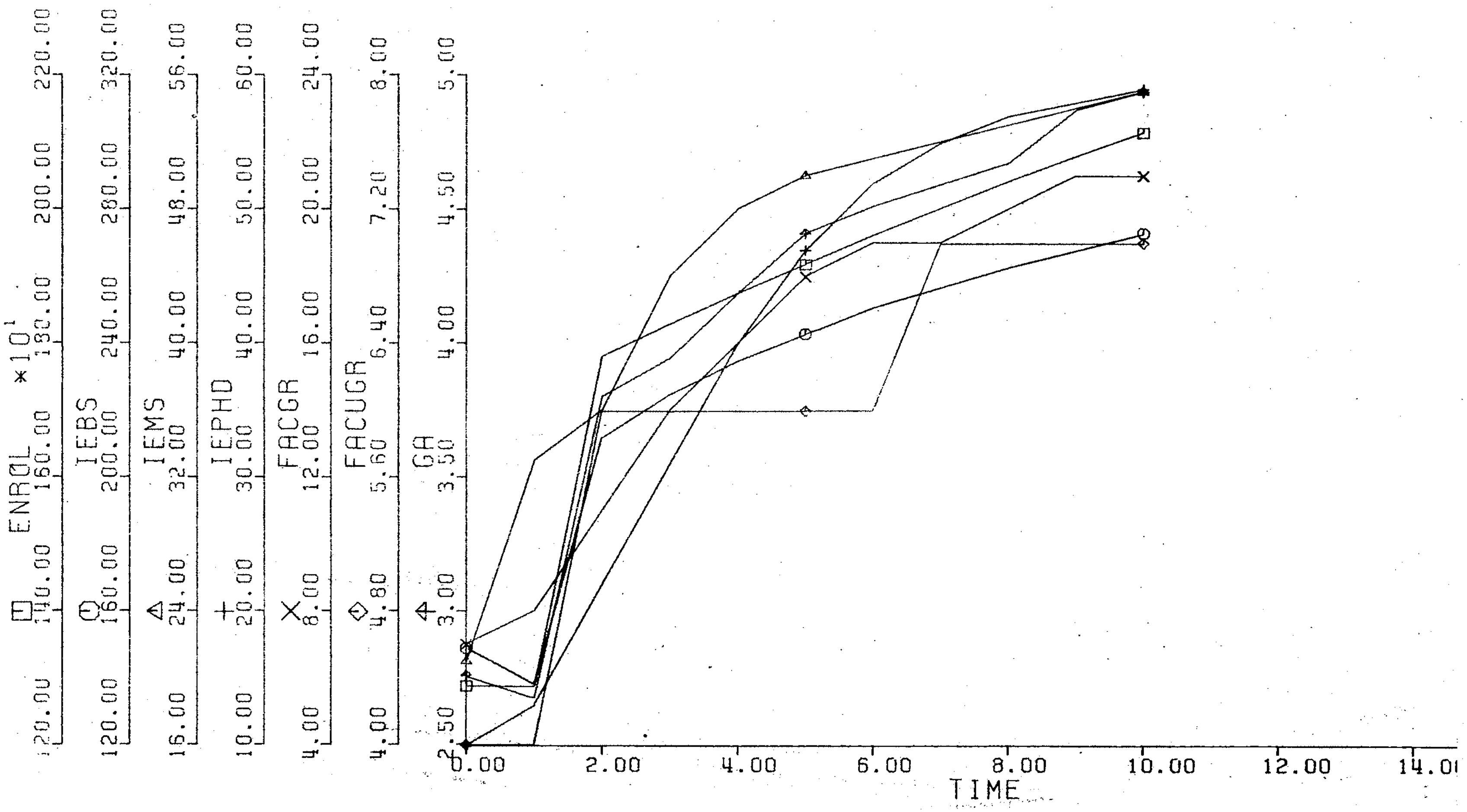

Figure 18. Departmental Model - Fast Growth - 1971-1981

moderate increase in both departmental quality from 248 to 265, and number of research projects, from seven to eight.

Figure 19, whose final results are tabulated in row 5 of the table, reflects for the fast Van Bertalanffy growth the additional research support demonstrated previously for the slow Van Bertalanffy curve. The period covered was again 1971-1981. As before, total engineering growth remained the same, industrial engineering enrollment at all levels increased slightly, the number of undergraduate faculty stayed constant, and quality, graduate faculty and research contracts increased substantially.

The two final simulation runs, each from 1971 to 1981, were made to check the model under linear enrollment growth conditions rather than the diminishing returns Van Bertalanffy curve. The results are shown in Figure 20 (for normal research support) and Figure 21 (for added research). The final values are tabulated in rows 6 and 7 of Table I. A comparison of the 1981 values from rows 2 and 3 with 6 and 7 demonstrates that, except for minor differences in the yearly growth curves (or timing of step changes), the final values are virtually identical. Actual differences are often less than apparent ones, for the scale values are varied automatically by the Cal Comp plotter, hence will differ between charts.

A sample copy of the program and several of the curves computed for the department runs which generated Figure 16 (slow Van Bertalanffy growth, less research, for the period 1961 to 1981) are included as Appendix B to provide additional information about the model.

