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THE DESIGN OF RESEARCH AND DEVELOPMENT POLICY*

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THE DESIGN OF RESEARCH AND DEVELOPMENT POLICY

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Problems of research and development managers demand a management laboratory for the design and testing of new policies. This laboratory approach is now possible based on the concepts and methodology of Industrial Dynamics and on a new systems framework for representing project life cycles. The bases for a behavioral model of R and D projects are presented, as are some results of the computer simulation studies of the model. Conclusions drawn from these investigations suggest the importance of risk-taking and integrity of R and D organizations, and also indicate several areas in which government procurement policies seem self-defeating.

Author

The major problems facing research and development managers demand a new approach to the design of structure and policies of research and development organizations. These problems are manifested in the poor performance indices of R and D projects. With regard to project costs, for example, studies of weapon systems[1] and space projects[2] have shown that the ratios of final costs to their earliest estimates indicate growth by as much as several thousand percent during the project lives. Along with these changes in costs have gone slippages in project schedules. A RAND study of aircraft engine procurements found schedules to be delayed

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[1] A. W. Marshall and W. H. Meckling, "Predictability of the Cost, Time and Success of Development", RAND Corporation Report, P-1821 (December 11, 1959), p. 22; M. J. Peck and F. M. Scherer, The Weapons Acquisition Process: An Economic Analysis (Boston: Harvard University, Graduate School of Business Administration, 1962), p. 429.

[2] Thomas W. Finch, "Factors that Influence Changes in Cost and Time Schedules of Research and Development Contracts" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, June, 1962), pp. 40-41.

by as much as four years beyond initial delivery estimates.[3] Lower product quality has also often accompanied these cost and schedule slippages, and at times major reductions in performance specifications have been needed to permit on-time or within-budget project completions. These low indices of over-all R and D effectiveness also appear in the rapid obsolescence of new products, in particular our military weapon systems, and in the high failure rate of research and development efforts. A management survey of over one hundred major companies showed that two-thirds of their new product attempts fail, while only one out of eight is successful in the chemical industry.[4]

The needs for higher managerial effectiveness that seem inherent in the problems cited are expanding rapidly. The basic problems have remained unsolved, while the substance of research and development has greatly increased in complexity. This burgeoning product complexity is shown, for example, in the number of electronic parts used in three succeeding "generations" of aircraft. In 1952 the B-47 contained less than twenty thousand electronic components. Four years later the B-52 required fifty thousand. And after another four years, the 1960 B-58 utilized about ninety-five thousand parts.[5] Thus, in less than ten years, the number

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[3] Burton Klein and William Meckling, "Applications of Operations Research to Development Decisions", <u>Operations Research</u> (May-June, 1958), pp. 359-360.

[4] C. Wilson Randle, "Problems of R and D Management", <u>Harvard Business Review</u>, Vol. 37, No. 1 (January-February, 1959), p. 128.

[5] John E. Hickey, Jr., "What Price Reliability?", <u>Electronic Industries</u>, Vol. 20, No. 9 (September, 1961), p. 142.

of components in relatively comparable weapon systems leaped by a factor of five. But perhaps more noteworthy than the mushrooming product complexity is the fact that research and development has become more and more critical to our way of life. Both government and industry R and D expenditures are shooting sky-high in demonstration of this importance, reaching a total annual rate of about sixteen billion dollars during the current year and still rapidly accelerating. This broadened spending makes more urgent the need for solutions to the underlying problems of the research and development industry.

The Need for a New Approach

One great difficulty in meeting the expanded demands is that the old approaches to R and D have not given better understanding of the policy aspects of the business. In general, the few improvements which have been made have been limited to somewhat mechanistic approaches to budgeting and scheduling. At the company level, devices such as PERT and Functional Analysis seem destined to command even more attention and financial support. Without questioning the yet unproven effectiveness of these tools, one should recognize that even if successful, they deal only with such things as the bases for schedules and reports. They do not treat such fundamental government considerations as funding policies, profit rates to be allowed on contracts, performance incentives, etc. Nor do they attack vital company policy questions regarding risk-taking, bidding integrity, project staffing, proposal strategy, resource allocation to various technologies or to funded versus unfunded work areas.

The demands for designing and experimenting with new policies and organizational forms in research and development thus cannot be met by merely having more of what has taken place until now. Further technique development alone will not solve underlying problems which stem from lack of managerial understanding. The pitfalls to finding the needed understanding lie within the mode of R and D organization itself, in managerial attitudes, and in the lack of effective management research in industry and university alike.[6]

Furthermore, requirements for solving R and D problems arising out of mistaken policies are of a different nature from those which have been needed in the past. For example, a new technique, like PERT, may be at least partly tested on one or more projects by being operated in parallel with some other method of data collection, analysis, or presentation. Results can be observed and compared, and judgments made as to the effectiveness of the new method. But policy experimentation is far more difficult to attempt through parallel schemes. For instance, the company which traditionally risks very little of its own funds prior to customer contractual support cannot, on a single project, simultaneously test the effect of a policy based on the usual assumption of high risks. The company which usually attempts to underbid its competition cannot at the same time on the same project experiment with a changed bidding strategy.

Similarly, when differences in managerial policies are the bases of experimentation, trying two approaches on two different projects does not

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[6] For a discussion of the reasons behind the generally poor conceptual understanding of R and D problems, see the author's article: "Toward a New Theory for Research and Development", Industrial Management Review, Fall, 1962.

work. In the first place, such experimental design is statistically inconclusive; second, it is surely not persuasive within or without the organization; and third, such an approach is subject to all the difficulties arising from lack of comparability of the task or staff situations. Thus no new policy would be adopted and implemented solely as a result of such unconvincing trials. Perhaps even more difficult is that neither the government customer nor the company manager of research and development feels justified in encouraging experiments in managerial policy in a lab or on a project in which he is interested or involved. The consequences of policy change are potentially too great.

It is this potential impact of revised R and D policies which necessitates the development of a workable approach to the design and testing of new managerial ideas. In the technical aspects of research and development, new designs have been developed and tested in engineering or scientific laboratories. Wind tunnels, ship-towing tanks, scale models, pilot plants, analog and digital simulators have all been used to check plans and ideas for flaws before any mistake could produce serious consequences. The success of these approaches to product pre-test is demonstrated by their increased utilization in all engineering fields. The concept of a management laboratory as a means for helping in the design and determination of R and D policy thus seems a logical next step. Here I suggest that the developments of the past five years, based largely on unifying principles of Industrial Dynamics[7] and on some new derivative

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[7] Jay W. Forrester, <u>Industrial Dynamics</u> (Cambridge: The M.I.T. Press, 1961).

concepts regarding the nature of research and development[8], have made possible this new approach.

The Framework for a New Approach

To erect a new building, one needs a plan, the tools and materials, and some skilled artisans to carry through the construction. In an analogous fashion, the development of a management policy laboratory for R and D requires a conceptual framework, tools and materials for filling in the frame, and able and interested R and D managers and management researchers to carry on the required effort.

The basis for a plan of attack has been provided by the Industrial Dynamics research program, started at the M.I.T. School of Industrial Management by Professor Jay W. Forrester six years ago. Industrial Dynamics emphasizes the information-feedback characteristics of all industrial and economic activities and studies the means by which "organization structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of an enterprise.... It is a quantitative and experimental approach for relating organizational structure and corporate policy to industrial growth and stability."[9] The program is based on the belief that top-level management problems are most appropriately viewed from a framework of the dynamic system in which the time-varying interactions of the industrial (or governmental) organization

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[8] Edward B. Roberts, "The Dynamics of Research and Development" (unpublished Ph.D. dissertation, M.I.T. Department of Economics, 1962).

