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NASA CONTRIBUTIONS TO MATHEMATICAL MODELING AND SIMULATION
WITH APPLICATIONS OUTSIDE OF THE AEROSPACE INDUSTRY

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Potentials for technology transfer can be found where you would least expect them. I approached the task in the title with great skepticism. Although NASA had undoubtedly made extensive use of mathematical modeling and computer simulation, it seemed unlikely that they could be used for anything except the special purpose for which they were intended. But I developed a methodical approach to try to find out.

First, a week in a NASA library with catalogues of report titles, abstracts and microfiche produced about 150 possible candidates - much to my surprise. The filtering process included discussions with other staff members at Abt Associates with first-hand knowledge of current problems in business, education, transportation, social programs, etc. and with senior people in NASA Headquarters who were generally familiar with the work that had been done and, more importantly, knew about current programs. With this background information, I knew who to visit in the NASA centers and what to talk about. Because of the time lag between completion of a project and publication of an abstract in a catalog of reports, memories fade about projects that were usually carried out by someone else several years ago. But there are usually more important projects whose abstracts have not yet made the archives.

The most promising models and simulations could be classified in the following 6 categories:

1. Management
2. Human Operators
3. Medical
4. Social Sciences
5. Structures
6. Reliability

Although there is not time to go into depth in all of these areas, some representative examples of projects would be useful not only for clarification, but also, perhaps, for stimulating your own responses for transfer opportunities.

1. Management
   a. A management control system for evaluating weight trends in the Apollo development program.
   b. A model of crew capabilities and operational requirements for a manned orbiting research laboratory.
   c. Probabilistic long-range planning for resource requirements.
   d. Cost estimating and analysis models.

2. Human Operators
   a. Application of human transfer functions to the design of the LEM landing simulator.
   b. Digital adaptive control systems.
   c. A mathematical model of the human operator's decision-making functions.
   d. Human performance control monitoring system.

3. Medical
   a. Model of the vestibular system.
   b. Biological systems models - the cardiovascular system.
   c. Biological control systems.
   d. Systems-oriented physiology.
   e. Neuro-muscular systems models.

4. Social Sciences
   a. Social indicators
   b. Inter-industry relationships in the Philadelphia economy.
   c. Impact of space activities on a local economy.
   d. Quantification of subjective data.

5. Structures
   a. JPL structural analysis program.
   b. General purpose program for structural analysis - Goddard.

6. Reliability
   a. Simulation of failure-responsive systems.
   b. Computerized reliability models.

The management models were described in some detail, with suggestions for their application outside of the aerospace industry, in a Technology Utilization Survey (NASA SP-5048). A brief summary of some of the applications that were suggested might be helpful in prompting other ideas.

A Description of the FAME System

The Apollo program office system, referred to as Forecasts and Appraisals for Management Evaluation (FAME) was designed to accomplish the weight control tasks. For each subsystem or component in the Apollo program, historical weight data must be collected, recorded, and analyzed, and forecasts of future weight trends must be made. The results of this analysis and forecast must

then be evaluated and forwarded to cognizant management levels. This is accomplished in FAME by the combination of several information and control techniques.

The FAME system begins with an information system designed to ensure the upward flow of accurate weight estimates from the myriad contractors to the program office. These raw historical data are then preprocessed by removing all nonrandom fluctuations caused by design changes. Also, a careful study of the mission requirements and constraints is pursued, yielding a set of control limits for the weight of each component or subsystem. Armed with these two sets of input, the preprocessed historical data and the appropriate control limits for these data, FAME is ready to proceed with the analysis of historical trends and the forecast which projects trends into the future.

The forecast analysis is accomplished by choosing one of four different mathematical models, each of which has its own advantages and drawbacks as a predictive tool. The four underlying statistical techniques may be described as follows:

1. A linear maximum-likelihood method
2. A nonlinear maximum-likelihood method
3. An asymptotic (logistic) exponential method
4. An adaptive (Fourier) exponential method

Each one will ascertain different "trends" in the data and furnish different forecasts of future developments. The choice of trend model can be made manually or automatically, depending on the user's requirements. The automatic mode provides a range of methods which test the validity of each mathematical model for predicting weight trends in a given subsystem. On the basis of these criteria, one model which generates the best trends for the problem at hand is chosen by the decision module. Finally, the forecasts produced by the model are adjusted for biases, expected program changes, and factors related to the program maturity. The probable errors in the forecasts are then computed as the final stage in the statistical treatment of the data. The output of this stage of FAME is, then, a set of historical trends, forecasted weights, and the probable errors in these forecasts for each relevant unit of the total spacecraft system.

