SYSTEM DYNAMICS MODEL OF AN ANALYTICAL SERVICES LABORATORY

Philip V. Rzasa, Ph.D.
John B. Hooper, Ph.D.
Eastman Kodak Company
Rochester, New York

ABSTRACT

A computer model of a typical analytical services laboratory is described. System Dynamics modelling was used to integrate the functional areas of testing, problem solving, development and instrumentation. Using the model, interactions among the flows of information, money, requests for services, personnel and instruments were studied.

Several examples are given which illustrate the use of the model, along with conclusions on its utility.

INTRODUCTION

The typical analytical services laboratory performs routine testing, solves problems and develops methods. It utilizes people and instrumentation to accomplish these tasks.

A system dynamics model was developed as a tool in the management of a medium to large size analytical laboratory. The model has the following objectives:

1. To determine the important (sensitive) variables in the laboratory's methods of operation.

2. To provide a means for examining the effects of changes in policies or procedures on operations.

3. To provide support for recommendations to higher management concerning people, instrumentation and facilities.

4. To be a planning and forecasting tool.

BACKGROUND

An Analytical Services Laboratory is a service division which provides analytical chemical analysis requested by production and development divisions. The individuals in the Lab perform several major activities that may be classified in the following manner.

The largest effort is devoted to standard method testing of samples which are sent to the Lab for analysis. Some of the techniques utilized include gas chromatography, liquid chromatography, infrared spectroscopy, nuclear magnetic resonance spectroscopy, thin layer chromatography, atomic absorption, emission spectroscopy, x-ray fluorescence and titration.

In order to establish standard method tests, effort is dedicated to the development of standard methods. This development work is necessitated by new complex compounds and new products or processes.

The second largest effort is devoted to analyzing non-routine samples and is associated with problem solving. This effort is aimed at solving problems

Proceedings of the 1982
Winter Simulation Conference
Highland * Chao * Madrigal, Editors

82CH1844-0/82/0000-0421 $00.75 © 1982 IEEE

(production and development) which are usually "one time only" occurrences.

With the increase in technology, the introduction of new instrumentation, and the aim of lowering testing costs, effort is focused on developing cost-efficient methods to replace the standard methods currently being used for testing.

Since instruments are used in almost all testing, the final major activity includes the evaluation, installation and maintenance of existing, replacement, and new instrumentation.

Given the major activities of standard method testing, problem solving, method development, cost-efficient replacement method development, and instrumentation evaluation, installation and maintenance, it is also useful to categorize the requests for service by major areas. The majority of Lab effort is devoted to supporting the on-going production activities. The emphasis of this support is standard method testing although there are some requests for problem solving and method development. With the introduction of a number of new products in recent years, an increasing amount of support is provided to product as well as process development. Both of these areas require a significant amount of method development work by the Analytical Services Laboratory as well as testing after the methods have been established. The fourth major area is support of environmental monitoring and environmental regulatory requirements. These requests may originate internally within company by divisions or groups such as an environmental technical service group or externally by state or federal environmental agencies. This effort focuses on both standard testing and method development. Finally, the Analytical Services Laboratory itself is the major impetus in developing and/or applying new analytical technology and in introducing new and also automated instrumentation. Thus the major areas for which an Analytical Services Laboratory provides services include: production support, product development support, process development support, environmental, and the Lab itself.

THE MODELLING APPROACH

System Dynamics, developed by Jay Forrester at M.I.T. in the early Fifties (1), was selected as an approach to model an Analytical Services Lab for the following reasons. System Dynamics would provide a single framework for integrating the functional areas of testing, problem solving, development and instrumentation. It allows for the study and analysis of the information-feedback characteristics of the Lab activity to show how the Lab's structure, policies, and time delays in decisions and actions interact to influence the operations. System Dynamics could specifically treat the interaction among the flows of information, money requests for service, personnel, and instrumentation. It is a quantitative and experimental approach for relating the Lab's structure and policy to its growth and stability. In an experimental mode, system dynamics would allow the asking of "what if?" questions about internal changes or various external effects. For example, what would be the effect of limiting the hiring rate next year or increasing the effort toward instrument automation? On the other hand, what would be the effect of a major product development effort or a year of no growth in requests?

The Analytical Services Laboratory model was developed initially from a verbal description of both the Lab's operation and the various interactions among personnel acquisition, personnel allocation, number of requsts, and budget utilization. This description was then transformed into a flow diagram which represented the structure and interactions. The next step was to translate the diagram into a set of mathematical equations using a programming language called Dynamo. Dynamo was developed by Jack Pugh (2) for the purpose of running system dynamics models on a computer.

The model, in its mathematical form, constitutes a straight-forward, understandable description of laboratory operations with all of the assumptions clearly specified. The running of the model over a specific time horizon with a specified behavior of the requests to the Lab is called a simulation. The model is an abstraction of the real system and simulates its operation under circumstances that are as realistic as was the original verbal description of the Lab. A time history of selected variables, e.g. personnel levels, tests completed, methods developed, cost of operation, can be examined and analyzed. It is relatively easy to simulate a change in organization structure or policies and view the effects of such changes at a cost that is insignificant compared with the cost of a real-life experiment. A great deal may be learned because the experimental conditions are fully known, controllable and reproducible, so that changes in the behavior of a variable can be traced directly to its causes. The running of the computer model generates a time history in tabular or graphical form showing the implications of the Laboratory's description when combined with the input conditions as specified.