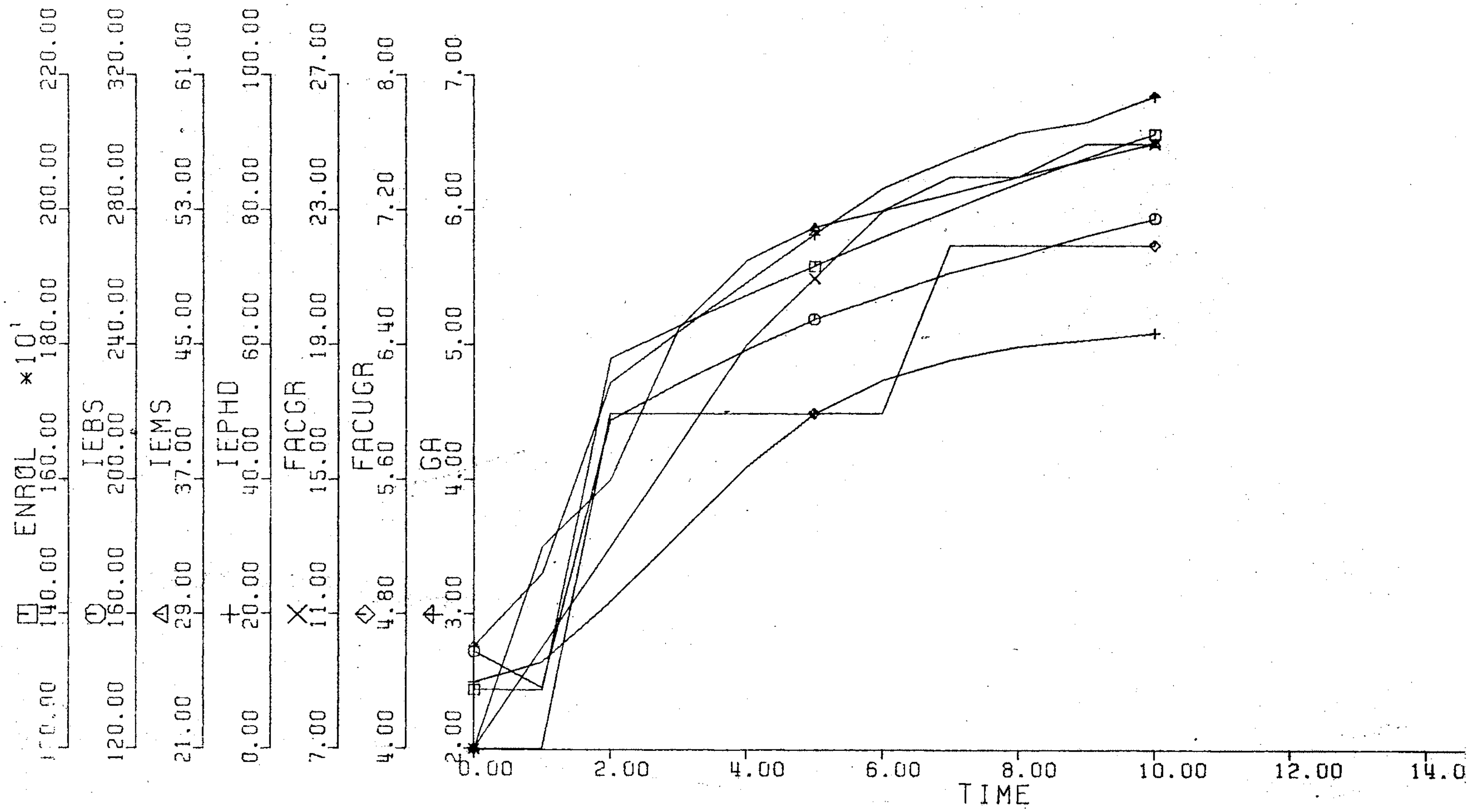

Figure 19. Departmental Model - Fast Growth - 1971-1981, Added Research

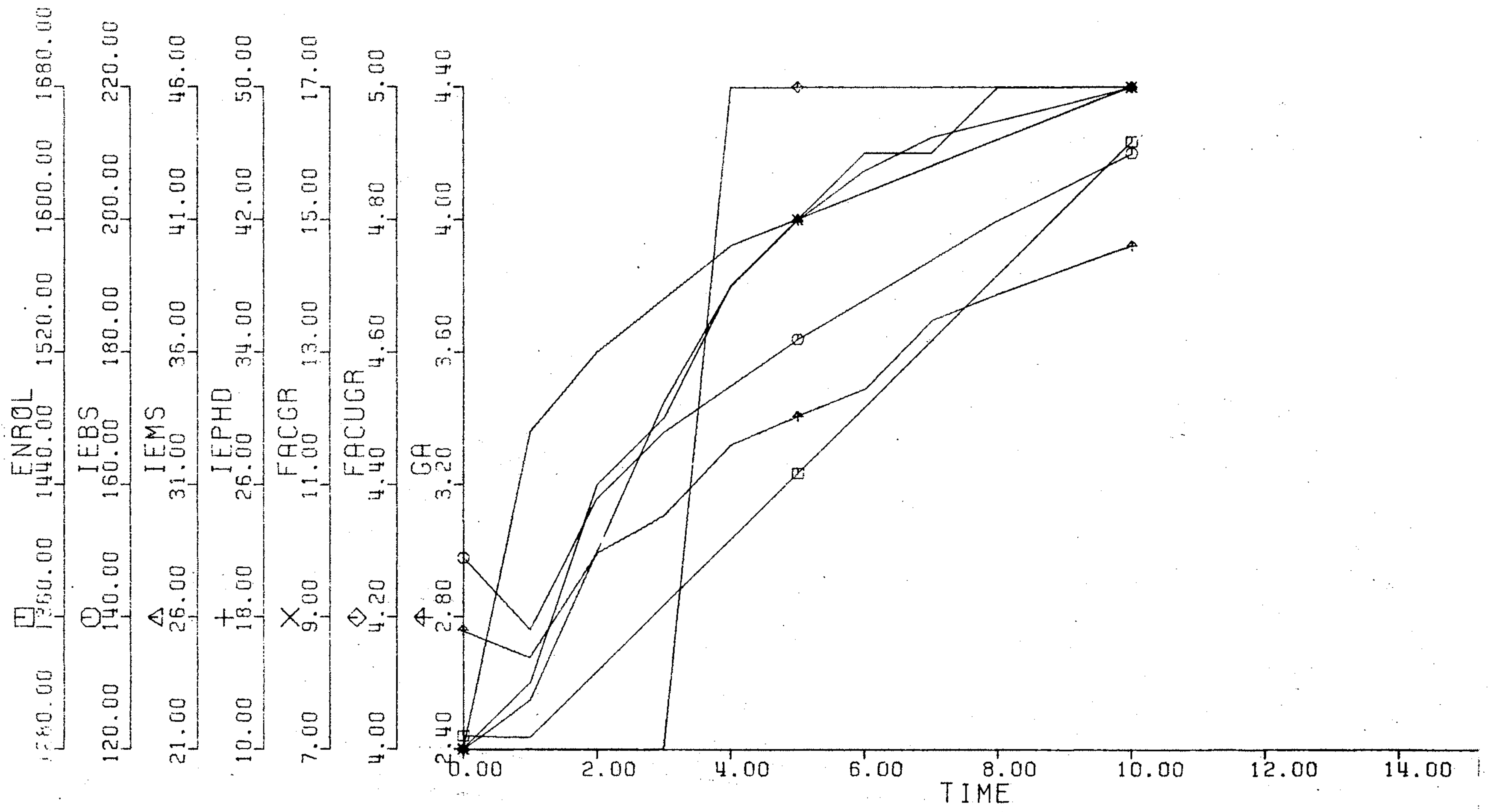

Figure 20. Departmental Model - Positive Linear Growth - 1971-1981

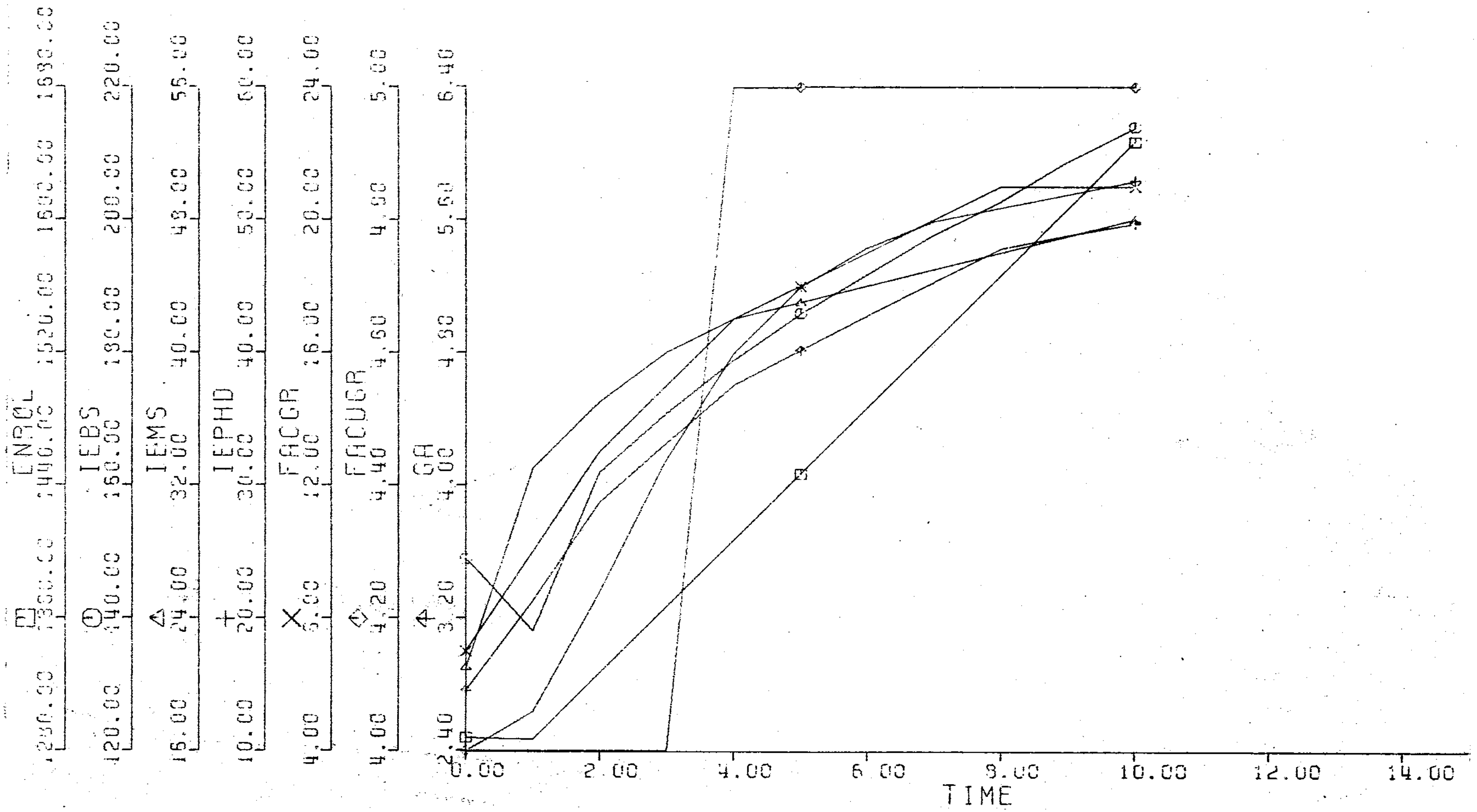

Figure 21. Departmental Model - Positive Linear Growth, Added Research - 1971-1981