To help management evaluate the data and forecasts which are generated, FAME performs a number of ancillary calculations. All of the trends are accumulated and summed to present a consistent picture of the total weight of the system. Each individual weight excess or predicted weight excess is then examined to ascertain the criticality of the problems involved. The degree of criticality for any particular unit is determined by an anlysis of the trade-offs and performance adjustments that will be required. The criticality rankings performed by the FAME program are a great aid in calling management's attention to the most immediate problems. The final element of the FAME system is the output and set of management reports necessary to transmit the historical data and forecasts to the propoer decision-makers. FAME provides for the transmission of the following information, either in the form of data or in graphical displays:

1. Current status of the program and its elements
2. Predicted status of the program and its elements
3. Problem areas
4. Criticality of the problem areas
5. Trade-offs necessary to correct the problem area

With this final element, the FAME program is a completed set of techniques for the purposes of management information and control. In brief review, it consists of the following important elements:

1. An information gathering system
2. A preprocessing technique for the data
3. A set of statistical techniques to assess historical trends and generate forecasts
4. A set of criteria to evaluate the data and forecasts in terms of their criticality to the program as a whole
5. An output and reporting system for transmission of the final appraisals.

Both the general format of the FAME system and the techniques used in its various elements hold great promise for application in many fields of endeavor. The statistical techniques used in FAME's forecast analysis have been packaged into an overall module in an innovative way so that the results are well suited for presentation to a decision-maker. Any statistical problem which demands the determination of trends in historical data and projection of these trends into the future may be efficiently attacked by the use of techniques included in this system.

Consumer-oriented industries may well wish to consider the utilization of systems similar to FAME to enhance their market research and sales forecasting efforts. Historical data in time-series form may be generated to describe the marketplace in terms of total primary demand, market share for a particular product, dollar sales for a particular product, etc. Any of these data may then be analyzed periodically by a FAME system. Many industrial enterprises already use certain statistical techniques for sales forecasting, but rarely are these forecasting efforts embedded in as complete a management control and information system as FAME.

An even larger potential use of FAME arises in the area of cost control for industrial enterprises. Effective cost control in any large industrial complex demands rather cumbersome budgetary techniques, periodic surveillance of actual cost data, and comparison of the actual cost data with the budgeted limits. A system similar to FAME could be utilized to automate these functions and to present the results to management in a form most convenient for decision-making. The system would also generate cost forecasts on the basis of historical trends, a task which could prove very helpful in identifying possible problem areas. Furthermore, the module of FAME which automatically ascertains the criticality of budgetary excesses is a feature usually absent in even the most advanced cost

control programs now in industrial use.

Another potential use of this type of information and control system is in the area of quality assurance for large manufacturing complexes. Wherever quality control data can be generated on a regular periodic basis, a system similar to FAME can be utilized to monitor, evaluate, and report on the results of a quality control program.

Finally, a system like FAME could be used in large decentralized enterprises to assess, analyze, and forecast profits automatically for all the operating units as the corporation's fiscal year progresses. This system could be used as a step away from the concept of totally decentralized operating units, or alternatively, it could be used solely as an information system designed to keep top management abreast of recent and projected developments with little or no feedback into a centralized control system.