[9] Forrester, p. 13.

are manifested. Thus an Industrial Dynamics analysis is not explicitly oriented to either the functional or the departmental components of a business. Rather it treats the underlying basic flows of men, money, materials, orders, and capital equipment, and the information flows and decision-making network which tie the others together. The philosophy and methodology of Industrial Dynamics are as applicable to the single project as they are to the national economy, as suitable for studying significant problems of production-distribution systems and factory management as for investigating the areas of product and corporate growth.[10]

What is needed as a first step in each Industrial Dynamics study is a specific dynamic theory of cause-and-effect interaction which encompasses the problem of interest. Such an hypothesis is now available for describing the life cycles of research and development projects. A research and development project consists of a set of underlying activities which continuously interact to produce the project history. The resulting actions continuously feed back upon the other decision areas of the project to induce still further changes. All R and D projects contain the closed-loop system of activities pictured in Figure 1 and described below.

1. The world situation is continuously changing with regard to the need for new products (military, industrial, and consumer) and the technological capabilities for obtaining them. These changing factors can be taken as inputs to any project system under consideration.

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[10]For discussions of such applications, see Forrester, op. cit., particularly Chapters 15-19.

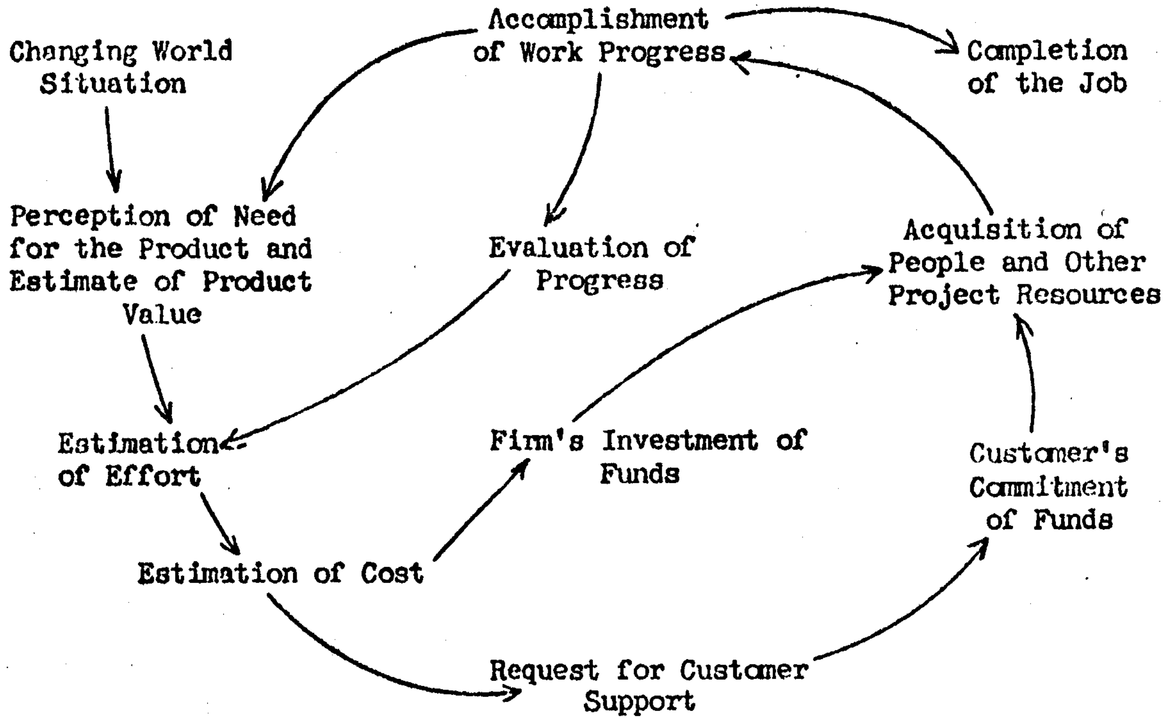

Figure 1. Dynamic System Underlying Project Life Cycles

2. Potential customers of new products and firms in the business of developing them are continuously engaged (consciously or unconsciously) in activities aimed at perceiving the need for and potential market value of new products.

3. Along with these value-perception activities, the customer and the firm both consider the technological feasibility of the product development effort, and estimate the manpower, materials, facilities, and equipment needed.

4. Based on this effort estimate, the customer and/or the firm attempt to judge the total cost of the program.

5. The firm now has two parallel alternatives.

    a. First, it can submit to the customer a request for financial support. The customer evaluates this request by comparing the estimated product worth with the estimated cost to complete the project. If he reacts favorably to the firm's request, the customer will commit funds to the project after a long delay.

b. In its alternate path of action, the firm invests its own money in the project. This decision involves risk, since the firm commits its own funds before the customer makes such a commitment.

Either or both of these parallel paths provides money to the project.

6. As the project group obtains funds, it begins to hire or reassign engineers and supporting manpower.

7. These employees accomplish progress on the job. Their rate of accomplishment reflects, among other factors, the magnitude of the manpower effort, the technological state of the art, managerial influences on productivity, engineering experience on the project, and inefficiencies due to organizational growth.

8. Both the customer and the firm continuously attempt to assess the progress. They evaluate the state of job completion by comparing their current interpretations of the results accomplished to date with their current perceptions of the end results desired.

9. Continuing progress evaluation creates new estimates of work yet to be done on the project, which feed back into the

closed-loop process already described. New evaluations are continuously being made by the firm, as to its appropriate investment rate in the project, and by the customer, as to possible modifications of the project programming and support.

This continuing cycle of activities takes place throughout every project life, leading in each case to eventual completion of the job or to cancellation at some point prior to full completion. Major events may take place at various intervals scattered throughout a project life, and changed estimates and evaluations may formally appear only in periodic reports. But the increments of progress and change, real and observed, take place continuously in the manner described. The activities included within this dynamic system contain the possibilities of producing the full range of observed R and D project life histories: on-time or late completion, customer stretch-out or acceleration of the project schedule, satisfactory performance or job cancellation can all result from the system interactions. Moreover, these various results, and the system which underlies them, are observable not only in government research and development projects, but also in commercial new product development programs. Thus the dynamic system structure shown in Figure 1 can be applied to investigation of managerial policies in all forms of R and D.

The Tools for Progress

With the framework provided above, we are now ready to specify the methods and materials to be used in developing our R and D management laboratory. For such a laboratory we must be able to represent effectively the research and development organizations and have the facility of experimentally modifying the represented structure and policies. The Industrial Dynamics program has developed the methods needed here. Its techniques for drawing flow diagrams and writing equations which describe organizational systems can be applied not only to studies of fluctuating behavior in manufacturing-oriented businesses, but can also be used to investigate evolving and ever-changing R and D organizations. The difficulties in applying the methods to research and development arise from our more hazy understandings of what is taking place in an R and D organization and from the less tangible variables which we must treat. But it is still possible to represent pictorially the effect of optimism on cost estimates, or the effect of risk-taking propensity on project investment decisions, in the same manner that we can show the relationship of inventory stocks to a reorder decision. The equations for such representations are similarly feasible. These flow diagramming and equation-writing techniques will therefore permit representation of the R and D problems.

Once represented, such systems require study by alteration of parameters and policies in search of both understanding and more effective management approaches. Here, too, the Industrial Dynamics research program has provided the needed tools through the DYNAMO digital computer simulation system.[11] DYNAMO is an automatic compiler and simulator for the IBM 704, 709, and 7090 computers which makes easy and inexpensive the multiple simulation runs that are required. The computer system permits

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[11] Alexander L. Pugh III, DYNAMO User's Manual (Cambridge: The M.I.T. Press, 1961).

valuable payoff by making the feedback of theory-test-results-theory more immediately available, thus allowing redesign of hypotheses and gradual synthesis of the findings. The DYNAMO computer program was initially used for studies of production-distribution systems but is readily applicable to all continuous dynamic system problems.