TABLE I

PROJECTED RESULTS OF TEN-YEAR SIMULATION - DEPARTMENTAL MODEL; 1971-81

	ENROL	IEBS	IEMS	IEPHD	RESF	FACGR	FACUGR	GA	QUAL
Initial Conditions 1971	1287	149	21	12	2	7	4	2.76	100
Slow Van Bertalanffy 1981 Values - From Figure 16	1621	207	47	50	7	17	5	3.88	248
Slow Van Bertalanffy Additional Research 1981 Values - From Figure 17	1621	211	48	53	20	21	5	5.50	275
Fast Van Bertalanffy 1981 Values - From Figure 18	2114	273	55	59	8	21	7	4.94	265
Fast Van Bertalanffy Additional Values 1981 Values - From Figure 19	2114	278	57	62	23	25	7	6.85	292
Positive Linear 1981 Values - From Figure 20	1647	210	46	50	7	17	5	3.92	247
Positive Linear Additional Research 1981 Values - From Figure 21	1647	214	48	53	5	21	5	5.58	275

Although considerable work was required to match the model with the operation of the department, such effort was worthwhile for greater confidence resulted in the model's ability to predict the impact of changes in any of its segments.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The dissertation objectives outlined in the first chapter included two major facets. One was an attempt to determine the applicability of systems analysis modeling techniques to institutions of higher education. The other involved a feasibility study of the International Business Machine Corporation compiler, S/360 CSMP (Continuous System Modeling Program) as a tool for model analysis. The university and departmental research results illustrated in Chapter IV and V demonstrated the potential value of the suggested approach.

The university model, though aggregated, served as an initial demonstration of the applicability of systems modeling techniques. It also provided a testing ground to evaluate the efficacy of the CSMP compiler for model analysis. The detailed departmental model which followed extended both phases of the research effort. The system was studied in more detail, which permitted greater accuracy, and the initial CSMP simulation was adjusted to match actual data, which increased its predictive and sensitivity utility.

As anticipated, system analysis becomes quite complex as the number of interacting factors is increased. Model accuracy can be increased with additional detail, but at the price of greater analytical and simulation difficulty. The departmental model match with actual conditions, for example, consumed considerable analytical and computer time.

Another major difficulty encountered was that of accurately formulating system equations. Estimation was frequently required where insufficient data existed for accurate curve-fitting. In addition, factors known to contribute were omitted because of their inherent complexity and the need to keep the model size within reasonable limits.

Although the effective application of system dynamics concepts requires considerable time and skill, they nevertheless provide a useful tool for the analysis of higher education systems. Since organizations operate as viable, dynamic units through a series of interacting parts tied together by information and communication networks, the concepts make it possible to study the individual facets and their interaction. This represents one of the strong contributions of the subject for information feedback loops and their interrelations with other sectors of an organization, the timing of decisions, and the impact of delays in planning and implementation are more effectively handled by the system concepts utilized in the treatise than by judgment alone.

Simulation of system models by CSMP greatly augments their efficacy. While it is a powerful compiler, it currently has the weakness of being able to plot only one variable per sheet. That weakness can, with some difficulty, be offset by utilizing sections of FORDYN to provide multiple plots, and can be effectively eliminated by further programming effort and use of the CALCOMP plotter. When combined, the hardware and software make it possible to conduct effective sensitivity analyses on the systems models.

Although the modeling and simulation procedure developed should prove very helpful in the improvement of institutions of higher education, additional work should prove fruitful in several areas. First, the models were necessarily simplified because of the time and complexity involved in a thorough study of such organizations. The work should be greatly expanded. Further, the concepts should prove valuable for educational institutions at all levels, including the primary and secondary sectors. An investment of effort in those areas should provide substantial returns. Finally, additional research on CSMP should make it still more effective. Superimposed plots might be obtained directly and additional useful subroutines currently available only in DYNAMO might be possible.

In summary, while additional improvement and extension of the work should be conducted, the analytical and simulation procedures studied should engender greater understanding of any system analyzed. The methodology should - and is - being extended into areas far beyond the industrial sector which was involved in its origin.