Public programs, particularly in large urban areas, also require fairly sophisticated information and control techniques in order to operate effectively. Many historical time-series of data are used in urban planning, and the techniques of FAME can be used to analyze, evaluate, and predict program needs on the basis of these data. In addition, the daily operating functions of the various urban authorities might well utilize a FAME system to evaluate parameters related to their spheres of responsibility. The FAME system would also be useful in other areas:

1. In public health - to aid in the monitoring and evaluation of current data on illnesses, particularly communicable diseases

2. In air pollution control - to monitor the level of pollutants in the air in various localities

3. In city administration - to increase the effectiveness of budgetary control procedures.

If data were available on the supply and demand for various categories of medical and paramedical manpower in a given geographic region, the FAME system could predict shortages and oversupplies of various skills for the medical facilities within the area. FAME could automatically process this data and present the regional health planner with indications of the degree of criticality of these shortages or oversupplies. On the basis of this knowledge, decisionmakers could move more quickly to correct the supply and demand balance by:

1. Increasing the outputs of various manpower training programs (such as graduation from nurses' "refresher" training or medical schools)

2. Redefining certain jobs for which labor shortages existed, to utilize oversupplies from other occupational areas

3. Promoting interarea or interregional mobility of available manpower to locations of labor shortages.

FAME could perform essentially the same function with respect to the occupance or utilization rates of medical facilities in an area, contributing solutions to local problems of peak and off-peak utilization differentials and apportioning patient demand between facilities

according to available supply. FAME could also monitor the construction of new medical facilities, adjusting bed capacity, for example, to revealed trends in the needs.

The FAME methodology is a data-handling and analysis system which could be used to evaluate the performance of a city's air pollution control, public transportation system, health program, and a number of other publicly operated programs. In each instance, the successful application of a FAME system would rest upon the collection of relevant statistics. These statistics might be pollution data, user rates for a transportation system, or health records. Since each of these programs represents a portion of the city's budget, a FAME system could be used to increase the effectiveness of the overall administration's budgetary control process.

The police department of a large urban area has a particularly acute need for an efficient data-handling and information system. Furthermore, it would be helpful if this information system could be used to predict the incidence of crime and traffic accidents across the city. An adaptation of the FAME data-handling and forecasting system could be used to monitor and evaluate crime statistics. The crime statistics could be segmented by type of crime and geographic region and an historical time-series of data collected and regularly updated. This data could be automatically analyzed for historical trends which could be projected into the future to forecast crime patterns across the city. These forecasts could provide a rational basis for the resource allocation and scheduling problems faced by large urban police departments.

Mathematical Simulation
of a Manned Space Mission

A mathematical model to simulate the complex interactions which occur aboard the Manned Orbital Research Laboratory (MORL) was developed for NASA by the Operations Research Division of General Dynamics.

Many operations and activities are needed to maintain such a spacecraft aloft. Maintenance, experiments, storage and disposal, logistics, and crew duty cycles must all be considered in the design problem. These various activities aboard a spacecraft are not independent, and all possible interactions must be analyzed. Unfortunately, many of these interactions will be far from obvious. For example, if a crewman becomes ill, there are many possible ramifications for the operation of the entire system. His absence from normal duties may affect maintenance or scientific experiments, or both. Clearly, the design, planning, and scheduling of activities for such a space station demands a carefully considered set of solutions. For this reason a detailed mathematical model has been developed to simulate the entire spacecraft.

The problems revolving around the selection and scheduling of the crew are analyzed in the model. Crews are selected on the basis of skills, crew training, and ability to provide the most effective experimental accomplishments. The crew is scheduled for optimal experimental results and the effect of unscheduled events is calculated. The model is developed to handle a crew of up to

24 men.

By scheduling all necessary events into 24-hour units, the model permits analysis of resource requirements, expected rate of mission accomplishment to different crew missions and different levels of crew training. The simulation model also permits the determination of the probable deviation of the mission from initial plans and can be used as a training aid for potential crews.

A separate program has been developed for mission evaluation. No single measure has been used as a measure of mission value; but a large number of indices were developed which can be presented in various combinations of cost and effectiveness. The effects of different amounts of crew training on experiments, for example, can be evaluated for the effect on the overall mission effectiveness.

The model thus can be used for a wide range of studies involving logistics, crew analysis, resource analysis, comparison between mission plans, logistic failures, and accidents. Nearly 3 years of orbiting time can be simulated with the mathematical model in about 30 minutes.

Any manpower-intensive system can be modeled with these these techniques, and the system design and personnel scheduling problem can be studied concurrently. There will be times when the expenses involved in developing this kind of model are too large compared to the advantages gained. The initial cost effectiveness of this type of model must be studied in each separate case before the development decision is made.