The third contributing basis for progress in a research and development management laboratory is not a result of Industrial Dynamics work. Rather it is the body of knowledge and understandings of parts of the R and D system, which knowledge is represented in the published literature and even more so in the minds of R and D managers. The literature generally refers only to the know-how on individual segments of the broad picture, but when the individual pieces are meaningfully treated, they supply potential for system integration. The experiences of the managers relate not only to the pieces separately, but to their interrelationships as well. This potential guidance is available for collecting material on the substance of research and development management problems and for assembling the material on the framework discussed earlier.

The Need for Management Experimenters

We initially suggested that to carry out a management laboratory approach to the design of more effective R and D policies, three elements would be needed: a framework, the tools and materials to put on the frame, and the craftsmen to carry out the job. The first two elements are now available -- only the people are lacking in number. But several R and D managers have already begun preparing themselves for this new managerial role. Several members of the M.I.T. School of Industrial Management's

Sloan Program in Executive Development, and some of their companies, have taken first steps to develop capabilities in the R and D management laboratory approach.[12] As part of their thesis research programs, these managers, on one-year leaves of absence from their organizations, have examined project management problems as well as aspects of R and D resource allocation, management of product-line diversification for corporate growth, and corporate level problems with decentralized laboratories. The researchers in these areas have come from responsible management positions in such companies as RCA, Boeing, IBM, Hughes, and Chrysler, as well as from government agencies such as the Air Force and the Navy.

The requirement for qualified people to conduct such innovative investigations is vital, but need not limit any research and development organization from going ahead in this area. R and D managers are themselves often ideally suited to undertake this work. Many have engineering backgrounds with servomechanisms, chemical process controls, or electronic information-feedback systems through which they have developed strong intuitive grasps of the nature of system behavior and of principles of systems design. Many have carried out simulation studies with physical systems and are aware of the insights to be gained from carefully thought-out and executed model simulations. And, most important, as managers these men have tackled and been confounded by the complexities of R and

[12]The first Industrial Dynamics study in the area of research and development was a thesis by a Sloan Fellow from RCA: Abraham Katz, "An Operations Analysis of an Electronic Systems Firm" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1958). This work was described by Katz in his article, "An Industrial Dynamic Approach to the Management of Research and Development", IRE Transactions on Engineering Management, Vol. EM-6, No. 3 (September, 1959), pp. 75-80.

D management. Thus they come prepared with understanding of both methodology and problems. What they require is the encouragement of top management which is willing to exercise the same patience with managerial policy design as is practiced with physical product design. If managed properly, the improved R and D policies can produce payoffs that dwarf the returns from any product innovation.

A Model for Testing R and D Policy

To demonstrate how the proposed laboratory approach might work, we shall consider a set of specific hypotheses to the initial dynamic systems framework (pictured in Figure 1), and from these develop a policy-oriented model for studying project management problems. At this point it is not really important whether or not each hypothesis is completely validated by data collection and analysis. Alternatives to any one of the hypotheses might be offered, based upon a particular set of company R and D experiences or oriented to the study of a specific policy area. What is important is that each hypothesis be plausible, that the set appear realistic, and that R and D managers be willing to accept the whole model as reasonably representative of some R and D situations, if not of their own cases. When this is accomplished, then the general usefulness of the laboratory approach to policy design can be demonstrated. Each organization would need only to change the model to be descriptive of its own experiences and problems.

The assumptions which follow spell out the relationships within each flow path of the Figure 1 system as well as the interconnections among these paths. The hypotheses are based on generalizations derived from the literature, personal experience in research and development organizations, and discussions with many R and D managers in industry and government over a four-year period of model evolution.

The Changing World Situation

Two underlying factors provide the dynamic context within which every research and development project is carried out. They are the bases for the value and cost of the product development effort. The first of these is the intrinsic product value, the real usefulness of a potential product at any point in time, whether recognized or not. The underlying usefulness of any particular product varies over time. Prior to some point in time there is little or no need for a product. This need may increase, in the military product market, for example, as world tensions in a given area increase, and later decrease as the product's usefulness begins to diminish. The need for a product is illustrated by a curve of the type shown in Figure 2. The gradual rise, the period of relatively unchanging mature value, followed by the decline into obsolescence, is characteristic of all product life cycles, and reflects the changing world situation.

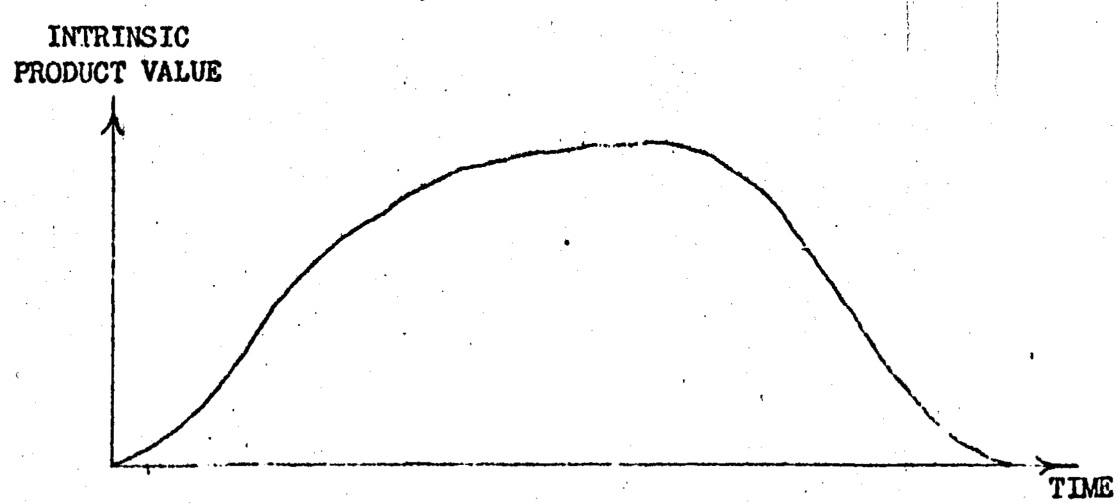

Figure 2. Time-Path of the Underlying Need for a Product

The second factor which underlies all projects is the changing requirement of project effort. The intrinsic size of the job, i.e., the scope and complexity of the product design and development task, may remain unchanged, but the potential effectiveness of the engineers working on the project changes as the technological state of the art advances. Figure 3 illustrates two hypothetical curves of technological growth. Each corresponds to a different changing world situation of the know-how that is available for application to an engineering effort. With the added know-how comes increased technical effectiveness and hence decreased cost of the effort.