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APPENDIX A

SAMPLE COMPUTER OUTPUT -
UNIVERSITY MODEL

```
          ****CONTINUOUS SYSTEM MODELING PROGRAM****

     ***PROBLEM INPUT STATEMENTS***

TITLE HIGHER EDUCATION
*
PARAM POWER=.7
CONST DELTAT=1.
CONST DPA=2.
CONST DPS=1500.
CONST FS=12000.
CONST FHT=1.
CONST T=1.
CONST FBT=2.
CONST MAX=40000.
PARAM US=9000.
PARAM GS=4500.
PARAM X=10000.
PARAM Y=1.15
PARAM P=5000.
PARAM Q=1.1
PARAM USTU=.28
PARAM USTG=.35
PARAM UAP=2500.
PARAM GAP=1400.
PARAM QF=0.75
PARAM QUA=2000.
PARAM QGA=1000.
PARAM AU=2000.
PARAM AG=1000.
PARAM GR=1750.
PARAM TS=10000.
PARAM DON=175000.
PARAM AL=100000.
PARAM LEG=9500000.
PARAM B=25000000.
PARAM INF=625.
PARAM NFP=625.
PARAM FHR=10.
PARAM IFC=2500000.
PARAM FAR=1250000.
PARAM FAC=2250000.
PARAM PREV=1000000.
PARAM RB=1250000.
PARAM UPK=1000000.
DYNAM
NOSORT
      IF(TIME)2,2,1
1     US=(1.-EXP(-POWER))*19000.
      GS=(1.-EXP(-POWER))*10000.
      POWER=POWER+.05
      C=NFP/INF
      USTU=USTU+.01
      TS2NFP=TS/NFP
      IF(TS2NFP.GT.18.5)USTU=USTU-.02
      UAP=USTU*C*US
      USTG=USTG+.01
      IF(TS2NFP.GT.17.5)USTG=USTG-.02
      GAP=USTG*(PGA+GS)*C
      QF=QF+0.02
      IF(TS2NFP.GT.18.5)QF=QF-0.03
      QUA=(UAP/4.0)*(MAX/TS)
      IF(QF.GT.1.)CF=1.
      QGA=GAP*QF
      AU=QUA
      AG=3.*NFP
      IF(AG.GT.QGA)AG=QGA
      DON=AL*DPA
      GR=(TS*.2)/DELTAT
      AL=AL+GR*DELTAT
      TS=TS+AU+AG-(GR*DELTAT)-(TS*.12)
      PGA=GR*DELTAT*.25
      LEG=1.02*LEG
      B=TS*DPS+DON+LEG
      INF=(.3*B)/FS
      NFP=NFP+FHR*DELTAT
      FHR=(INF-NFP)/FHT
      IFC=.1*B
      FAR=IFC/FBT
      FAC=FAC+(FAR*DELTAT)+PREV
      PREV=IFC-FAR
      RB=12000.*NFP
      IF(RB.GT..25*B)RB=.25*B
      UPK=.05*B
2     CONTINUE
TIMER DELT=1.,FINTIM=25.,PRDEL=1.,OUTDEL=1.
PREPAR UAP,GAP,AU,AG,GR,NFP
PRTPLT  UAP,GAP,AU,AG,GR,NFP
LABEL  HIGHER EDUCATION CSMP MODEL
END
STOP

OUTPUTS     INPUTS   PARAMS  INTEGS + MEM BLKS  FORTRAN  DATA CDS
41(500)   76(1400)  43(400)    0+  0=  0(300)   39(600)      45


ENDJOB
```

```
TIME = 1.0000E 00    US     = 8.8904E 03    GS   = 4.8452E 03    USTU = 2.9000E-01    USTG = 3.6000E-01
                     TS2NFP = 1.6000E 01    UAP  = 2.8682E 03    GAP  = 1.7803E 03    QF   = 7.7000E-01
                     QUA    = 2.8682E 03    QGA  = 1.3708F 03    AU   = 2.8682E 03    AG   = 1.3708E 03
                     GR     = 2.0000E 03    TS   = 1.1089E 04    DON  = 2.0000E 05    AL   = 1.0200E 05
                     PGA    = 5.0000E 02    LEG  = 9.6900E 06    B    = 2.6449E 07    INF  = 6.6121E 02
                     NFP    = 6 3500E 02    FHR  = 2 6213E 01    IFC  = 2.6449E 06    FAR  = 1.3224E 06
                     FAC    = 4.5724E 06    PREV = 1.3224E 06    RB   = 6.6121E 06    UPK  = 1.3224E 06

TIME = 2.0000E 00    US     = 1.0871E 04    GS   = 5.4356E 03    USTU = 3.0000E-01    USTG = 3.7000E-01
                     TS2NFP = 1.7384E 01    UAP  = 8.1321E 03    GAP  = 2.1091E 03    QF   = 7.9000E-01
                     QUA    = 2.8373E 03    QGA  = 1.6662E 03    AU   = 2.8373E 03    AG   = 1.6662E 03
                     GR     = 2.2078E 03    TS   = 1.2010E 04    DON  = 2.0400E 05    AL   = 1.0421E 05
                     PGA    = 5.5195E 02    LEG  = 9.8838E 06    B    = 2.8103E 07    INF  = 7.0257E 02
                     NFP    = 6.6121E 02    FHR  = 4.1355E 01    IFC  = 2.8103E 06    FAR  = 1.4051E 06
                     FAC    = 7.3000E 06    PREV = 1.4051E 06    RB   = 7.0257E 06    UPK  = 1.4051E 06

TIME = 3.0000E 00    US     = 1.1804E 04    GS   = 6.9020E 03    USTU = 3.1000E 01    USTG = 3.6000E-01
                     TS2NFP = 1.8164E 01    UAP  = 3.4439E 03    GAP  = 2.1867E 03    QF   = 8.1000E-01
                     QUA    = 2.8675E 03    QGA  = 1.7712E 03    AU   = 2.8675E 03    AG   = 1.7712E 03
                     GR     = 2.4020E 03    TS   = 1.2805E 04    DON  = 2.0842E 05    AL   = 1.0661E 05
                     PGA    = 6.0050E 02    LEG  = 1.0081E 07    B    = 2.9498E 07    INF  = 7.3745E 02
                     NFP    = 7.0257E 02    FHR  = 3.4884E 01    IFC  = 2.9498E 06    FAR  = 1.4748E 06
                     FAC    = 1.0180E 07    PREV = 1.4749E 06    RB   = 7.3745E 06    UPK  = 1.4748E 06

TIME = 4.0000E 00    US     = 1.2692E 04    GS   = 6.3458E 03    USTU = 3.2000E-01    USTG = 3.5000E-01
                     TS2NFP = 1.8227E 01    UAP  = 3.8692E 03    GAP  = 2.3162E 03    QF   = 8.3000E-01
                     QUA    = 3.0215E 03    QGA  = 1.9224E 03    AU   = 3.0215E 03    AG   = 1.9224E 03
                     GR     = 2.5611E 03    TS   = 1.3652E 04    DON  = 2.1322E 05    AL   = 1.0917E 05
                     PGA    = 6.4027E 02    LEG  = 1.0283E 07    B    = 3.0974E 07    INF  = 7.7434E 02
                     NFP    = 7.3745E 02    FHR  = 3.6891E 01    IFC  = 3.0874E 06    FAR  = 1.5487E 06
                     FAC    = 1.8204E 07    PREV = 1.5487E 06    RB   = 7.7434E 06    UPK  = 1.5487E 06
```

```
 HIGHER EDUCATION CSMP MODEL                                         PAGE   1

                        MINIMUM              AU     VERSUS TIME           MAXIMUM
                       2.0000E 03                                        4.4867E 03
 TIME          AU          I                                                 I
0.0          2.0000E 03    +
1.0000E 00   2.7738E 03    ---------------+
2.0000E 00   2.6435E 03    ------------+
3.0000E 00   2.6312E 03    ------------+
4.0000E 00   2.7306E 03    --------------+
5.0000E 00   2.7921E 03    ---------------+
6.0000E 00   2.8724E 03    -----------------+
7.0000E 00   2.9474E 03    -------------------+
8.0000E 00   3.0261E 03    --------------------+
9.0000E 00   3.1045E 03    ----------------------+
1.0000E 01   3.1841E 03    -----------------------+
1.1000E 01   3.2642E 03    -------------------------+
1.2000E 01   3.3451E 03    ---------------------------+
1.3000E 01   3.4268E 03    ----------------------------+
1.4000E 01   3.5167E 03    ------------------------------+
1.5000E 01   3.6134E 03    --------------------------------+
1.6000E 01   3.7111E 03    ----------------------------------+
1.7000E 01   3.8109E 03    ------------------------------------+
1.8000E 01   3.9118E 03    --------------------------------------+
1.9000E 01   4.0136E 03    ----------------------------------------+
2.0000E 01   4.1162E 03    ------------------------------------------+
2.1000E 01   4.2194E 03    --------------------------------------------+
2.2000E 01   4.3231E 03    ----------------------------------------------+
2.3000E 01   4.3552E 03    -----------------------------------------------+
2.4000E 01   4.4703E 03    -------------------------------------------------+
2.5000E 01   4.4867E 03    --------------------------------------------------+
```

```
                        MINIMUM              GR     VERSUS TIME           MAXIMUM
                       1.7500E 03                                        3.7466E 03
 TIME          GR          I                                                 I
0.0          1.7500E 03    +
1.0000E 00   2.0000E 03    ------+
2.0000E 00   2.1939E 03    -----------+
3.0000E 00   2.3461E 03    --------------+
4.0000E 00   2.4576E 03    -----------------+
5.0000E 00   2.5708E 03    --------------------+
6.0000E 00   2.6717E 03    -----------------------+
7.0000E 00   2.7680E 03    -------------------------+
8.0000E 00   2.8580E 03    ---------------------------+
9.0000E 00   2.9433E 03    -----------------------------+
1.0000E 01   3.0239E 03    -------------------------------+
1.1000E 01   3.1000E 03    ---------------------------------+
1.2000E 01   3.1718E 03    -----------------------------------+
1.3000E 01   3.2396E 03    -------------------------------------+
1.4000E 01   3.2992E 03    --------------------------------------+
1.5000E 01   3.3500E 03    ----------------------------------------+
1.6000E 01   3.3952E 03    -----------------------------------------+
1.7000E 01   3.4355E 03    ------------------------------------------+
1.8000E 01   3.4720E 03    -------------------------------------------+
1.9000E 01   3.5052E 03    -------------------------------------------+
2.0000E 01   3.5356E 03    --------------------------------------------+
2.1000E 01   3.5636E 03    ---------------------------------------------+
2.2000E 01   3.5892E 03    ----------------------------------------------+
2.3000E 01   3.6491E 03    -----------------------------------------------+
2.4000E 01   3.6794E 03    ------------------------------------------------+
2.5000E 01   3.7466E 03    --------------------------------------------------+
```

```
                        MINIMUM              AG     VERSUS TIME           MAXIMUM
                       1.0000E 03                                        2.0685E 03
 TIME          AG          I                                                 I
0.0          1.0000E 03    +
1.0000E 00   1.3955E 03    ------------------+
2.0000E 00   1.6279E 03    -----------------------------+
3.0000E 00   1.6802E 03    -------------------------------+
4.0000E 00   1.7674E 03    -----------------------------------+
5.0000E 00   1.8255E 03    --------------------------------------+
6.0000E 00   1.8840E 03    -----------------------------------------+
7.0000E 00   1.9316E 03    -------------------------------------------+
8.0000E 00   1.9733E 03    ---------------------------------------------+
9.0000E 00   2.0074E 03    -----------------------------------------------+
1.0000E 01   2.0347E 03    ------------------------------------------------+
1.1000E 01   2.0551E 03    -------------------------------------------------+
1.2000E 01   2.0685E 03    --------------------------------------------------+
1.3000E 01   2.0546E 03    -------------------------------------------------+
1.4000E 01   2.0161E 03    -----------------------------------------------+
1.5000E 01   1.9726E 03    ---------------------------------------------+
1.6000E 01   1.9229E 03    -------------------------------------------+
1.7000E 01   1.8684E 03    ----------------------------------------+
1.8000E 01   1.8096E 03    -------------------------------------+
1.9000E 01   1.7468E 03    ----------------------------------+
2.0000E 01   1.6804E 03    -------------------------------+
2.1000E 01   1.6107E 03    ----------------------------+
2.2000E 01   1.7190E 03    ---------------------------------+
2.3000E 01   1.6348E 03    -----------------------------+
2.4000E 01   1.7527E 03    -----------------------------------+
2.5000E 01   1.8499E 03    ---------------------------------------+
```

```
                        MINIMUM              NFP    VERSUS TIME           MAXIMUM
                       6.2500E 02                                        1.0930E 03
 TIME          NFP         I                                                 I
0.0          6.2500E 02    +
1.0000E 00   6.3500E 02    -+
2.0000E 00   6.5860E 02    ---+
3.0000E 00   6.9209E 02    -------+
4.0000E 00   7.1805E 02    ---------+
5.0000E 00   7.4443E 02    ------------+
6.0000E 00   7.6860E 02    ---------------+
7.0000E 00   7.9204E 02    -----------------+
8.0000E 00   8.1441E 02    --------------------+
9.0000E 00   8.3599E 02    ----------------------+
1.0000E 01   8.5680E 02    ------------------------+
1.1000E 01   8.7690E 02    --------------------------+
1.2000E 01   8.9631E 02    ----------------------------+
1.3000E 01   9.1507E 02    ------------------------------+
1.4000E 01   9.3243E 02    --------------------------------+
1.5000E 01   9.4827E 02    ----------------------------------+
1.6000E 01   9.6317E 02    ------------------------------------+
1.7000E 01   9.7730E 02    -------------------------------------+
1.8000E 01   9.9083E 02    ---------------------------------------+
1.9000E 01   1.0039E 03    ----------------------------------------+
2.0000E 01   1.0165E 03    -----------------------------------------+
2.1000E 01   1.0289E 03    -------------------------------------------+
2.2000E 01   1.0409E 03    --------------------------------------------+
2.3000E 01   1.0595E 03    ----------------------------------------------+
2.4000E 01   1.0727E 03    -----------------------------------------------+
2.5000E 01   1.0930E 03    --------------------------------------------------+
```