DESCRIPTION OF THE ANALYTICAL SERVICES LABORATORY MODEL

A. Testing, Problem Solving, and Method Development

Requests from an area enter the Lab along with a chemical sample for analysis. The result of the analysis or test is information (e.g. chemical content and amount) which is sent to the area making the request. When a sample enters the Lab, it is first determined whether (1) it can be analyzed by a standard method, (2) it is a problem, or (3) a standard method needs to be developed to analyze the sample.

The model, in its mathematical form, constitutes a straight-forward, understandable description of laboratory operations with all of the assumptions clearly specified. The running of the model over a specific time horizon with a specified behavior of the requests to the Lab is called a simulation. The model is an abstraction of the real system and simulates its operation under circumstances that are as realistic as was the original verbal description of the Lab. A time history of selected variables, e.g. personnel levels, tests completed, methods developed, cost of operation, can be examined and analyzed. It is relatively easy to simulate a change in organization structure or policies and view the effects of such changes at a cost that is insignificant compared with the cost of a real-life experiment. A great deal may be learned because the experimental conditions are fully known, controllable and reproducible, so that changes in the behavior of a variable can be traced directly to its causes. The running of the computer model generates a time history in tabular or graphical form showing the implications of the Laboratory's description when combined with the input conditions as specified.

DESCRIPTION OF THE ANALYTICAL SERVICES LABORATORY MODEL

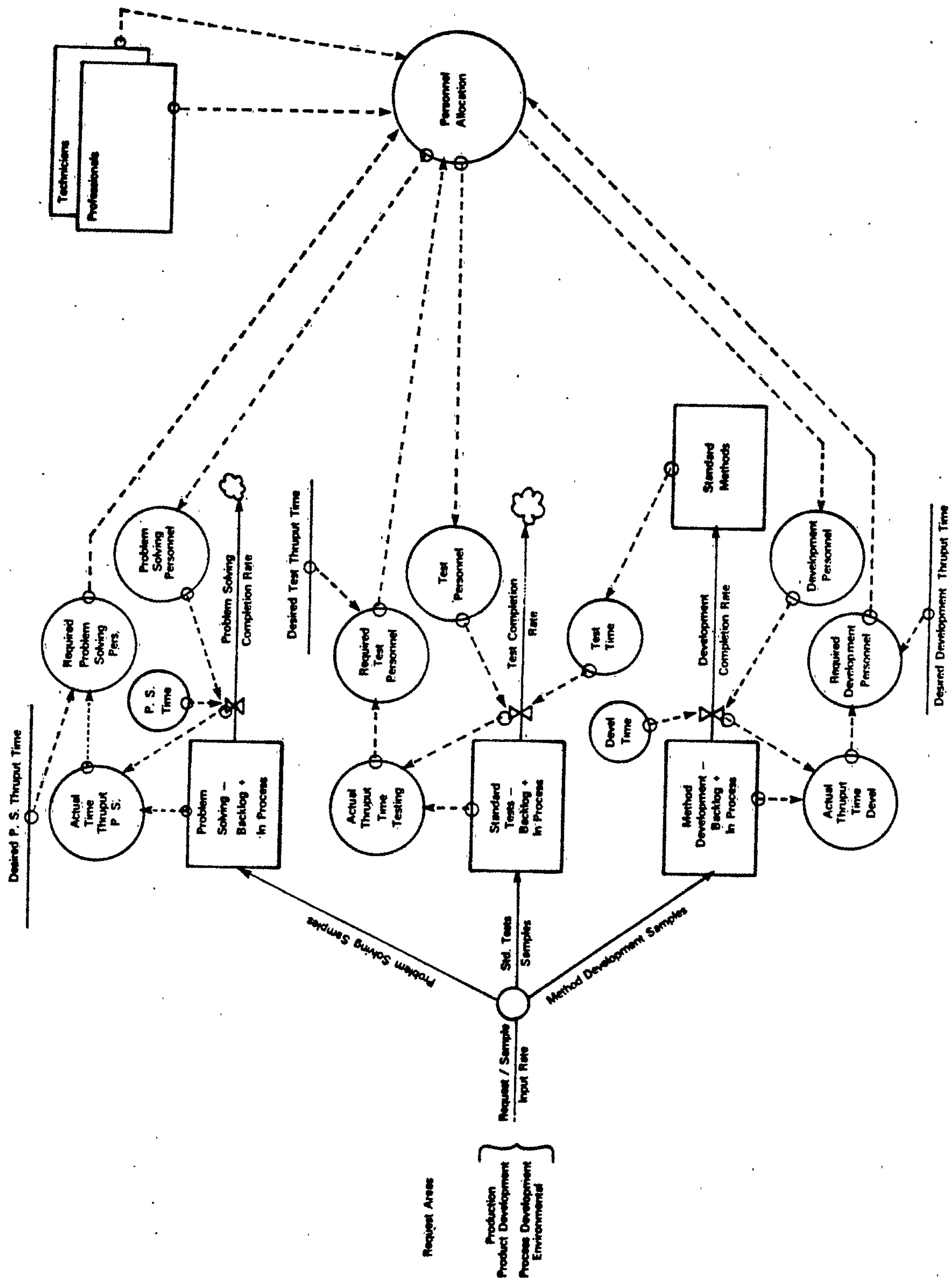
A. Testing, Problem Solving, and Method Development

Requests from an area enter the Lab along with a chemical sample for analysis. The result of the analysis or test is information (e.g. chemical content and amount) which is sent to the area making the request. When a sample enters the Lab, it is first determined whether (1) it can be analyzed by a standard method, (2) it is a problem, or (3) a standard method needs to be developed to analyze the sample.