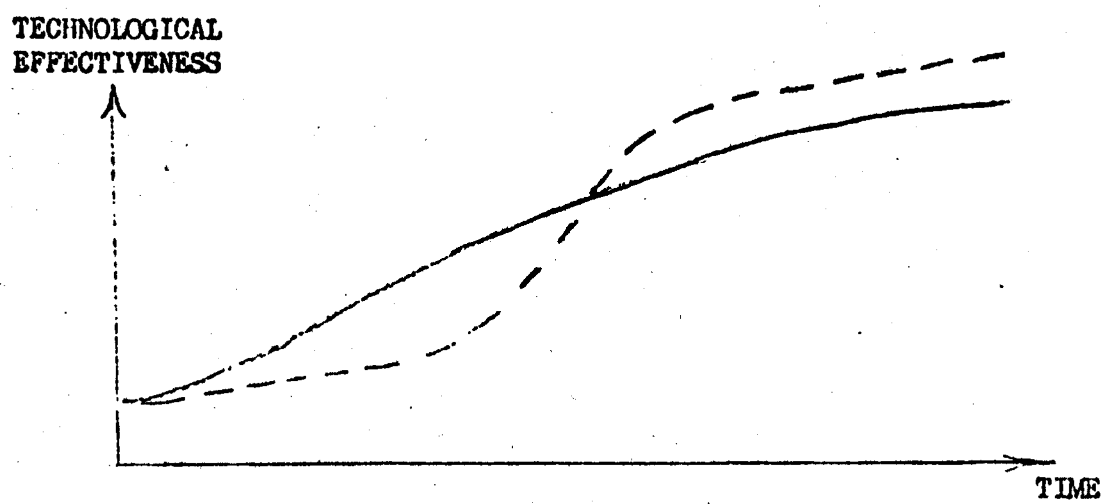

Figure 3. Comparative Curves of Technological Growth

Taking both of the basic inputs into account, we can easily recognize the importance of the value-cost relationship in R and D. Figure 4 presents the implications of the two concepts. A job undertaken too soon will get completed at a cost which is excessive for the value derivable from the product. Too late a completion leads to the same problem. But a real source of managerial difficulty in R and D is that neither of the two curves pictured in Figure 4 can be known by the manager, nor can the

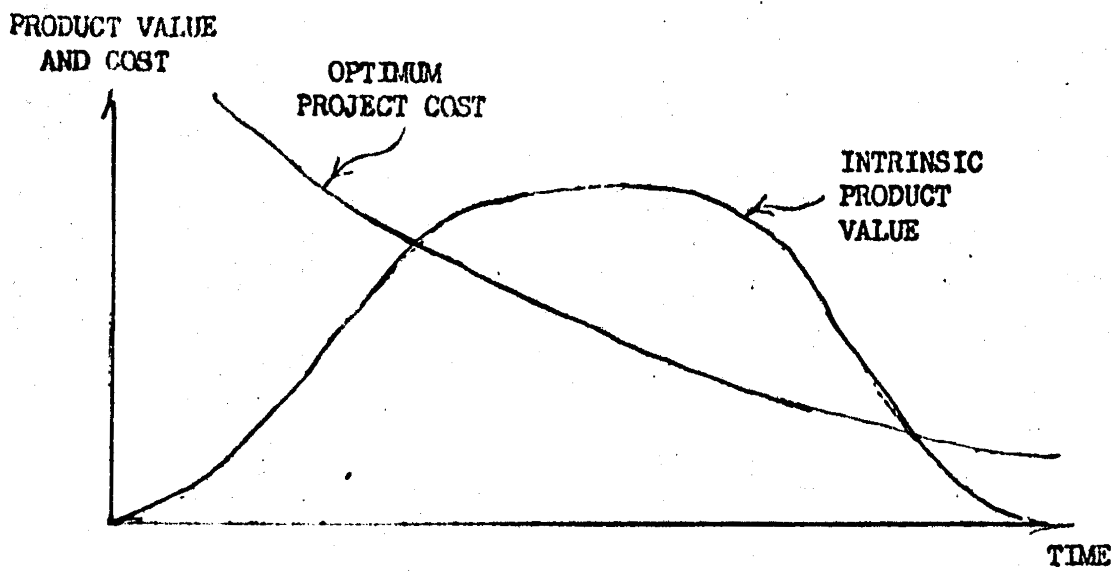

Figure 4. The Relationship of Product Value to Cost

optimum cost be attained. The manager in both industry and government can only estimate the value and cost situations, and as pointed out earlier, his performance is not very good in either area. But this brings us to the second link in the R and D system.

Perception of Product Value

The initial organizational behavior aspect to consider is the recognition of the need for and value of a potential product. In all R and D companies at least a few engineers or scientists are engaged in activities to develop new product opportunities. The people who conduct these studies may be part of a research laboratory, an advanced projects group, or a preliminary design section, or they may just be regular members of the engineering team looking into the extensions of some product ideas beyond the current contracted projects. These activities result in insights which aid the perception of the need for and value of a potential product. The recognition of product value is thus primarily influenced by the developing technical know-how of the organization.

But decisions on R and D projects are not based on the believed current value of the product, for the product is only a potential one and does not presently exist in the desired form. Estimates are necessary of the future value of the product at some time by which the organization believes the product can be developed. The estimate is therefore influenced by the organization's willingness to accept risk by committing itself to uncertain future possibilities. A few firms base their research programs on demands which they expect ten years in the future; others are afraid to "venture beyond their front pastures".

Estimation of Effort and Cost

Considerations of research and development undertakings are in part based on estimates of the effort which is going to be required to get the job accomplished. This effort estimate in turn represents the combination of an estimate of the job size and complexity with the organization's estimate of the technical effectiveness of the engineers who will be performing the work. Early estimates of the scope of the job are influenced by three factors: (1) the relationship of the previous job-size experience of the organization to the current project's intrinsic size; (2) the general tendency to underestimate the job size; and (3) the overall managerial and technical capability of the organization, which affects the degree of error in the estimates. Revisions of the job size estimates during the project life stem principally from recognition that the work is not progressing according to schedule.

The early estimates by either customer or firm of the relevant technical effectiveness of the engineers reflect the organization's optimism and confidence in the firm's engineers, the recent recognized state of the art, and the organization's ability. The estimates of effectiveness are revised during the project in response to both realized and anticipated further technological developments, and by gradual correction of errors in the earlier estimates.

The cost estimates are readily derived from the effort estimates by applying as multiplier an estimated monthly cost of support for each engineering man-month of work believed required.

Request for Customer Support

During the early part of the project, the firm seeks customer support of its current research activities in the project area. But as the firm begins to feel that a larger-scale undertaking is warranted, it will request funds for a full development project. This feeling of timeliness may result from the customer's request for proposals on the project, or it may stem from the firm's own opinion that the cost-value relationship of the project will soon be deemed suitable by the customer. In either case the firm will present to the customer an estimate of costs which reflects not just the firm's own internal estimate but also its integrity. Most firms consciously understate the expected costs of the project in their attempts to win project support. Should such a firm receive the contract, its requests for revisions of the level of customer support during the project will reflect not just the expected cost overruns (or underruns) but will also be influenced by the firm's integrity. For example, the firm will not, immediately after receipt of the contract, request a major contract revision, even though it may realize that the costs are seriously underestimated.

Customer's Commitment of Funds

The customer's consideration of the suitability of the project takes into account the expected cost and value of the project outcome. The decisions are based upon figures and opinions which reflect a combination of the customer's own prior estimates and the estimates presented by the firm. The customer's confidence in the firm determines the extent of influence of the firm's bid. The customer has more projects to support than his available funds will permit. In addition, previous customer experience leads him to expect that the final project cost will be greater than the initial estimate. For both these reasons the customer will not invest in a project until the expected value is much greater than the expected cost. The value-cost ratio will influence the customer's enthusiasm for the project, which in turn will affect the level of allocations which the customer establishes and gradually releases for project use.

During the project life the customer exerts control pressure on the firm by altering the rate of funding available -- stretch-out or acceleration is effected by reducing or increasing the funding rate. Cancellation and crash programs are merely the extremes, respectively, of this stretch-out and acceleration process.

Firm's Investment of Funds

Before becoming able to get customer support of its efforts, the firm usually has to sponsor some work to build up its own capabilities and understanding of the project problems. In making a decision to invest in an area of work, the firm estimates the likelihood of eventual customer support of a full-scale project. The firm then tries to estimate the profits it would derive from such a project, and it is willing to invest a fraction of those expected profits. This fraction depends on the risk-taking propensity of the firm. The firm allocates the funds it is willing to invest over a period of time, thus establishing a desired rate of spending and, consistent with this, a desired level of engineering effort.