In industry, this type of simulation model can be used to study various work group situations. The working environment on an assembly line may be particularly well suited for an adaptation of this type of study. The design of surrounding facilities can be analyzed in conjunction with the problem of personnel scheduling. This type of simulation approach has the important advantage of considering the system as a whole, with all its interactions. Because of this advantage, the simulation technique may prove superior to the separate and artificially segregated analyses of subproblems within the working environment.

Schools, public health facilities, welfare agencies, police and fire protection units, and other manpower-intensive activities all have the interrelated problems of functional design and personnel scheduling. Simulation models can be developed as a systematic approach to problems in all these areas.

Certain specialized problems involved in the management of police and fire protection systems deserve special comment. One of the foremost problems of city administration is the scheduling of available police and fire personnel. The scheduling problems for a large urban police force are so complicated that systems techniques should be used to perform cost-benefit analyses of different scheduling strategies. The effects of different assignments of men should be determined. These problems can be attacked with simulation techniques similar to the one developed for NASA to study the scheduling problems on manned spacecraft. This type of simulation technique allows the user to study concurrently the facilities design, resource allocation, and scheduling problems which arise from the man-machine interaction. The simulation technique can also be used to simulate various uncertain events and their effect upon the standard scheduling procedures. For example, not only the normal crime incidence but a large urban riot could be simulated; and the ability of the personnel scheduling system to adjust to this riot could be studied. In general, the techniques of man-machine-environment simulation can provide a convenient framework for analyzing scheduling procedures.

The General Dynamics scheduling model for the Manned Orbiting Research Laboratory (MORL) is most useful in this context for estimating short term resource requirements. The techniques developed for this model can be used for an R&D laboratory. The model matches the skills of experimenters with the skills required by experiments, thereby identifying quantitative and qualitative requirements for manpower and how these requirements might be changed by unforseen breakdowns of experimental equipment.

As the production process becomes more complex, the ability of operations analysts to solve systems problems becomes more limited. Many large manufacturing processes have become so complex that it is not practical to solve production problems with closed form analytical techniques. This is particularly ture for manpower intensive processes where the human elements introduce uncertainties into an already formidable problem. In such problematic situations, the use of simulation techniques holds real promise for a practical systems approach. NASA has utilized simulation techniques to design and schedule complex space missions. Similar simulation techniques could be adopted to study many manpower intensive facilities in industry.

The real problem surrounding these complex manpower intensive facilities is that facility design and subsequent manpower scheduling are closely interrelated. The facility cannot be adequately designed without knowledge of the availability of manpower and requisite skills, and the manpower skills cannot be scheduled and analyzed without knowledge of the facility design. In simpler terms, the man-machine interface leads to the major unsolved problems in designing manufacturing processes. The simulation developed with NASA funding approaches these problems in several steps. First, a preliminary requirements model is used to assess the feasibility of particular operations and to select the manpower (in terms of numbers and skills) which will be necessary for these operations. Second, the planning model is used to perform all the scheduling and logistics functions associated with the particular operations and the particular crew developed by the preliminary requirements model. Finally, the full-scale simulation model is used to determine the effects of various contingencies on the nominal man-machine design. Nonstandard equipment failures are simulated, and their effects on the crew are determined. Human failures and illnesses are simulated to determine their effects on the scheduling problems. The use of this full-scale simulation model may reveal numerous problems arising from the man-machine interface which would otherwise go unnoticed. The nominal design can then be altered to provide for the contingencies revealed by the simulation. This same three-stage approach to the analysis and

simulation of manpower intensive functions can be employed profitably by industrial corporations in the design of manufacturing facilities. This approach will allow concurrent study and solution of the problems associated with facilities design and manpower scheduling in a manufacturing process.

Probabilistic Long-Range Planning

With the aid of NASA funding, a number of related studies in the area of long-range probabilistic planning were undertaken at Texas A&M University. Long-range probabilistic planning is a general class of mathematical techniques used to facilitate the estimation of cost and personnel requirements. The mathematics of linear algebra and statistical analysis are combined into an overall systematic framework for dealing with managerial problems. An adaptation of these techniques should be applicable to those parts of both the public and private sector which operate on a program or project basis.