Associated with each category, standard test, problem, or method development, are two times. The first time is the time required by Lab personnel to perform the analysis, solve the problem, or do the development work. Average times based upon historical data were used. The analysis, problem solving and development times may be influenced by the development of more efficient methods. The second time is the desired thruput time, i.e. the desired time from when the sample enters the Lab until the results are sent to the requesting area. These desired thruput times have been established based upon the analysis, problem solving, and development times, as well as the Lab's understanding of what customer divisions expect.

The test completion rate, problem solving rate, and method development completion rate are controlled by the allocation of personnel, professionals and technicians, to the various activities. The actual thruput times in the

FIGURE 1
FLOW DIAGRAM FOR PROBLEM SOLVING, TESTING, AND METHOD DEVELOPMENT



model can be determined by considering the completion rates as well as the number of samples in backlog and in process. The comparison of the actual thruput times to the desired thruput times provides the means for deployment of personnel. A flow diagram of this section is illustrated in Figure 1.

In Figure 1, the solid lines with arrows indicate the rate of flow of requests and samples in terms of requests per time period or samples per time period. The standard test box contains the number of samples currently in the Lab either waiting as a backlog or in process. Rates that are controllable by the Lab are recognizable by the valves (   ) on the rate line. The test completion rate is controlled or influenced by the test time and test personnel. This influence is noted by the dashed lines leading into the rate value. Dashed lines leading away from the test completion rate and standard test box are information flows which are used in calculating the actual thruput time. The circles represent auxiliary variables. These variables are determined from the various rates, levels, or other auxilliaries in the model. A straight line with a name above or below represents a constant. For example, the desired test thruput time is a constant which is used with the actual thruput time to determine the required test personnel.

Associated with the standard methods is the average time to perform the analysis. This is indicated by the dashed line from the standard method block to the test time.

B. Efficient Method Development

Efficient methods are developed for the purpose of decreasing the test times of the current methods. This decrease in test times lowers the cost of service. Cost-efficient method development is funded by general management. Each year the Lab receives a budget for this type of effort. Since this is a yearly budget, the Lab management may desire to spend these dollars evenly over the year. However, during times of increased requests, there exists a minimum level of effort for efficient method development which the management does not desire to go below. During times of decreased requests, there exists a maximum level of effort which the management does not desire to surpass. As these efficient methods are developed, they replace the current standard methods and also reduce the average standard test time. This part of the model is illustrated in Figure 2.

C. Instrumentation

Instruments are used in all phases of activity in the Lab. Instruments which become obsolete must be replaced. New non-replacement instruments must first be evaluated and approved before being ordered. Lab personnel time is required in the evaluation phase, the installation phase and for maintenance of instruments in use. The basis for determining the number of instruments needed is a desired ratio of instruments per person. If the actual ratio of instruments per person is less than the desired ratio, then the test times, problem solving times and development times are increased due to the non-availability of instruments. The instrumentation section and its affects on the various times is illustrated in Figure 3.

D. Personnel

The Lab currently operates in a reactive mode regarding personnel acquisition. That is, if there exists a current need for more personnel, then requisitions are submitted for additional people. The requisition rate is dependent upon the average attrition rate and the difference between the personnel available and the personnel required to complete each activity within its desired thruput time. If the required number is larger than available, then it is desirable to requisition personnel to make up the difference plus replace attrition. If the personnel required is less than available, the current Lab policy is to replace only one-half of attrition. This policy is necessary because some of the personnel lost through attrition have specific skills which must be replaced.

Given the required personnel for problem solving, testing, development and instrumentation, there exists