APPENDIX B

SAMPLE COMPUTER OUTPUT - DEPARTMENTAL MODEL

```
        . ****CONTINUOUS SYSTEM MODELING PROGRAM****

     ***PROBLEM INPUT STATEMENTS***

MACRO  A=XLOG(Q,QO,F)
       A=F * ALOG(Q/QO) + QO
ENDMAC
TITLE  DEPT. MOD./SLOW VAN BERT. GROWTH
STORAGE  CARMS(2),CARPHD(4)
INITIAL
*
*  STUDENT SECTION CONSTANTS
*
CONST  BSFRAC=.00112,BSQ=1.0,FBS=20.0,FMS1=010.0,FMS2=010.0,FPHD1=100.0
CONST  FPHD2=100.0,MSDR1=0.04,MSDR2=0.01,MSFRAC=0.00100,MSGR1=0.7
CONST  MSGR2=0.25,MSQ=0.084,PHDDR1=0.06,PHDDR2=0.01,PHDDR3=0.005
CONST  PHDDR4=0.005
CONST  PHDFRA=0.00175,PHDGR1=0.0,PHDGR2=0.38,PHDGR3=0.3900,PHDGR4=0.15
CONST  PHDQ=0.0095,DT=1.0
TABLE  CARMS(1-2)=2*10.0,CARPHD(1-4)=4*1.5
*
*  RESEARCH SECTION CONSTANTS
*
CONST  IHFAC=0.2,OHQ=0.02,RESTF=0.75
*
*  STAFF SECTION CONSTANTS
*
CONST  FACRP=0.25,GARP=0.125,HBSIE=0.4,HBSNIE=0.039,HMSIE=0.6,HPHDIE=0.8
CONST  POSGR=0.111,POSUGR=0.075,THMS=0.25,THPHD=0.67,UNFRGA=0.29
CONST  UNFRGF=0.20,UNFRUF=0.51
*
*  QUALITY SECTION CONSTANTS
*
CONST  PAPGF=1.0,PAPMS=0.1,PAPPHD=0.2,PAPRES=1.0,QPGF=3.5,QPMS=1.0
CONST  QPPAP=3.5,QPPHD=2.5,QPMS=1.2,QPRP=4.0,QPUGF=2.0
*
*  STUDENT SECTION PARAMETERS AND INITIAL VALUES
*
PARAM  ENGR=0900.0,KOUNT1=0.0,SUM1=0.0,KOUNT2=0.0,SUM2=0.0
PARAM  ENROL=900.0,IEBS=90,IEMS=5,IEPHD=1
PARAM  X=.5
*
*  RESEARCH SECTION PARAMETERS AND INITIAL VALUES
*
PARAM RESF=2.
*
*  STAFF SECTION PARAMETERS AND INITIAL VALUES
*
PARAM  HUNGR=105.0,HGRAD=17.0,HTHES=10.0,FACRES=0.5,GARES=0.0,FACGR=2.5
PARAM  FACUGR=6.,GA=1.
*
*  QUALITY SECTION PARAMETERS AND INITIAL VALUES
*
PARAM PAPERS=10,QUAL=100,QUALO=95.
*
DYNAMIC
  NOSORT
      IF (TIME) 2,2,1
*
*  STUDENT SECTION
*
  1   ENROL=ENGR
      ENGR=(1.-EXP(-X))*2300.
      X=X+.04
      XLOGA=XLOG(QUAL,QUALO,FMS1)
      XLOGB=XLOG(QUAL,QUALO,FMS2)
      RRMS=MSFRAC*XLOGA*IEBS+MSQ*XLOGB
      DRMS=MSDR1*CARMS(2)+MSDR2*CARMS(1)
      GRMS=MSGR1*CARMS(2) + MSGR2*CARMS(1)
      CALL BOXC(RRMS,OUT,CARMS,KOUNT1,1,2,SUM1)
      XLOGC=XLOG(QUAL,QUALO,FPHD1)
      XLOGD=XLOG(QUAL,QUALO,FPHD2)
      RRPHD=PHDFRA*XLOGC*IEMS+PHDQ*XLOGD
      DRPHD=PHDDR1*CARPHD(4)+PHDDR2*CARPHD(3)+PHDDR3*CARPHD(2)+PHDDR4...
              *CARPHD(1)
      GRPHD=PHDGR1*CARPHD(1)+PHDGR2*CARPHD(3)+PHDGR3*CARPHD(2)+PHDGR4...
              *CARPHD(1)
      CALL BOXC(RRPHD,OUT,CARPHD,KOUNT2,1,4,SUM2)
      XLOGE=XLOG(QUAL,QUALO,FBS)
      IEBS=AINT(BSFRAC*XLOGE*ENROL+0.5)
      IEMS=AINT((IEMS+(RRMS-GRMS-DRMS)*DT)+0.5)
      IEPHD=AINT((IEPHD+(RRPHD-GRPHD-DRPHD)*DT)+0.5)
*
*  RESEARCH SECTION
*
      IHRESR=IHFAC*FACGR
      OHRESR=OHQ*(ALOG(QUAL/QUALO)+QUALO)
      RESTR=RESTF*RESF
      RESF=AINT((RESF+(IHRESR+OHRESR-RESTR)*DT)+0.5)
*
*  STAFF SECTION
*
      HUNGR=HBSIE*IEBS+HBSNIE*(ENROL-IEBS)
      HGRAD=HMSIE*IEMS+HPHDIE*IEPHD
      HTHES=THMS*IEMS+THPHD*IEPHD
      FACRES=FACRP*RESF
      GARES=GARP*RESF
      FACGR=AINT((FACRES+POSGR*(HGRAD+HTHES)+ POSGR*UNFRGF*HUNGR)+0.5)
      FACUGR=AINT(POSUGR*UNFRUF*HUNGR+0.5)
      GA=GARES+POSUGR*UNFRGA*HUNGR
*
*  QUALITY SECTION
*
      PAPERS=AINT((PAPGF*FACGR+PAPMS*IEMS+PAPPHD*IEPHD+PAPRES*RESF)+0.5)
      QUAL=100.0*(ALOG((QPGF*FACGR+QPUGF*FACUGR+QPPAP*PAPERS+QPPHD...
              *IEPHD+QPMS*IEMS+QPRP*RESF)/QUALO)+1.0)
*
2     CONTINUE
TIMER  DELT=1.0,FINTIM=20.0,PRDEL=1.0,OUTDEL=1.0
PREPAR ENROL,IEBS,IEMS,IEPHD,FACGR,FACUGR,GA
PRINT ENROL,RRMS,DRMS,GRMS,RRPHD,DRPHD,GRPHD,...
      IEBS,IEMS,IEPHD,IHRESR,OHRESR,RESTR,RESF,HUNGR,...
      HGRAD,HTHES,FACRES,GARES,FACGR,FACUGR,GA,PAPERS,QUAL
PRTPLT  ENROL,IEBS,IEMS,IEPHD,FACGR,FACUGR,GA
LABEL  DEPT. MOD./SLOW VAN BERT. GROWTH
END
STOP
```

```
DEPT. MOD./SLOW VAN BERT. GROWTH                            INTGRL NOT USED

TIME  =  0.0          ENROL =  9.0000E 02      RRMS   =  0.0              DRMS   =  0.0              GRMS   =  0.0
                      RRPHD =  0.0             DRPHD  =  0.0              GRPHD  =  0.0              IEBS   =  9.0000E 01
                      IEMS  =  5.0000E 00      IEPHD  =  1.0000E 00       IHRESR=  0.0               OHRESR=  0.0
                      RESTR =  0.0             RESF   =  2.0000E 00       HUNGR  =  1.0500E 02       HGRAD  =  1.7000E 01
                      HTHES =  1.0000E 01      FACRES=  5.0000E-01        GARES  =  0.0              FACGR  =  2.5000E 00
                      FACUGR=  6.0000E 00      GA     =  1.0000E 00       PAPERS=  1.0000E 01        QUAL   =  1.0000E 02

TIME  =  1.0000E 00   ENROL =  9.0000E 02      RRMS   =  1.6619E 01       DRMS   =  5.0000E-01       GRMS   =  9.5000E 00
                      RRPHD =  1.8274E 00      DRPHD  =  1.2000E-01       GRPHD  =  1.3800E 00       IEBS   =  9.7000E 01
                      IEMS  =  1.2000E 01      IEPHD  =  1.0000E 00       IHRESR=  5.0000E-01        OHRESR=  1.9010E 00
                      RESTR =  1.5000E 00      RESF   =  3.0000E 00       HUNGR  =  7.0117E 01       HGRAD  =  8.0000E 00
                      HTHES =  3.6700E 00      FACRES=  7.5000E-01        GARES  =  3.7500E-01       FACGR  =  4.0000E 00
                      FACUGR=  3.0000E 00      GA     =  1.9000E 00       PAPERS=  8.0000E 00        QUAL   =  7.8863E 01

TIME  =  2.0000E 00   ENROL =  9.0498E 02      RRMS   =  1.6858E 01       DRMS   =  7.6477E-01       GRMS   =  1.4133E 01
                      RRPHD =  2.3297E 00      DRPHD  =  1.3964E-01       GRPHD  =  1.3800E 00       IEBS   =  9.3000E 01
                      IEMS  =  1.4000E 01      IEPHD  =  2.0000E 00       IHRESR=  8.0000E-01        OHRESR=  1.8963E 00
                      RESTR =  2.2500E 00      RESF   =  3.0000E 00       HUNGR  =  6.8867E 01       HGRAD  =  1.0000E 01
                      HTHES =  4.8400E 00      FACRES=  7.5000E-01        GARES  =  3.7500E-01       FACGR  =  4.0000E 00
                      FACUGR=  3.0000E 00      GA     =  1.8729E 00       PAPERS=  9.0000E 00        QUAL   =  8.9230E 01

TIME  =  3.0000E 00   ENROL =  9.5968E 02      RRMS   =  1.6704E 01       DRMS   =  8.4051E-01       GRMS   =  1.5955E 01
                      RRPHD =  3.0169E 00      DRPHD  =  1.7305E-01       GRPHD  =  1.5044E 00       IEBS   =  1.0100E 02
                      IEMS  =  1.4000E 01      IEPHD  =  3.0000E 00       IHRESR=  8.0000E-01        OHRESR=  1.8987E 00
                      RESTR =  2.2500E 00      RESF   =  3.0000E 00       HUNGR  =  7.3888E 01       HGRAD  =  1.0800E 01