A Brief Description of the Methodology

This methodology for estimating cost and personnel needs, developed by Texas A&M University, can be used in the following type of situation: Consider an organization which is currently conducting a number of projects and will be conducting other projects in the future. How can such a firm predict its future manpower and resource requirements? The essence of this problem is that a firm cannot always be certain that it will receive a contract, nor can it be certain when it will receive such a contract. These two elements of uncertainty are inherent in such a situation, and the methods devised in this study can be used as a planning tool for these probabilistic situations.

The models use a combination of matrix techniques and standard statistical analysis. The basis is a forecasted manpower matrix. This matrix can be constructed when the firm divides the duration of the proposed contract into a number of equal time periods and decides what types of employees and how many of each will be needed during each period. In general, the forecasted manpower matrix has rows, each corresponding to a time period, and columns, each corresponding to a type of employee.

Once the matrix has been constructed, a manpower acquisition matrix can be generated by subtracting the $(j-1)^{th}$ row from the jth row of the forecasted manpower matrix. This new matrix can be further divided into two matrices, one dealing with manpower acquisition from within the firm, and the other from outside.

The same type of analysis can be applied to budgetary estimation. One type of calculation that can be handled in this way is acquisition costs, obtained by forming a matrix in which rows represent the different types of personnel and columns represent the different types of costs associated with hiring new personnel, and multiplying this hiring cost matrix by the appropriate manpower matrix. Similar calculations can be performed for determining maintenance costs, production costs, etc.

Thus far, the probabilistic aspect of the problem has been neglected. The study uses two statistical concepts in an attempt to cope with this aspect:
1. Application of subjective probabilities concerning the possibility of acquiring proposed projects

2. Application of probability distributions for determination of the starting period of the proposed projects.

The subjective probabilities for acquiring proposed projects may be obtained by considering the opinions of various key individuals in the firm and averaging their opinions to obtain a probability.

The study discusses three methods for estimating the starting date of a project. The first method, called the single best estimate, may be used when there is insufficient data from past experience with similar projects to form a probability distribution of the starting date. In this case, a single deterministic starting date is postulated. The second method may also be used when there is insufficient data from other projects. In the second method the starting date is a subjective probability distribution estimated by management personnel.

When sufficient historical data are available, a probability distribution of the starting date can be formed. The time periods used in forecasting the starting date are the same as those used in establishing the manpower requirements. In some instances, the volume of historical data may allow the probability of acquiring a project to be considered as a family of distribution functions, each of which is applicable during a given time period.

Having determined the subjective probabilities and derived the appropriate estimation of the starting date, these findings can be used to alter the entries in the forecasted manpower matrix and the other matrices derived from it. The new manpower matrices account for the nondeterministic aspect of long-range planning.

By using this system for each of the ongoing and proposed projects, management can construct a set of master manpower matrices for determining the quantity of each type of worker who should be hired or released during each time period. The costs of these personnel changes may also be calculated. By standard statistical techniques, management can compute means, variances, standard deviations, etc., of the number of employees required and the costs associated with them.

Potential Applications

The methodology developed in this study can be useful for businesses, government agencies, or any organization responsible for the operation and coordination of a number of discrete projects. An organization that is engaged in a large number of similar size projects and whose potential projects are of approximately the same size may find the techniques particularly useful. This characteristic is important, because the models developed in the study are often based on expected value calculations. Thus the models do not always allow for hedging against uncertainty.

The usefulness of the methodology can be increased if it can be applied to situations in which the time between the construction of the manpower matrix and the expected starting date of the project can be minimized. This is desirable because the accuracy of management's manpower estimates decreases as the time between planning and expected implementation increases. Technological change during the intervening time could alter both the types and number of employees needed for the project.

The Manned Spacecraft Cost Model

The manned spacecraft cost model, developed by General Dynamics, is a computerized procedure for analyzing the basic costs incurred in developing and operating a spacecraft system.

The model is composed of independent sub-models. The decision-maker thus may get an overview of the system and yet be able to study any section in depth. Subsystems may be modified or updated without reprograming the entire model. This feature allows parallel development and independent testing of the various program functions.