FIGURE 2
FLOW DIAGRAM
FOR EFFICIENT METHOD DEVELOPMENT

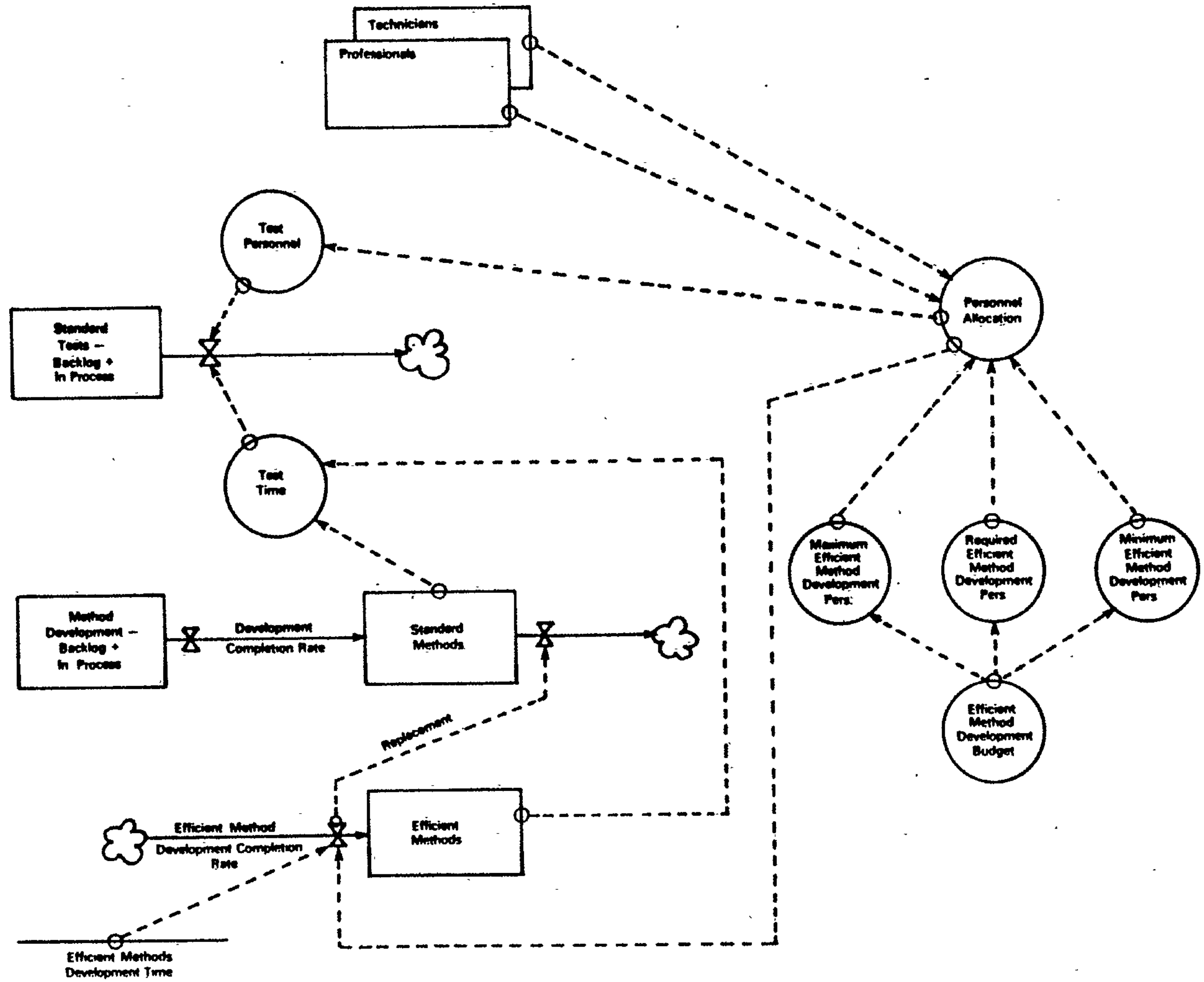
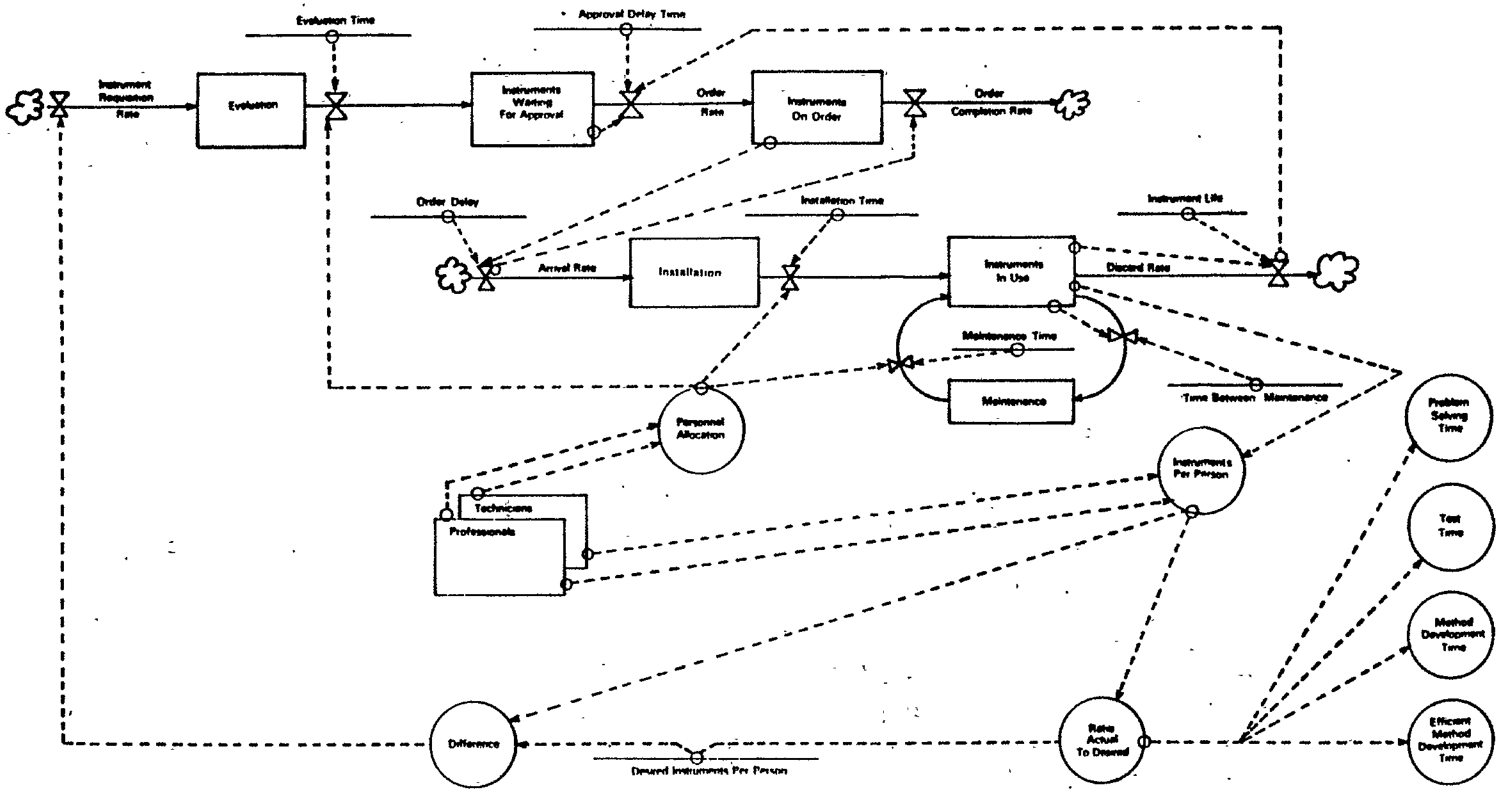