Acquisition of People

Based on its own or the customer's expected funding, the firm hires or reassigns engineers and supporting manpower to bring actual employment in line with the desired level. This takes place continuously throughout the project, requiring several months whenever recruiting is needed. New engineers on the project require training or at least orientation by the more experienced engineers on the job. As the job nears completion (or as funds are withdrawn), some of the engineers are transferred from the project (or, reluctantly, from the firm).

Accomplishment of Work Progress

In making progress on the job, the engineers work with the available state of technology. The engineering effectiveness in utilizing the state of the art is influenced in general by the over-all managerial and technical ability of the firm and by the build-up of on-the-job experience during the project life. In addition, of course, the progress rate is affected by the number of engineers working on the project and their deployment as trainees, trainers and managers, and full-time engineers. The size of the organization may also affect the efficiency of engineering utilization.

Evaluation of Progress

Based on the believed job size and the believed effectiveness of the engineers, both customer and firm form estimates and schedules of the rate of progress. Errors in these estimates gradually cumulate and produce pressures to revise the earlier beliefs. These pressures become more influential as the project gets to its late stages, when physical indications of real progress begin to show up.

Translating the Verbal Model into Mathematical Form

The foregoing descriptions provide a set of verbal hypotheses for each flow within the research and development system. This task is more difficult and more important than the mathematical equation-writing which can follow it. From the verbal statements alone we can trace through some of the implications of various customer and firm policies. The mathematical model, however, permits this more readily and more exactly. To develop the equations, each definitive verbal sentence must be translated into mathematical form. The equations then constitute a precise statement of the relationships that are believed to control a typical research and development project. As a demonstration of the method, equations which represent the accomplishment of progress on the project are developed in the appendix to this article.

Results of Model Simulation

The completed model of research and development can be simulated on a digital computer to produce project time histories for the particular input conditions and policies provided. The model contains about 250 variable equations and an additional 135 constants and initial conditions. These describe the causes of actions by both customer and firm as well as the characteristics of the product. Calculation of the values of these equations at successive time intervals produces the life cycle of the research and development project being simulated. Alteration of any system parameter or policy will produce changes in the project life cycle which can be detected through use of simulation studies.

Basic Project Dynamics

We shall now discuss a typical project history as it evolves from the computer simulation. The project is similar to a large number of government R and D undertakings, requiring from 600 to 3000 man-years of engineering effort, depending on the state of the art advances which can be utilized and on the over-all ability of the firm's management and engineers. This effort requirement indicates project costs between 18 million dollars and 90 million dollars, a range covering such projects as a new highly advanced computer system for the Atomic Energy Commission, a radar-control center for airport traffic for the Federal Aviation Agency, a small jet engine for Navy helicopters, an air-to-ground missile for the Air Force, or a satellite communications system for the National Aeronautics and Space Administration. These and the simulated project all relate to areas in which the relevant technology is rapidly advancing, the need for the product is changing as times and circumstances change, and both the firms and customers involved have earlier experiences with each other and with at least somewhat similar types of undertakings.

The entire project history is pictured in Figure 5, which depicts the project life cycle from several points of view. The curves shown here are actual outputs of the computer simulation. These results have been generated by the interactions of those policies of the customer and firm that were described earlier. The graphed data seem to correspond to our general notions about the dynamic behavior of research and development projects. For example, the cycle of the product value phenomenon is clearly visible: the intrinsic product value, which is the principal input to the model run, grows, levels off, then falls gradually to zero; in partial response to this, the perceived current value of the product lags the real value throughout the life cycle; the estimated future product value lags at first, then rapidly advances, overshooting the real value by a large factor, finally falling back toward zero. This relationship between the behaviors of the real and the believed product value is an important characteristic of all R and D projects.

Another vital phenomenon is the changing curve of estimated project cost. Starting very high relative to product worth at that time (lack of technical feasibility implies infinite costs), estimated effort and cost on the project gradually fall with the rising technological state of the art. As expected costs fall and perceived product value rises, the firm hires (or assigns) more engineers to the project area. When the cost estimate is sufficiently low relative to anticipated value to attract the customer's support, the project moves into a full-scale development program.

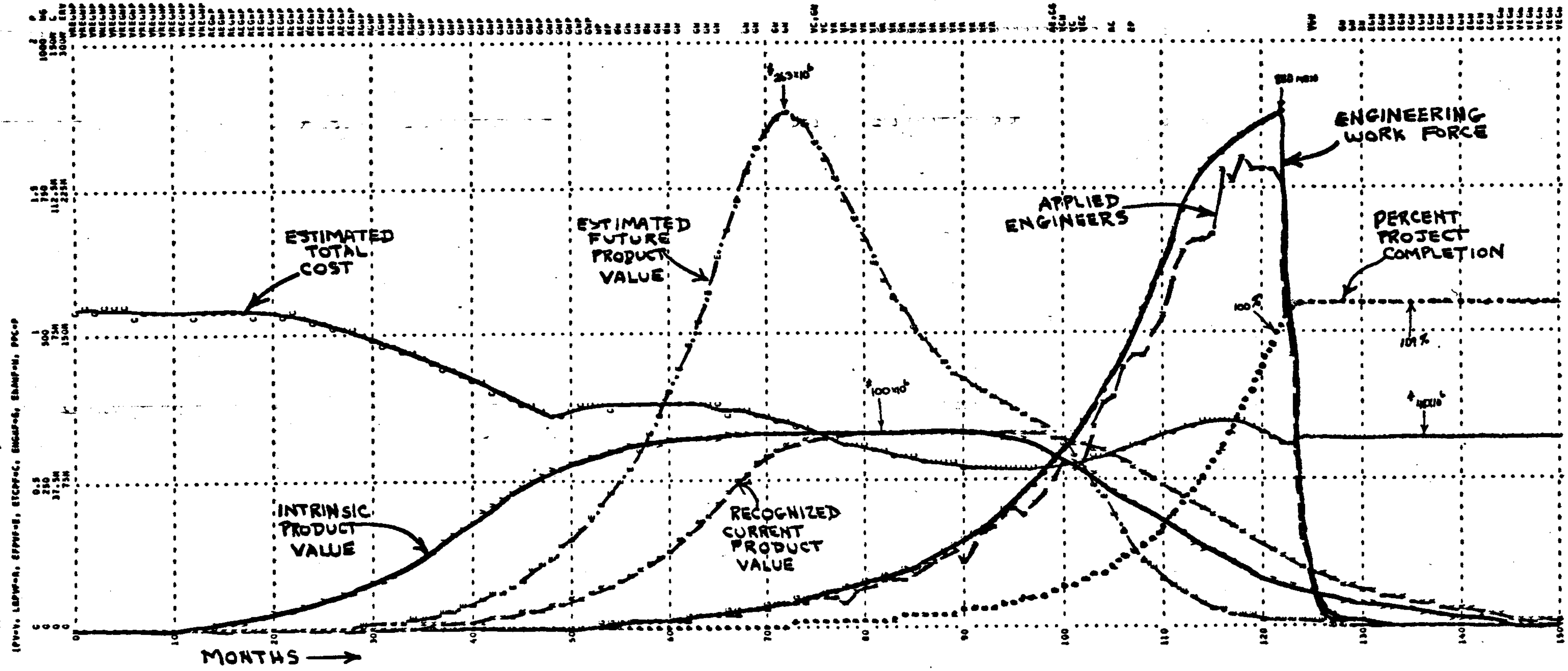

Figure 5 Basic Project Dynamics

The resulting increase in engineering effort tends to stabilize the earlier decline in estimated cost as the firm begins to form a more realistic impression of the real magnitude of the job and of the effectiveness of the engineers. Cost estimates gradually rise during the remainder of project life, with final costs about 20 percent greater than those expected during the early growth phase of the project.