The model generates total costs by using information stored in a Cost Estimating Relationship (CER) library. A CER is the relationship between cost and various system parameters. CER's may be derived from data of past spacecraft programs. If sufficient data are available, multivariate regression analysis of the data can provide the "best-fit" cost relationship. If a subsystem is produced more than once, a learning curve submodel can adjust the associated CER's for decreasing costs to scale.

The model generates the program costs in a variety of ways. Total costs are broken down into increasingly smaller cost units from those of the entire space program to the spacecrafts, modules, and subsystems. The information is stored on tape and is available in any desired degree of detail. These total costs may also be used to estimate the time dependency of funding requirements.

The funding submodel predicts the spreading of an operation's absolute cost over time. The programer supplies the model with the starting and finishing times of an activity or the time at which a certain percentage of the activity is to be completed. The spreading of expenditures for similar previous operations determines the shaping parameters of a funding distribution function. Using the time "milestones" and the predetermined shaping parameters, the model estimates the required expenditures (adjusted for inflation, if desired) at fixed time intervals. The Center planning model performs similar operations to generate Manned Spacecraft Center personnel requirements.

To supplement the cost data, the model computes a measure of effectiveness per unit cost. Unfortunately, it is not easy to establish criteria of effectiveness because social, political, and scientific "profits" are difficult to quantify. Planners often use less satisfying, but more easily computable, criteria such as the probability of mission success. Cost effectiveness computations at this level of sophistication can provide crude guidelines for the decision-maker.

The contingency planning model assesses effects of unforeseen occurrences upon original cost estimates. There are eight contingencies whose impact the long-range planner may wish to analyze:

1. Technological stretchout - delays in the programs schedule due to technological difficulties

2. Budget constraint - an annual ceiling placed upon some part of a program budget

3. Cost sharing - common usage of some subsystems and facilities

4. Cancellation - cancellation of part or all of a program in terms of lost effort

5. Technological recovery - substitution of one system by another with different technological complexities

6. Acceleration - compressions of a previously defined schedule

7. Parallel systems - development of two systems to perform the same function with the understanding that one will eventually be canceled in favor of the other

8. Fixed costs - consideration given to incremental cost required to achieve additional operational capability

Knowing the consequences of possible contingencies and their likelihood enables decision-makers to determine policy in accord with their expected preferences.

Systematic analysis and modeling of the costs of a complex organization is by no means confined to aerospace applications.

The estimation of future costs is a recurring corporate function. All planning procedures require adequate cost data before the strategic decision-making process can begin. Given the central importance of these cost estimates, how do corporations establish cost-estimating procedures? The procedures used by some firms can seriously distort corporate decision-making. In fact, standard procedures for cost estimation are never really established in many corporations, and cost estimates are made rather haphazardly as the need arises. The various cost estimates emerging from a haphazard process are often the product of different methods of estimation, different assumptions, and different people. This lack of underlying consistency is very unsatisfactory from the decision-maker's point of view. Many of the decisions a firm must make will ultimately boil down to a choice between mutually exclusive alternatives. This choice should be made on the basis of consistent cost estimates. It is necessary, therefore, to develop a set of cost-estimating procedures which can, at the very least, provide a consistent basis for comparing alternative deicisions. Furthermore, the cost-estimating techniques should be reasonably flexible so they can produce cost estimates on many different types of proposed projects. Finally, it would be desirable to have as efficient a set of cost-estimating programs as the task allows. The criteria used to evaluate cost-estimating systems, therefore, should be consistency, flexibility, and efficiency.

NASA has been confronted with these same cost-estimation problems for each project that it has undertaken. As the space program has progressed, reasonably sophisticated and efficient cost-estimating procedures have been developed to solve these problems. An excellent example of a cost-estimating system developed with NASA funding is the manned spacecraft cost model. These same methods can be altered for utilization by large industrial corporations. The basic steps can be as follows:

1. Take the basic systems whose costs must be estimated, and break them down into subsystems, assemblies, components, etc.

2. Continue this breakdown until the level most convenient for cost estimation is reached

3. Characterize the units on this level in terms of all relevant parameters, e.g., weight, personnel, performance variables, etc.