                      HTHES =  5.5100E 00      FACRES=  7.5000E-01        GARES  =  3.7500E-01       FACGR  =  4.0000E 00
                      FACUGR=  3.0000E 00      GA     =  1.9821E 00       PAPERS=  9.0000E 00        QUAL   =  9.2118E 01

TIME  =  4.0000E 00   ENROL =  1.0122E 03      RRMS   =  1.7518E 01       DRMS   =  8.3674E-01       GRMS   =  1.5907E 01
                      RRPHD =  3.1253E 00      DRPHD  =  2.2095E-01       GRPHD  =  1.8229E 00       IEBS   =  1.0700E 02
                      IEMS  =  1.5000E 01      IEPHD  =  4.0000E 00       IHRESR=  8.0000E-01        OHRESR=  1.8994E 00
                      RESTR =  2.2500E 00      RESF   =  3.0000E 00       HUNGR  =  7.8104E 01       HGRAD  =  1.2200E 01
                      HTHES =  6.4300E 00      FACRES=  7.5000E-01        GARES  =  3.7500E-01       FACGR  =  5.0000E 00
                      FACUGR=  3.0000E 00      GA     =  2.0738E 00       PAPERS=  1.0000E 01        QUAL   =  1.0362E 02

TIME  =  5.0000E 00   ENROL =  1.0627E 03      RRMS   =  1.8311E 01       DRMS   =  8.6776E-01       GRMS   =  1.6439E 01
                      RRPHD =  3.7067E 00      DRPHD  =  2.3847E-01       GRPHD  =  2.3291E 00       IEBS   =  1.1500E 02
                      IEMS  =  1.6000E 01      IEPHD  =  5.0000E 00       IHRESR=  1.0000E 00        OHRESR=  1.9017E 00
                      RESTR =  2.2500E 00      RESF   =  4.0000E 00       HUNGR  =  8.2961E 01       HGRAD  =  1.3600E 01
                      HTHES =  7.3500E 00      FACRES=  1.0000E 00        GARES  =  5.0000E-01       FACGR  =  5.0000E 00
                      FACUGR=  3.0000E 00      GA     =  2.3044E 00       PAPERS=  1.2000E 01        QUAL   =  1.1753E 02

TIME  =  6.0000E 00   ENROL =  1.1112E 03      RRMS   =  1.9328E 01       DRMS   =  9.0761E-01       GRMS   =  1.7197E 01
                      RRPHD =  4.3605E 00      DRPHD  =  2.8039E-01       GRPHD  =  2.7137E 00       IEBS   =  1.2400E 02
                      IEMS  =  1.7000E 01      IEPHD  =  6.0000E 00       IHRESR=  1.0000E 00        OHRESR=  1.9043E 00
                      RESTR =  3.0000E 00      RESF   =  4.0000E 00       HUNGR  =  8.8102E 01       HGRAD  =  1.5000E 01
                      HTHES =  8.2700E 00      FACRES=  1.0000E 00        GARES  =  5.0000E-01       FACGR  =  6.0000E 00
                      FACUGR=  3.0000E 00      GA     =  2.4162E 00       PAPERS=  1.3000E 01        QUAL   =  1.2656E 02

TIME  =  7.0000E 00   ENROL =  1.1579E 03      RRMS   =  2.0357E 01       DRMS   =  9.5624E-01       GRMS   =  1.8108E 01
                      RRPHD =  4.8546E 00      DRPHD  =  3.2941E-01       GRPHD  =  3.0799E 00       IEBS   =  1.3100E 02
                      IEMS  =  1.8000E 01      IEPHD  =  7.0000E 00       IHRESR=  1.2000E 00        OHRESR=  1.9057E 00
                      RESTR =  3.0000E 00      RESF   =  4.0000E 00       HUNGR  =  9.2447E 01       HGRAD  =  1.6400E 01
                      HTHES =  9.1900E 00      FACRES=  1.0000E 00        GARES  =  5.0000E-01       FACGR  =  6.0000E 00
                      FACUGR=  4.0000E 00      GA     =  2.5107E 00       PAPERS=  1.3000E 01        QUAL   =  1.3105E 02
```

```
 DEPT. MOD./SLOW VAN BERT. GROWTH                                               PAGE   1
                            MINIMUM                FACGR   VERSUS TIME               MAXIMUM
                           2.5000E 00                                             1.0000E 01
 TIME            FACGR          I                                                         I
0.0             2.5000E 00      +
1.0000E 00      4.0000E 00      -----------+
2.0000E 00      4.0000E 00      -----------+
3.0000E 00      4.0000E 00      -----------+
4.0000E 00      5.0000E 00      -------------------+
5.0000E 00      5.0000E 00      -------------------+
6.0000E 00      6.0000E 00      ---------------------------+
7.0000E 00      6.0000E 00      ---------------------------+
8.0000E 00      6.0000E 00      ---------------------------+
9.0000E 00      7.0000E 00      -----------------------------------+
1.0000E 01      7.0000E 00      -----------------------------------+
1.1000E 01      7.0000E 00      -----------------------------------+
1.2000E 01      8.0000E 00      ------------------------------------------+
1.3000E 01      8.0000E 00      ------------------------------------------+
1.4000E 01      8.0000E 00      ------------------------------------------+
1.5000E 01      9.0000E 00      ---------------------------------------------------+
1.6000E 01      9.0000E 00      ---------------------------------------------------+
1.7000E 01      9.0000E 00      ---------------------------------------------------+
1.8000E 01      1.0000E 01      ----------------------------------------------------------+
1.9000E 01      1.0000E 01      ----------------------------------------------------------+
2.0000E 01      1.0000E 01      ----------------------------------------------------------+
```

```
                            MINIMUM                FACUGR VERSUS TIME                MAXIMUM
                           3.0000E 00                                              6.0000E 00
 TIME            FACUGR         I                                                         I
0.0             6.0000E 00      ----------------------------------------------------------+
1.0000E 00      3.0000E 00      +
2.0000E 00      3.0000E 00      +
3.0000E 00      3.0000E 00      +
4.0000E 00      3.0000E 00      +
5.0000E 00      3.0000E 00      +
6.0000E 00      3.0000E 00      +
7.0000E 00      4.0000E 00      -------------------+
8.0000E 00      4.0000E 00      -------------------+
9.0000E 00      4.0000E 00      -------------------+
1.0000E 01      4.0000E 00      -------------------+
1.1000E 01      4.0000E 00      -------------------+
1.2000E 01      4.0000E 00      -------------------+
1.3000E 01      4.0000E 00      -------------------+
1.4000E 01      4.0000E 00      -------------------+
1.5000E 01      5.0000E 00      ---------------------------------------+
1.6000E 01      5.0000E 00      ---------------------------------------+
1.7000E 01      5.0000E 00      ---------------------------------------+
1.8000E 01      5.0000E 00      ---------------------------------------+