FIGURE 3

FLOW DIAGRAM FOR INSTRUMENT SECTOR



appropriate levels of professional effort and technician effort. Standard testing utilizes a higher concentration of technician effort versus professional effort. On the other hand, development requires more professional input. Therefore, the required total number of personnel for each activity can be separated into professionals and technicians. The required number of professionals and technicians for the Laboratory is found by summing the appropriate required numbers from each activity. Since the requests received by the Lab are not constant over the year, the number of required personnel varies over the year. It is therefore desirable to smooth these variations over several months before using them for determining the required personnel levels.

Several steps are necessary to attain a qualified professional or technician. First is a requisition which, after a time delay, becomes approved. Next is the procurement of individuals and their initial training. This entire process may take anywhere from one month for technicians to six months for professionals.

In addition to professionals and technicians, two other categories of personnel include support and supervision. Support personnel includes clerical and data processing individuals. It is assumed that there are desired ratios for both support personnel and supervisory personnel to the total number of professionals and technicians. Both the support and supervisory personnel follow the same steps as professionals and technicians in order to be qualified. A flow diagram of the personnel sector is illustrated in Figure 4.

In Figure 4, all of the constants and influences are not included for the sake of clarity. The support personnel acquisition is similar in nature to the supervisory acquisition. It should be noted that the requisition rate may also be influenced by an external management growth limit. In some years company policy may limit the acquisition of new personnel even though the determined required personnel level indicates a higher requisition rate is needed.

E. Personnel Allocation

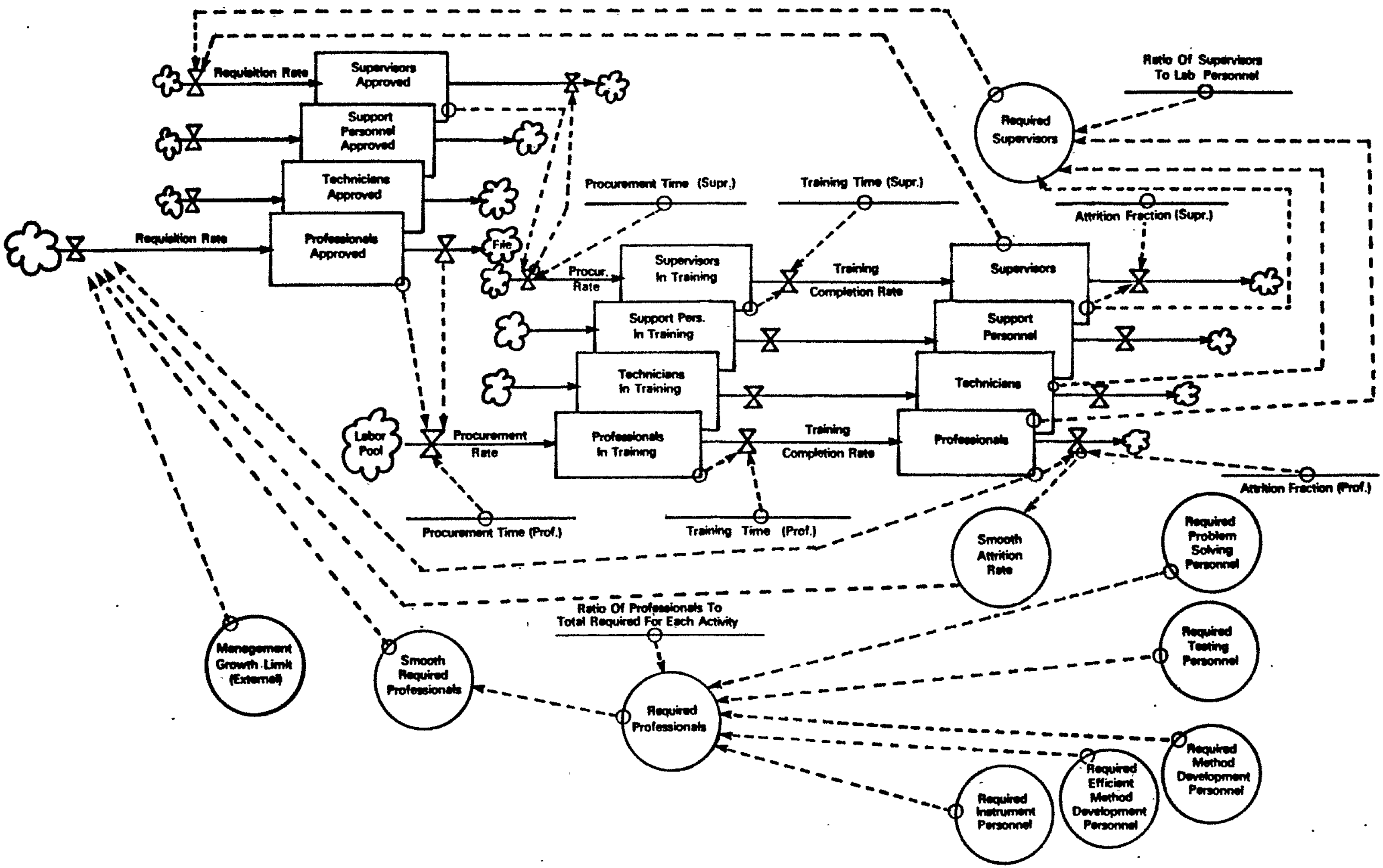
Personnel are allocated to the five activity areas on the basis of a set of priority rules and established minimum levels of effort. The priority order from highest to lowest is (1) instrumentation, (2) testing, (3) problem solving, (4) method development, and (5) efficient method development. Minimum levels of effort are established in the following manner. Instrumentation receives the necessary personnel since unavailability of instruments makes all other Lab activity less efficient. As a guide, testing minimums are based on the required number of personnel to satisfy production; however, the effort is distributed based on the ratios of required personnel for each request area to the total required personnel for testing. Problem solving personnel minimums are established in a similar manner to testing. Method development personnel minimums are based on satisfying production and environmental requests within the desired thruput times and allowing product development and process development support to maintain at least three people in each area. Efficient method development effort is designed to utilize the entire budget during a calendar year but will allow the minimum effort to drop to one percent of the total Lab personnel during the first quarter and two percent of the total Lab personnel during the second quarter of the year.