4. For each of these units, develop "Cost-Estimating Relationships" (CER's) which express cost as a function of the above parameters

5. Store these CER's in a data library for use with the computer system

6. Build a computer program which, given a description of the system whose cost must be estimated, will call the appropriate CER's and assemble the results into overall cost estimates

Using this basic framework, it is possible to overlay several sophisticated techniques, such as contingency costing systems. The advantages of the costing system outlines above are as follows:

1. If designed properly, the elements of the CER library will be flexible enough to accommodate many diverse cost-estimating jobs

2. The CER library establishes a common set of costing relationships, so that the resultant estimates are consistent among themselves

3. The automation of the system provides an efficient time-saving approach to the problems of cost estimation

Of course, the success of the system depends on the accuracy of the individual CER's. These CER's can be as complex or as simple as the problem allows. For example, accurate costing relationships can often be generated by multivariate regression analysis using historical cost data. Or alternatively, simple formulas or rules of thumb may be generated for some units.

This type of systematic and efficient approach to costing seems particularly appropriate for large processes or manufacturing industries with reasonably stable manufacturing techniques. It may be useful whenever cost-estimation problems arise frequently enough to warrant the expense of developing a consistent but flexible cost-estimating system.

Although we did not analyze the models that were identified in the five other categories besides management, we did encounter some promising potentials. The company that played a major role in the Houston mission control center built on the skills they developed to assist a power and light company with their control system. A company that had done extensive work for NASA in mathematical models of human operators in flight control systems is developing templates for the Bureau of Public Roads of the overtaking and passing process on 2 lane rural roads. Continuing research for the Bureau of Public Roads includes the study of commercial vehicles and the effect of rain. Also, roadbed and vehicle sensor systems are being developed. Both design and regulation applications are expected.

The social science model area consisted primarily of econometric models of inter-industry flows and employment multiplier studies to estimate local economic effects of NASA facility investments. In addition, NASA supported the writing of a very important book, _Social Indicators_, that has had pervasive influence and applications in many areas of social science.

NASA work in reliability modeling has produced several computer programs of varying levels of complexity that can be used to speed up reliability calculations wherever they are made.

NASA work in both structural and medical modeling may very well precipitate a significant revolution in these disciplines. The comprehensive computer programs based on the finite element energy approach at Goddard and JPL may cause major changes in structural engineering education and practice. The modeling work in systems-oriented physiology may contribute to a new approach to medical research and practice. The modeling discipline may direct research to the crucial cause and effect relationships that impede medical knowledge. Models of the vestibular, cardiovascular, respiratory, thermal regulation, renal, and central nervous systems are under development.

If we agree that the management tasks of the aerospace projects are similar to many problems which occur outside the aerospace industry, then we must reasonably expect the transfer of systems technology. Undoubtedly the largest and most important part of this transfer flow will occur through the natural and nondirect diffusion of technology. NASA-supported projects have obviously contributed to the recent growth in the general body of knowledge and level of expertise surrounding systems management. This overall expertise is diffusing, and will continue to diffuse, through many related areas. Typical channels through which this diffusion occurs are universities, nonprofit institutions, and diversified corporations operating partially in the aerospace field. Furthermore, the space program is developing a large body of experts trained in the methods of systems analysis. As these highly skilled people venture into other areas of endeavor, they will naturally bring their skills in systems techniques to bear on new and different problems.

These channels for natural diffusion may be the most important media for eventual utilization of systems techniques outside the aerospace industry. Because of the indirect character of the diffusion process, though, it is a difficult phenomenon to document with any concrete detail.

Before proposing more direct technology utilization, it is instructive to consider the nature of a management system and its relation to technology. A management system, be it for an aerospace project, a corporate enterprise, or an urban and social program, must be a structure specifically tailored to the nature of the problem areas within which it will operate. There are no general formulas of structures which are universally applicable to systems management problems. It is useless to speak of transferring mathematical management systems in the sense of lifting

complete management systems from one prob-
lem context and applying them completely to
another. The possibilities for application
are, of necessity, much less all-inclusive
opportunities. A management system is a
collection of techniques "packaged" into an
overall unit adapted for problem solving. It is
these individual techniques, referred to as
systems analysis techniques or models, which
may be transferred to new and different en-
deavors. The elements of a potential manage-
ment model which is to be transferred must be
suitably altered, and recombined into an over-
all problem-solving approach in the new prob-
lem context. Only then will the application
process be successful.