The curve of engineering employment on the project also shows the rise and fall in the life cycle. For a long time only a single engineer is working in the product area. This effort level is so small relative to the later engineering activity on the project that it does not even show up on the graphed simulation results. Then the engineering employment curve shows the gradual growth that takes place as the firm invests more of its own funds in the project area. As the project receives customer support, the staff grows steadily and ever more rapidly, tapering in its growth only as the project nears completion. The last phase of the engineering curve shows the period of transfer of engineers from the project to other areas. The more jagged curve of applied engineering effort on the project takes into account the usual holidays, vacations, and absenteeism of engineers assigned to the job. This curve more closely resembles the curves of engineering effort which are occasionally published.[13]

The last curve in Figure 5 shows the real cumulative percent completion

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[13]For example, see the IRE Transactions on Engineering Management, Vol. EM-8, No. 1 (March, 1961). The illustrated simulation results resemble the plots which appear on the cover of that issue; simulation curves produced using other parameters or policies appear to be more similar to the data shown on page 5 of the publication.

of progress on the project task. This curve is hardly visible for many months of the project life cycle. During the embryonic phase of the project, up to about month 70, the percent of project completion appears to have a zero value. Only as the project activities enter their early growth phase does project accomplishment begin to appear on the graph. In part, this is misleading. For although the engineering output relative to that needed for project completion (this is the concept plotted) was almost nonexistent during the entire period of time, some very essential achievements had already been accomplished. These achievements were organizational or conceptual in nature: (1) the engineering staff had been increased to form a nucleus for the project expansion; (2) cost estimation on the project had been firmed up; and (3) funds had been allocated by the customer. These achievements were all vital to the project, but none of them can be directly related to the elements of engineering needed to finish the product development. In addition, these achievements all took place prior to the large expenditures of effort or funds which characterize the "formal" beginnings of a research and development project. The "preconditioning" phase of a project life which precedes the larger-scale effort is much longer in time than the high activity phase of the project. But managers or management researchers who ignore the existence of this earlier phase of a life cycle are forgetting the very sources of the entire project concept and execution.

From month 100, the project engineering tasks are gradually accomplished, and the percent completion rises correspondingly. About 80 percent of the effective work on the project is done in the last year and one half of the project life (from about month 105). The work was actually completed in month 122 and some extras added while the engineers were being transferred from the project.

Prior to month 100, by which time full-scale activities were under way, only about 300 cumulative man-years of engineering effort had been invested out of the 1395 man-years ultimately needed for completion. From that time, an additional two years were needed to finish the project work. When the job was finally completed, the customer was dissatisfied, feeling that the costs had exceeded the product value and that the product was no longer particularly useful. Such is often the case in military research and development undertakings.

The computer results demonstrate the plausibility of the hypothesized model. With such a model (or with an alternate model, if preferred), managers can begin to determine experimentally the effects of changes in characteristics of the product, customer, or firm, or in the policies of the customer or firm. Some results of such simulation experiments with the model are now described.

The Case of the Conservative Firm

Too often the problems of research and development are blamed on the complexities of the product, rapid changes in technology or in the competitive situation, or on faults in customer planning or decision-making. To be sure, such factors are significant in determining the outcomes of R and D projects, and simulation studies related to these aspects could have been discussed here. However, the policies and practices of organizations actually doing the research and development work also vitally influence project success and failure and are more directly controllable by R and D managers. For example, one characteristic that distinguishes between R and D firms is the relative optimism or pessimism, speculativeness or conservatism of the firms. This attitude or policy of the firm not only biases its estimates of future product value, technological progress, and engineering effectiveness, but also importantly influences the amount of funds the firm is willing to risk as a project investment before the customer provides substantial support.

The firm involved in the project pictured in Figure 5 had a high risk-taking propensity. To illustrate the effects of conservatism on project dynamics, the basic simulation was rerun, with the only modification being that the modeled firm was conservative instead of speculative. The new results are shown in Figure 6. The changes are obvious. First to show up is the fact that the firm's estimate of the future value of the product falls far short of the more speculative estimate in the Figure 5 project life. This lessened expected value makes the project far less attractive to the firm with smaller expected profits. Furthermore, the conservative firm is unwilling to risk much of even these expected profits, waiting instead for the customer to provide financial support. This policy retards the growth of an engineering team for the project, contributes additional delay to the customer's funding, and significantly slows project progress. By month 122, the project had been completed in the earlier simulated case; however, by month 122 in the present project, the customer has become sufficiently dissatisfied that he has already begun cutting back on funding in anticipation of project cancellation within the next six months. By month 130 engineering on the job has come to a halt with only 75 percent of the task completed.

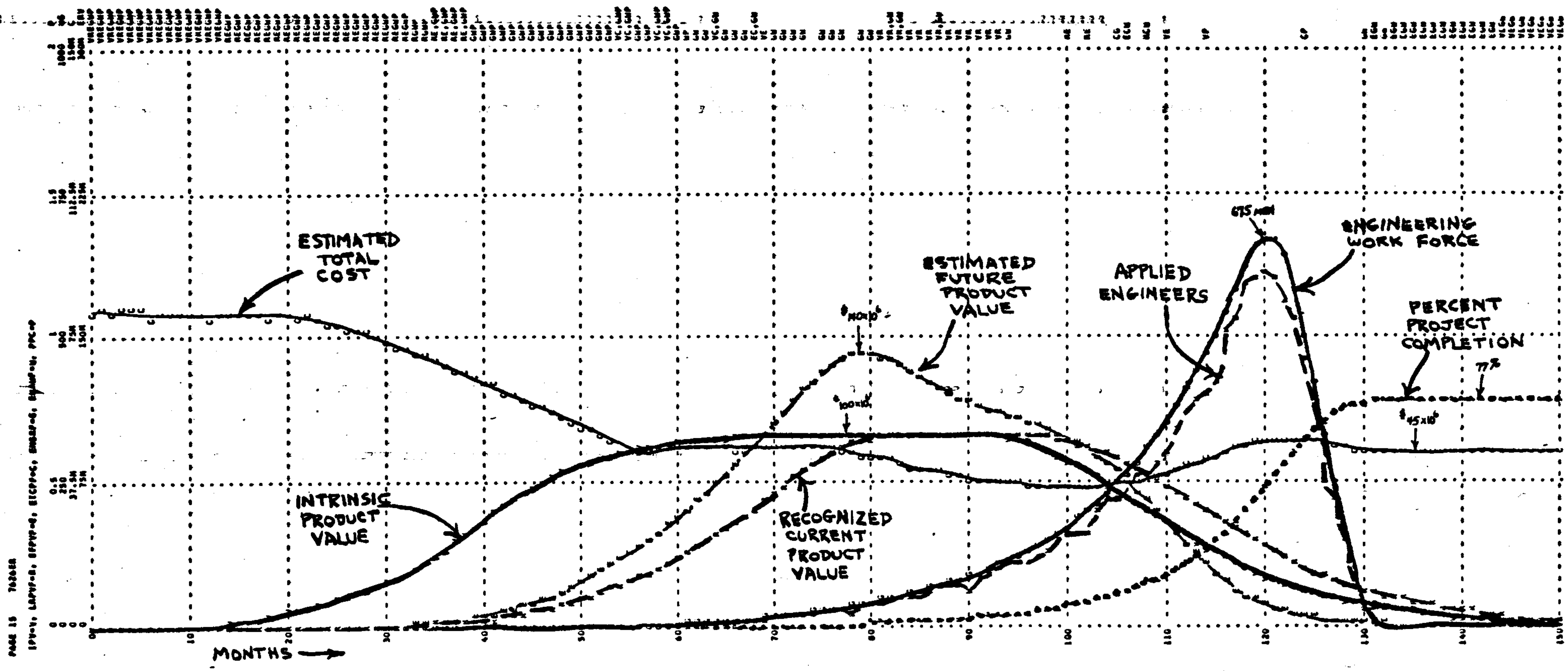

Figure 6 Effects of Company Conservation

Thus, in this particular case the firm's policy of conservatism actually caused the failure of the job and the waste of the 34 million dollars that the customer had already spent on the effort. Under other project circumstances perhaps the conservative approach is the more advisable policy for the firm to adopt. The power of simulation is that it permits study to determine both the likely results of various policies and the conditions under which particular policies are preferable.