If there are sufficient personnel to complete all the activities at desired thruput times, any available extra personnel are allocated in the established priority order (except for instrumentation). Additional personnel are allocated until the actual thruput times are at their minimum levels, which would essentially be the respective times to perform the activities.

A small amount of overtime is incorporated into the required level of effort for testing and problem solving. The amount of overtime hours which may be incurred in the Lab is established by specifying the maximum number of overtime hours per person per year. Overtime hours allow the flexibility of handling upward surges in requests without having to request additional personnel in the short run.

FIGURE 4

FLOW DIAGRAM FOR PERSONNEL SECTOR



F. Cash Flows

Cash flows in the model are easily attained once personnel levels, instruments in use, and personnel allocations are determined. The Lab essentially operates on a non-profit basis. Costs are made up of personnel salaries, capital and instrument depreciation, and other overhead costs such as utilities. Income is generated by charging the requesting organizations a fee per hour. This per hour charge rate differs for professionals and technicians. The professional charge rate is higher than the technician charge rate. On the average the charge for performing a standard test is much lower than the charge for developing a method. This is due to the test time and a higher concentration of technician effort for testing versus method development. Thus income is received by charging for the analytical services performed for production, product development, process development, environmental and general management requests.

MODEL RESULTS AND ANALYSIS

A. Model Validation

Validation of the model has been an on-going process. Initially, the structure of the model was tested for being representative of the actual system. This was accomplished by describing the model and incorporating the modifications suggested by Lab supervisors and selected groups of Lab professionals and technicians. The model was then tested over an unusually wide range of sample input. The "reasonableness" of the model's behavior under extreme conditions was analyzed and resulted in further modifications. Where available, historical data was collected and used to establish starting conditions, constants, and other model parameters. The model was fine-tuned in an iterative process as model behavior and results were compared to the behavior and results in the actual system.

B. Experiments

Each model simulation run, in which one or more parameters are changed, is called an experiment. The original model, called the Base, is established to reflect the current structure and policies of the Laboratory. Several experiments were designed to investigate the effects of changes upon Laboratory operation.

The first experiment, NG80, was designed to examine the effects of no growth in samples in 1980. In the Base run, the projected increase of samples into the Laboratory is 10% in 1980 compared to 1979. It was desirable to examine the differences in personnel levels, overtime and thruput times not only in 1980 but also the following years.

The second experiment, LM81, was designed to investigate the effects of limiting employment in 1981. Total Lab personnel were held constant during 1981. Sample input rates were identical to those in the Base run. It was desirable to see the effects of a hiring curtailment upon overtime and thruput times.
The last experiment, AUTO, was designed to investigate the effects of a one time major effort to automate testing during 1980. In the model, automation is incorporated by increasing the instruments per person which affects the standard test time. Continued automation efforts were not included in this experiment. It was desirable to examine the influence of automation on personnel levels, overtime, and thruput times.

C. Results and Analysis

The model runs were started from the beginning of 1977. The resulting values of the various parameters are identical through 1979 since changes from the Base are implemented during 1980 and 1981. All of the tables and graphs present the data from 1979 through 1983. The model updates the calculations on a daily basis. The input to the model in samples is transformed into a sample index and is given in Table 1. Run NG80 has the same number of samples for 1980 as for 1979. Thereafter, a one year lag exists as compared to the other three runs.

A personnel index (base 100 in 1979) and overtime hours per person projected by the model for each of the simulation runs are presented in Table 2. The personnel level in the Base grows very little in 1982 and the overtime hours for 1981 and 1982 are fairly low compared to the other years. This indicates that the Lab appears to be sufficiently staffed to handle the samples during this time period. Continued growth in samples, however, require larger personnel increases and more overtime. In contrast, the NG80 run shows that there would be little need for additional staff during 1980 if the sample input remains the same as in 1979. If the number of Lab personnel remains constant during 1981, LM81 run, it can be seen that the overtime required is double the amount needed for the Base run. It should be noted that personnel levels and overtime hours are approximately the same for the Base and LM81 during 1983. If the overtime hours are not considered excessive and the thruput times are acceptable during 1981 and 1982, then limiting personnel hires during 1981 may be a justified strategy. The final experiment, AUTO, illustrates a dramatic effect upon personnel and overtime as compared to the Base. In the AUTO case, personnel levels are significantly decreased beyond 1981 and no overtime is requried during 1981.