1.9000E 01      5.0000E 00      ---------------------------------------+
2.0000E 01      5.0000E 00      ---------------------------------------+
```

```
                            MINIMUM                GA      VERSUS TIME               MAXIMUM
                           1.0000E 00                                              3.5468E 00
 TIME             GA            I                                                         I
0.0             1.0000E 00      +
1.0000E 00      1.9000E 00      --------------------+
2.0000E 00      1.8729E 00      --------------------+
3.0000E 00      1.9821E 00      ----------------------+
4.0000E 00      2.0738E 00      -------------------------+
5.0000E 00      2.3044E 00      ------------------------------+
6.0000E 00      2.4162E 00      --------------------------------+
7.0000E 00      2.5107E 00      ----------------------------------+
8.0000E 00      2.5958E 00      -------------------------------------+
9.0000E 00      2.6716E 00      --------------------------------------+
1.0000E 01      2.7616E 00      ----------------------------------------+
1.1000E 01      2.8346E 00      ------------------------------------------+
1.2000E 01      2.9062E 00      --------------------------------------------+
1.3000E 01      3.1094E 00      ------------------------------------------------+
1.4000E 01      3.1785E 00      -------------------------------------------------+
1.5000E 01      3.2465E 00      ----------------------------------------------------+
1.6000E 01      3.3134E 00      -----------------------------------------------------+
1.7000E 01      3.3791E 00      ------------------------------------------------------+
1.8000E 01      3.4281E 00      -------------------------------------------------------+
1.9000E 01      3.4919E 00      ---------------------------------------------------------+
2.0000E 01      3.5468E 00      ----------------------------------------------------------+
```

```
 DEPT. MOD./SLOW VAN BERT. GROWTH                                    PAGE   1

                        MINIMUM             IEBS   VERSUS TIME              MAXIMUM
                       9.0000E 01                                         1.9700E 02
 TIME          IEBS        I                                                  I
0.0           9.0000E 01   +
1.0000E 00    9.7000E 01   ---+
2.0000E 00    9.3000E 01   -+
3.0000E 00    1.0100E 02   -----+
4.0000E 00    1.0700E 02   -------+
5.0000E 00    1.1500E 02   -----------+
6.0000E 00    1.2400E 02   ---------------+
7.0000E 00    1.3100E 02   -------------------+
8.0000E 00    1.3700E 02   ---------------------+
9.0000E 00    1.4200E 02   ------------------------+
1.0000E 01    1.4900E 02   ---------------------------+
1.1000E 01    1.5400E 02   -----------------------------+
1.2000E 01    1.5900E 02   --------------------------------+
1.3000E 01    1.6500E 02   -----------------------------------+
1.4000E 01    1.7000E 02   -------------------------------------+
1.5000E 01    1.7500E 02   ---------------------------------------+
1.6000E 01    1.8000E 02   ------------------------------------------+
1.7000E 01    1.8500E 02   --------------------------------------------+
1.8000E 01    1.8800E 02   ---------------------------------------------+
1.9000E 01    1.9300E 02   ------------------------------------------------+
2.0000E 01    1.9700E 02   --------------------------------------------------+
```

```
                        MINIMUM             IEPHD  VERSUS TIME              MAXIMUM
                       1.0000E 00                                         2.0000E 01
 TIME          IEPHD       I                                                  I
0.0           1.0000E 00   +
1.0000E 00    1.0000E 00   +
2.0000E 00    2.0000E 00   --+
3.0000E 00    3.0000E 00   -----+
4.0000E 00    4.0000E 00   -------+
5.0000E 00    5.0000E 00   ----------+
6.0000E 00    6.0000E 00   -------------+
7.0000E 00    7.0000E 00   ---------------+
8.0000E 00    8.0000E 00   ------------------+
9.0000E 00    9.0000E 00   ---------------------+
1.0000E 01    1.0000E 01   -----------------------+
1.1000E 01    1.1000E 01   --------------------------+
1.2000E 01    1.2000E 01   ----------------------------+
1.3000E 01    1.3000E 01   -------------------------------+
1.4000E 01    1.4000E 01   ----------------------------------+
1.5000E 01    1.5000E 01   ------------------------------------+
1.6000E 01    1.6000E 01   ---------------------------------------+
1.7000E 01    1.7000E 01   ------------------------------------------+
1.8000E 01    1.8000E 01   --------------------------------------------+
1.9000E 01    1.9000E 01   -----------------------------------------------+
2.0000E 01    2.0000E 01   --------------------------------------------------+
```

```
                        MINIMUM             IEMS   VERSUS TIME              MAXIMUM
                       5.0000E 00                                         3.1000E 01
 TIME          IEMS        I                                                  I
0.0           5.0000E 00   +
1.0000E 00    1.2000E 01   -------------+
2.0000E 00    1.4000E 01   -----------------+
3.0000E 00    1.4000E 01   -----------------+
4.0000E 00    1.5000E 01   -------------------+
5.0000E 00    1.6000E 01   ---------------------+
6.0000E 00    1.7000E 01   -----------------------+
7.0000E 00    1.8000E 01   -------------------------+
8.0000E 00    1.9000E 01   --------------------------+
9.0000E 00    2.0000E 01   ----------------------------+
1.0000E 01    2.1000E 01   ------------------------------+
1.1000E 01    2.2000E 01   --------------------------------+
1.2000E 01    2.3000E 01   ----------------------------------+
1.3000E 01    2.4000E 01   ------------------------------------+
1.4000E 01    2.5000E 01   --------------------------------------+
1.5000E 01    2.6000E 01   ----------------------------------------+
1.6000E 01    2.7000E 01   ------------------------------------------+
1.7000E 01    2.8000E 01   --------------------------------------------+
1.8000E 01    2.9000E 01   ----------------------------------------------+
1.9000E 01    3.0000E 01   ------------------------------------------------+
2.0000E 01    3.1000E 01   --------------------------------------------------+
```