The Case of the Intentional Low Bidder

At times company "optimism" gets to such an extreme, particularly with respect to cost and effort estimates submitted as part of R and D proposals, that the estimates really reflect intentional low bidding. Many companies are led to underestimate project costs in their attempts to get awards of R and D contracts. Under Cost Plus Fixed Fee (CPFF) contracts, the firm is not penalized for the resulting overruns on project costs. However, as Figure 7 illustrates, the firm's policy of intentional cost underestimation, encouraged by the CPFF practices, has significant effects on project dynamics, and through these on the firm and customer too. The simulated project life cycle pictured on the next page evolved from the basic situation portrayed in Figure 5, the only change being in the degree of integrity of the firm, affecting the cost estimates it submits to the customer. The smaller initial contract size induced by the low bid causes a rate of engineering effort much lower than what is really needed. This leads to a considerable stretch-out of the project, with attendant fluctuations in the size of the engineering effort during the project. The project is finally completed at month 145, about two years

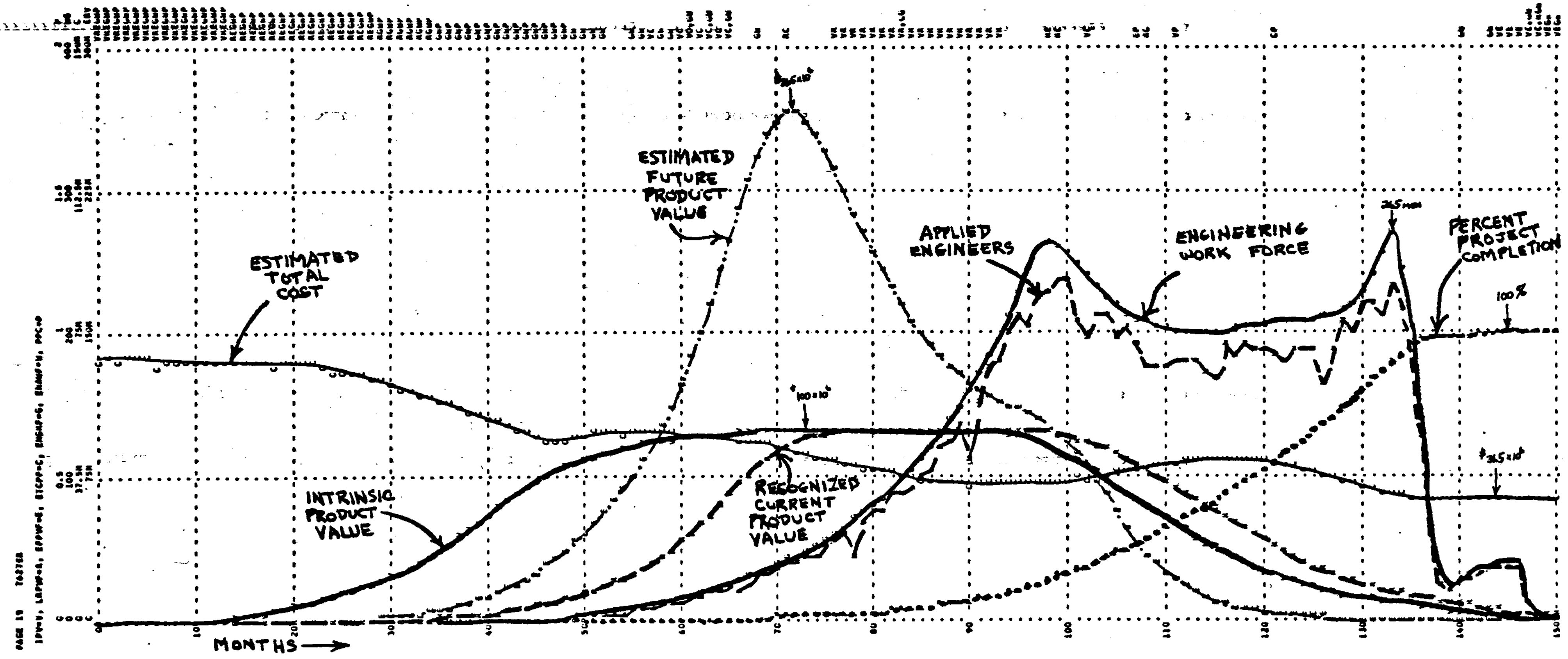

Figure 7 Effects of Low Bidding Practices

after the completion date of the original simulated project. Though less money is spent by the customer in this project (the slower growth is more efficient and the engineers also take advantage of some later developments in the state of the art), the customer is still far less satisfied than in the original project due to the much delayed project completion. In addition, the customer is upset by the almost 100 percent growth in project costs from the firm's initial bid to final completion. The firm suffers too as a result of its own policy; not only do its reputation and relationships with the customer worsen, but also the firm's profits are 5 percent lower than in the original project studied. In many projects, however, the company with low bidding integrity does increase its profits by following this policy. Again, these results highlight the need for further simulation studies of R and D policies in different company-customer-product situations.

The Self-Defeating Nature of Government Policies

The two case examples cited in Figures 6 and 7, when supported by other more thorough simulation studies, highlight some interesting conflicts within government R and D procurement policies. The computer results convincingly demonstrate that high risk-taking propensity as well as a high degree of integrity by the firm very favorably affect the outcomes of research and development projects, i.e., from the customer's point of view. Greater company willingness to assume risk and invest in potential projects, for example, gets jobs finished sooner for those which do reach completion, and pushes progress to a further point even for projects which are eventually cancelled. However, under existing government contracting practices, neither high risk-taking nor high integrity are profitable to the firm. The company assuming greater risks almost always suffers, at least in the short run; the company exercising greater honesty in bidding reduces its individual project profits as often as it gains. Thus the policies followed by the government seem to influence companies to adopt practices which are counter to the government's best interests. The responsibility for the resulting poor performance of R and D contracts can, to this extent, be laid in the government's own lap. A changed philosophy, matched by revised procurement policies, can thus benefit both the R and D companies as well as the effectiveness of the nation's research and development program. In this area a management systems laboratory offers great potential as a means of studying the design of improved policies. Even a small gain in effectiveness so achieved would mean annual cost savings or performance improvements in the order of hundreds of millions of dollars.

Appendix: Mathematical Model of Engineering Productivity

As an illustration of the equation-writing techniques, we describe here the equations for the engineering productivity sector of the R and D model.[14] For ease of identification these equations use variable names corresponding closely to the usual English description. The time notation for the equations, pictured in Figure 8 below, is similar to the traditional difference equation subscript notation, but is written in a manner immediately admissable as input to a digital computer.