The effects of the four simulation runs on testing thruput times are illustrated in Figure 5. The desired testing thruput time is noted on the graph. In the Base run the actual thruput time remains at the desired time during 1980 and drops during the second quarter of 1981. The thruput time

samples during this time period. Continued growth in samples, however, require larger personnel increases and more overtime. In contrast, the NG80 run shows that there would be little need for additional staff during 1980 if the sample input remains the same as in 1979. If the number of Lab personnel remains constant during 1981, LM81 run, it can be seen that the overtime required is double the amount needed for the Base run. It should be noted that personnel levels and overtime hours are approximately the same for the Base and LM81 during 1983. If the overtime hours are not considered excessive and the thruput times are acceptable during 1981 and 1982, then limiting personnel hires during 1981 may be a justified strategy. The final experiment, AUTO, illustrates a dramatic effect upon personnel and overtime as compared to the Base. In the AUTO case, personnel levels are significantly decreased beyond 1981 and no overtime is requried during 1981.

The effects of the four simulation runs on testing thruput times are illustrated in Figure 5. The desired testing thruput time is noted on the graph. In the Base run the actual thruput time remains at the desired time during 1980 and drops during the second quarter of 1981. The thruput time

reaches a minimum of 33% below the norm during the third quarter of 1981 and then increases until it reaches the desired thruput time during the second quarter of 1982. This is an indication that there were available personnel during 1981 to reduce test time below the norm. The no growth simulation run (NG80) shows a decrease in thruput test time during 1980. This means that the Lab had to increase personnel in prior years for the purpose of decreasing a large backlog of work. Therefore, when the sample workload remains constant, the personnel previously devoted to backlog work become available to decrease thruput test times. Holding the personnel level constant through 1981 (LM81) appears to be an acceptable strategy with respect to thruput test time. There are a sufficient number of personnel to keep thruput test time at the desired level during 1981. A major automation program started at the beginning of 1980 starts to have an influence during the second quarter of 1980. Automation has not only a pronounced impact upon thruput test time but also upon the personnel levels when compared to the Base. As the automation effort was a single occurrence while sample volume continued to increase, testing thruput times rise to the norm by mid-1982.

Figure 6 illustrates the affect upon problem solving thruput times for the four simulation runs. Excessive thruput time during 1979 implies a higher than normal backlog. Problem solving thruput time for the Base run does not reach the desired level until 1980. The NG80 run displays a drop in problem solving thruput time which is characteristic of the drop for test thruput time. As the sample input starts to increase in 1981, the problem solving thruput time increases. Delays in the system due to averaging the required personnel, approval and

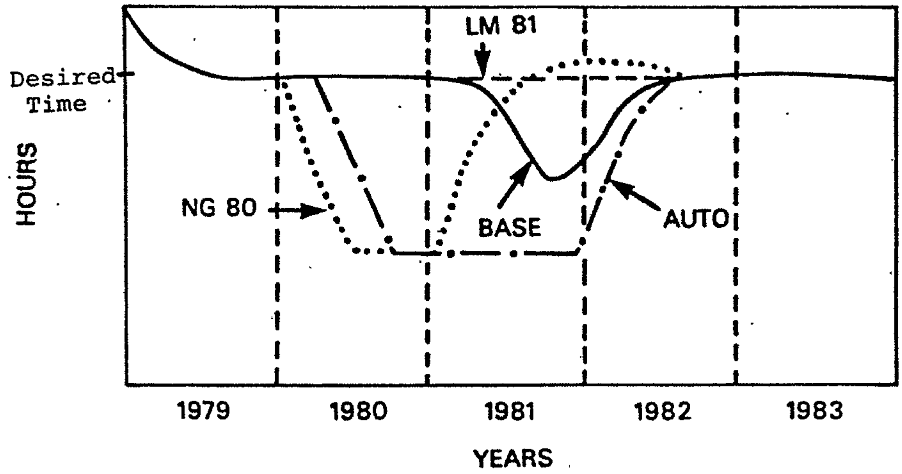
TABLE 1

Experimental Condition	TOTAL SAMPLE INDEX End of Year 1979	1980	1981	1982	1983
Base, LM81, AUTO	1.00	1.10	1.17	1.24	1.31
NG80	1.00	1.00	1.10	1.17	1.24

TABLE 2

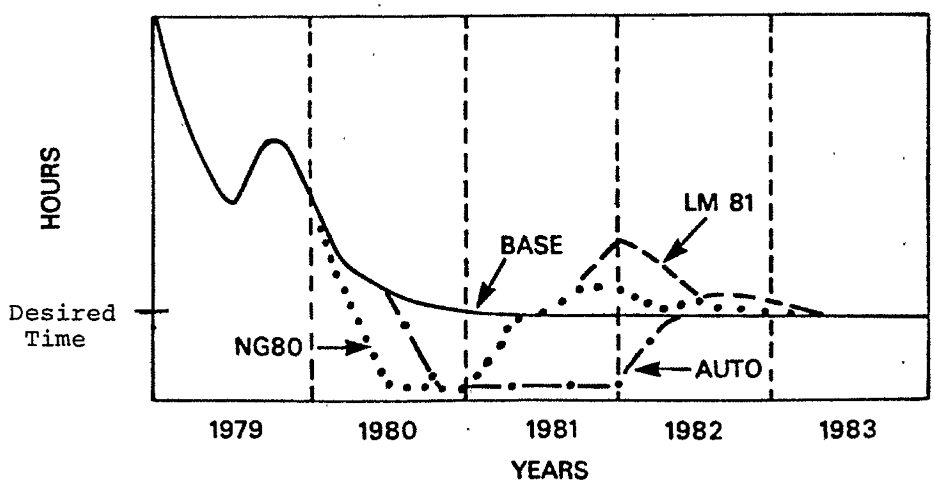
PERSONNEL INDEX AND OVERTIME HOURS PER PERSON