VITA

John Leonard Imhoff

Candidate for the Degree of

Doctor of Philosophy

Thesis: ANALYSIS OF HIGHER EDUCATION MANAGEMENT SYSTEMS THROUGH THE USE OF DYNAMIC MODELING CONCEPTS

Major: Engineering

Biographical:

Personal: Born in Baltimore, Maryland, February 9, 1923, the son of John H. and Elizabeth F. Imhoff. Married to the former Lois Johnson, March 20, 1948. Children, John Edwin, Karen Elizabeth, and Carl Henning.

Education: Graduated from Baltimore Polytechnic Institute, Baltimore, Maryland, in June, 1940; received the Bachelor of Science degree in Mechanical Engineering from Duke University in 1945; received the Master of Science degree in Mechanical Engineering (Industrial Engineering major) from the University of Minnesota in 1947; completed requirements for the Doctor of Philosophy degree at Oklahoma State University, with a major in Industrial Engineering and Management, in May, 1972.

Professional Experience: Employed by Crosse and Blackwell Corporation, Baltimore, Maryland, in Plant Layout Activities, 1940-41; American Rolling Mill Corporation, Baltimore, Maryland, in Combustion and Metallurgical Studies, 1941-43. Have done consulting work (part-time) while on Minnesota faculty, 1947-52, and for the following firms since joining the University of Arkansas faculty: Vickers Corporation, Joplin, Missouri, in Production and Cost Control, Management Analysis, 1953-54; Army Ordnance Management Training School, Rock Island, Illinois, Future Planning, 1953; Cities Service Corporation, Bartlesville, Oklahoma, Executive Development Program, 1954-57; International Paper Company, Crossett, Arkansas, Refuse Disposal Project, 1958-59; Foster-Cowan Company, Shirley, Arkansas, Management and Production Analysis, 1962; Zero-Mountain, Incorporated, Fayetteville, Arkansas, Materials Handling and Flow Analysis, 1962-63; Southwestern Bell

Telephone Company, Little Rock, Arkansas, Engineering Economic Analysis, 1964; Ethyl Corporation, Baton Rouge, Louisiana, Analysis of Industrial Engineering Operations, 1965; Panel Member, NSF Engineering Research Proposal Evaluation, Chicago, Illinois, 1965; Plastics Research Company, Rogers, Arkansas, Production and Cost Control, 1965-66; Southwestern Bell Telephone Company, Little Rock, Arkansas, Labor Relations Problem, National Labor Relations Board Case, 1966; Baxter Laboratories, Mountain Home, Arkansas, PERT and CPM Activities, 1966; Olin Corporation, West Monroe, Louisiana, Analysis of Industrial Engineering Operations and Seminar, 1968; Arkansas Foundry Corporation, Little Rock, Arkansas, Management and Supervisory Training, 1968-69; Conducted several technical conferences through IREC-STS, at the request of Arkansas Industry at Little Rock, Fort Smith, Fayetteville, and Rogers, 1968-70. Educational employment includes rank of Instructor and Assistant Professor, Mechanical Engineering Department (Industrial Engineering Division), University of Minnesota, 1947-52 and Head, Industrial Engineering Department, University of Arkansas, 1952-present.

Organizations: Member of American Association for Advancement of Science; American Institute of Industrial Engineers (former President and Director, Little Rock Chapter; Chairman, Southwest Region Student Chapters, and National Vice-President two terms); American Society for Engineering Education (former National Chairman, Industrial Engineering Division; National Nominating Committee; Executive Board, Council of Sections and Branches West; Chairman, Missouri-Arkansas Section; and Editorial Committee, Journal of Engineering Education); American Statistical Association; Engineers Council for Professional Development (Chairman, High School Guidance Committee for Arkansas, 1960-present); Arkansas Chairman, Junior Engineers Technical Society (High School Engineering Society), 1965-68; International University Contact Society for Management Education (Holland); National Council, Industrial Engineering Academic Department Heads (Board Member and former National Chairman); National Society of Professional Engineers (Member of several committees); Operations Research Society of America; Alpha Pi Mu (Member, Advisory Board; former National President); Phi Beta Kappa, Omicron Delta Kappa (President, Duke University Chapter); Pi Tau Sigma (Vice President, Duke Chapter); Pi Mu Epsilon; Phi Eta Sigma; Tau Beta Pi (President of Duke Chapter); Registered Professional Engineer in Arkansas and Minnesota.