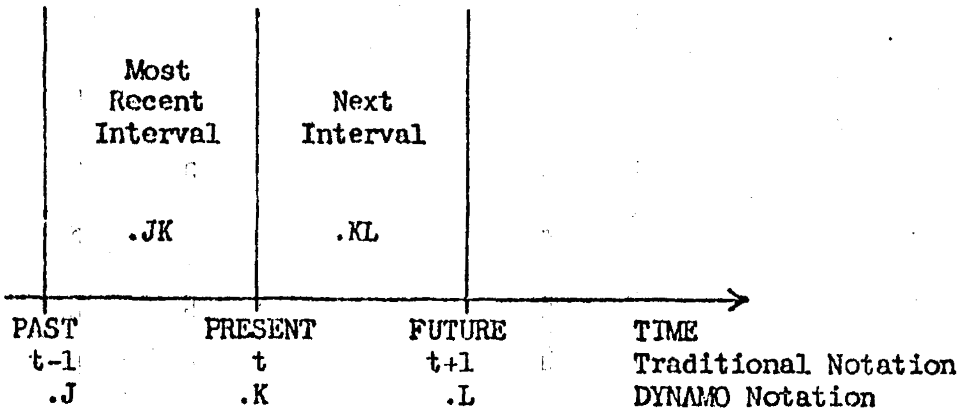

Figure 8. Time Notation

Let us start the model description with an equation which indicates the level of existing project know-how as the accumulation of all previous engineering productivity on the project. The equation below states that the total effective effort put into the job up to the present time, .K, equals the total effort at the previous time, .J, plus the change in total effective effort that has taken place between time J and time K.

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[14]This sector is more fully developed in the author's dissertation, pp. 266-273.

KLEVF.K=KLEVF.J+(DT)(ENPRF.JK) Eq. 1

KLEVF--Know-how LEVel of the Firm (effective man-months of effort)
DT --Delta Time, the time interval between solutions of the equations (months)
ENPRF--ENgineering Productivity Rate at the Firm (effective man-months of effort /month)

ENPRF.JK indicates the monthly rate of effective engineering effort which occurred during the time interval from J to K. DT is a constant which the model user supplies to DYNAMO to specify the length of the time interval between calculations of the values of all the model equations.

The second equation which we shall write describes the engineering productivity rate, determined at the present time, .K, and persisting

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ENPRF.KL=(RPEWF.K)(TEEF.K) Eq. 2

ENPRF--ENgineering Productivity Rate at the firm (effective man-months of effort/month)
RPEWF--Relative Productivity of Engineers actually Working at the Firm (effective man-months of effort/month
TEEF --Technical Effectiveness of Engineers at the Firm (percent effectiveness)

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until redetermined at the next point in time, .L. The equation shows engineering productivity as the product of the relative engineering effort being applied and the average technical effectiveness of that effort.

Equation 3 represents the average technical effectiveness of the applied engineering effort as the product of three terms: (1) the basic level of effectiveness which derives from the available state-of-the-art; (2) the additional benefits to productivity resulting from project experience; and (3) the modifying influence that stems from the over-all level of quality of the firm's management and engineers. The use of this auxiliary (helper) equation simplifies the earlier equation for ENPRF, and

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TEEF.K=(ATEF.K)(BEPIK.K)(QF) Eq. 3

TEEF --Technical Effectiveness of Engineers at the Firm (percent effectiveness)
ATEF --Available Technological Effectiveness at the Firm (percent effectiveness)
BEPIK--Beneficial Effect on Productivity due to Increased Know-how (percent)
QF --Quality of the Firm (percent)

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separately labels a concept of significance in the system, here the technical effectiveness of the firm's engineers. Had we wished to make Equation 2 slightly more complex, the auxiliary equation 3 could have been eliminated by directly substituting into ENPRF.

In the research and development model, both ATEF and QF are defined in sectors other than engineering productivity. We shall similarly omit their inclusion here. The effect of project experience, however, will be indicated next. Figure 9 depicts the relationship which we believe represents the benefits to project productivity which result from earlier project progress. The curve indicates the belief that the new specific knowledge developed in solving the R and D project problems can supplement the general skills and understandings of the engineers. Increments to engineering effectiveness are shown as being larger initially than later, since the number of engineering problems yet unsolved on the project decreases as the project progresses. This lessens the likelihood that new

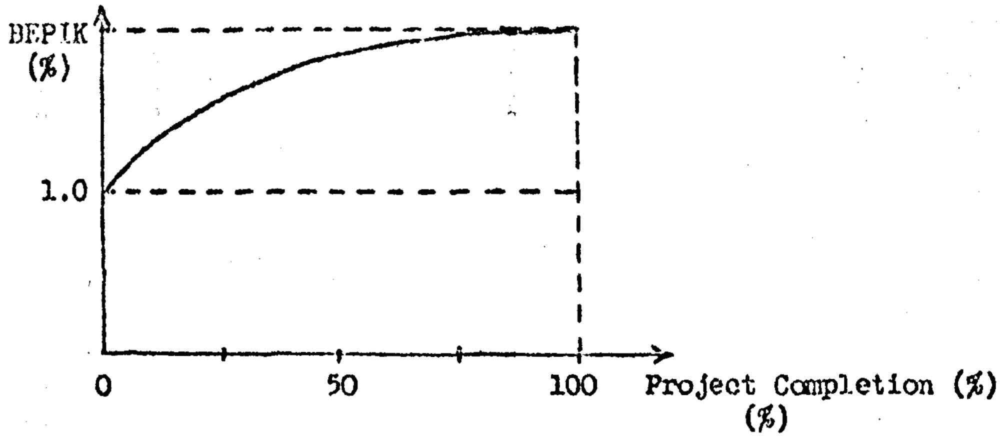

Figure 9. Effect of Project Achievements on Productivity

project accomplishments made late in the life cycle will find still further use on this project. Thus the curve of Figure 9 continuously increases, but at a decreasing rate as the project achievements cumulate.

This effect may be modeled in the DYNAMO system by the following equation:

BEPIK.K=TABLE(TBPIK,PPC.K) Eq. 4

BEPIK--Beneficial Effect on Productivity due to Increased Know-how (percent)
TABLE--a DYNAMO notation which indicates that a TABLE of constants will be provided for determining the value of BEPIK as a function of PPC
TBPIK--Table of constants, for Benefits to Productivity due to Increased Know-how (constants have dimension of percent)
PPC --Percent of Project Completed (percent)

The final equation to be specified is the representation of RPEWF, used in Equation 2, the Relative Productivity of Engineers actually Working at the Firm. This concept attempts to take consideration of the fact that the engineer's direct project productivity will be affected by his training, other company activities, and percent of time on the job. Equation 5 thus distinguishes among the engineers who are fully experienced, those in training, those doing the training and supervision, and those being transferred from the job, and recognizes a different average productivity for each type of situation.

$$\text{RPEWF.K}=(\text{PWAW})\Big[(\text{ENITF.K})(\text{PRIT})+(\text{ENATF.K})(\text{PRAT})+(\text{ENBTF.K})(\text{PREBT})+(\text{ENFEF.K})(\text{NPREF})\Big] \qquad \text{Eq. 5}$$

RPEWF--Relative Productivity of Engineers actually Working at the Firm (effective man-months of effort/month)
PWAW --Percent of Workers Actually at Work (percent)
ENITF--ENgineers In Training at the Firm (men)
PRIT --PRoductivity of engineers In Training (months of effective effort/months of work)
ENAFT--ENgineers Assigned as Trainers and supervisors at the Firm (men)
PRAT --PRoductivity of engineers Assigned as Trainers (months of effective effort/month of work)
ENBTF--ENgineers Being Transferred by the Firm (men)
PREBT--PRoductivity of Engineers Being Transferred (months of effective effort/month of work)
ENFEF--ENgineers Fully Experienced at the Firm (men)
NPREF--Normal PRoductivity of Engineers at the Firm (months of effective effort/month of work)

All the constants indicated in the equation (PWAW, PRIT, PRAT, PREBT, and NPREF) are defined by a set of values prior to each model simulation.

Changing the constant values in different runs permits simulation testing of the relative sensitivity of project results to such productivity factors.

Any other aspect of the research and development model can be specified by a similar set of equations, plus the necessary constants. Motivational factors, size of group effects, or other believed influences upon engineering productivity could similarly be added to the simple productivity model defined above.