Experimental Condition	Parameter	End of Year 1979	1980	1981	1982	1983
Base	Personnel Overtime	100 27	107 30	112 10	113 13	120 23
NG80	Personnel Overtime	100 27	102 5	103 14	110 24	118 20
LM81	Personnel Overtime	100 27	107 30	107 21	115 30	121 23
AUTO	Personnel Overtime	100 27	106 15	104 0	104 19	112 26



TESTING THRUPUT TIMES

FIGURE 5

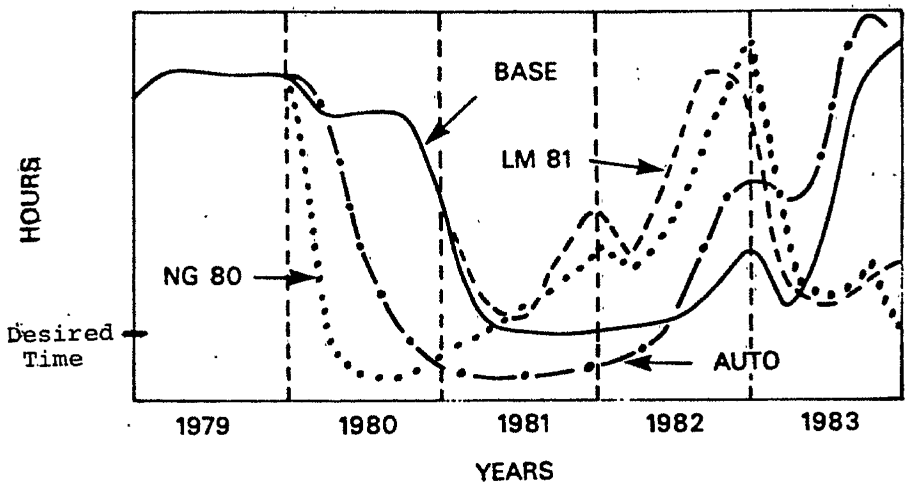


PROBLEM SOLVING THRUPUT TIMES

FIGURE 6

training result in a build-up of backlog for problem solving. This is reflected in an increase in thruput time until it reaches a peak at the end of 1981. At this time, personnel become available to assist in decreasing the backlog. Limiting personnel hires during 1981 has detrimental effect on problem solving thruput time after mid-year. Thruput time begins a turndown at the end of the first quarter after personnel hiring resumes. It is seen that automation of testing has a side benefit of making personnel available to reduce problem solving thruput times to a minimum.

Figure 7 shows the development thruput times for the simulation runs. The development backlog returns to a normal level during 1981 for the Base. There is a slight increase during 1982 and a large increase during 1983 which indicates the need for more personnel or more overtime than is currently allowed. The NG80 development thruput time follows the same pattern illustrated by problem solving and testing during 1980. The Lab has sufficient personnel to handle the increased workload during 1981 until the third quarter. The averaging process for required personnel



DEVELOPMENT THRUPUT TIMES

FIGURE 7

delays increasing the requisition rate. This results in the thruput time reaching a peak during the fourth quarter of 1982. At this time, a sufficient number of personnel have completed training and are assigned to aid in decreasing the development thruput time. Limiting personnel hiring during 1981 appears to be too stringent a policy when viewing development. The development thruput time for LM81 follows the Base curve in the early part of 1981 but, unlike the Base, the LM81 curve rapidly increases during the remaining part of the year. However, the additional personnel acquired during 1982 and the beginning of 1983 provide the resources to drop the development thruput time close to the desired level by the end of 1983. The profound affect of automation is once again illustrated in viewing the development thruput time for AUTO. Development thruput time reaches the minimum level through all of 1981. The general pattern of AUTO development thruput time for 1982 and 1983 is similar to that exhibited by the Base run. Peaks for thruput times in the Auto exceed those for the Base due to the average of the number of required personnel for AUTO being lower than the Base during 1981 and the first half of 1982.

CONCLUSION

A system dynamics model of a typical analytical services laboratory was described. Several sections of the model, based upon reasonable assumptions about the interactions present and the operating policies, were illustrated by flow diagrams. A base run, designed to reflect the "current" Lab operation, as well as several different experiments were simulated to demonstrate the usefulness of the model for examining the consequences of changes in workload and internal policy.

Working with the model and running experiments should assist laboratory supervision in developing an understanding of the current operation and potential consequences of projected policies. Changes in the hiring policy as well as a major emphasis upon automation may be evaluated for potential impact upon personnel levels, thruput times and test times.

Although this model was designed to be applicable to general analytical services laboratories staffed by more than 200 people, it could easily be adapted to other types of service organizations.

BIBLIOGRAPHY

1. Forrester, Jay W., Industrial Dynamics, Cambridge, Massachusetts: The M.I.T. Press, 1961.

2. Pugh III, Alexander L., Dynamo User's Manual, Fifth Edition, Cambridge, Massachusetts: The M.I.T. Press, 1976.

Dr. Philip V. Rzasa
Senior Industrial Engineer
Eastman Kodak Company
1669 Lake Avenue
Rochester, New York 14650