

THE DYNAMICS OF RESEARCH AND DEVELOPMENT

by

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Mr. Edward B. Roberts  
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On behalf of the department, I am happy to give you permission to have your thesis printed instead of typewritten, in accordance with the Institute regulation on page 44 of the Graduate Student Manual (September 1959).

Sincerely yours,

Ralph E. Freeman  
Chairman, Department of  
Economics and Social Science

REF:af

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Professor Philip Franklin  
Secretary of the Faculty  
Massachusetts Institute of Technology

Dear Professor Franklin:

In partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Economics and Social Science, I herewith submit a dissertation entitled, "The Dynamics of Research and Development".

Very truly yours,

Edward B. Roberts

## ABSTRACT

## THE DYNAMICS OF RESEARCH AND DEVELOPMENT

by

EDWARD BAER ROBERTS

Submitted to the Department of Economics on May 11, 1962, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

A general theory of research and development is formulated, which theory encompasses the system of interactions between the manifested characteristics of the R and D product, the firm, the customer, and the organizational processes required by the nature of the work. These interactions take place continuously during project life cycles, which cycles involve a set of ongoing activities: perception of the need for a new product; estimation of effort requirements; cost estimation; company requests for financial support, and customer evaluation followed by funding response to these requests; or, company investment in its own project ideas; application of engineering effort and the accomplishment of job progress; evaluation of the progress; and reformulation of new product value and effort estimates, with continuation of the activity life cycle.

An Industrial Dynamics model of this process is developed, and extensive computer simulation experiments on the model elements are reported and analyzed. Three basic product-related factors are found to be important influences on the outcomes of research and development projects: (1) the intrinsic job size; (2) the intrinsic product value; and (3) the state of the product technology. Five characteristics of the firm are examined and three are determined as significant in their project effects: (1) the overall quality of the firm; (2) the firm's willingness to undertake risk; and (3) the integrity of the firm. The financial resources and the previous job-size experience of the firm are found to have little effect except under extreme situations. The important customer aspects are discovered to be present in some manifestations of customer quality and risk-taking propensity. The requirement for rapid but effective organizational growth is seen to have major bearing on project results, while the inefficiencies due to organizational size contribute only a scaling effect to the research and development process.

Policies for treating many of these critical areas are suggested, emphasizing particularly the apparent conflicts between the objectives and the implementation of the existing government approach to research and development contracting.

The general applicability of the study is discussed and suggestions for further research undertakings are provided.

Thesis Supervisor: Franklin M. Fisher

Title: Associate Professor of Economics

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There are many others, however, whose contributions have been more explicit. From a time perspective, the first among these is Abraham Katz, who, in 1958, while a Sloan Fellow at the M.I.T. School of Industrial Management from the Radio Corporation of America, wrote a very insightful thesis entitled "An Organizational Analysis of an Electronic Systems Firm". In this thesis Mr. Katz recognized the possibility of developing a model of a research and development operation, and identified characteristics of the customer, firm, and product, most of which have been adopted in the present work.

Second in time, and throughout a lengthy duration, came the assistance and guidance of my doctoral dissertation committee. Professor Franklin M. Fisher contributed in two very significant ways: (1) he was willing to accept and in fact encouraged the pursuit of this research study, which in content, orientation, and methodology is so different from the practices apparently accepted as traditional-and-good for the usual Ph.D. dissertation in economics; (2) his quick and thorough grasp of the subject matter enabled him to make valuable suggestions for the organization and presentation of the material, which suggestions lend much to whatever clarity has been achieved in this work.

I greatly appreciate the help provided by Professor Donald G. Marquis, who has given most generously of his time and of his extensive knowledge of human and group behavior. I have personally enjoyed and benefited from the many lengthy discussions we have shared about the substance of my undertaking and its broader implications for organizational research and understandings. His enthusiasm for the study and warm interest in even the initial tentative results did much to stimulate my own attitudes and effort. Finally, the finished version of this dissertation reflects much attention by Professor Marquis to the written presentation of the findings.

To Professor Jay W. Forrester my debt of gratitude goes far beyond an appreciation for assistance on this dissertation. Under his active support, strong guidance, and personal example I have for four and one-half years learned and helped develop the philosophy and methodology of the Industrial Dynamics approach to socio-economic systems. Professor Forrester's brilliance has nurtured, enriched, and developed my own mind and ideas with continuing energizing transfusions to the point that not just my substantive knowledge but, more importantly, my personal goals and objectives and even my ethical code reflect his teachings.

The other person who has directly contributed to this effort during the past several years has been my wife Nancy. She has been patient, enduring, and encouraging throughout the very time-consuming and often tiring process of investigation and writing of this dissertation. But, moreover, she has helped enhance the understandability of this work by continuously trying, though not always succeeding, to

get me to transform my often cumbersome writing style into something more easily readable. Finally, Nancy has made obvious and substantial tangible contributions to the preparation of the final copy of this work by drawing most of the system flow diagrams for the Appendices of Chapters 2 through 6, and by compiling the extensive Bibliography of this volume.

Three other groups complete the list of those whose aid on this work has been particularly noteworthy. First is the Ford Foundation, whose far-seeing grant for fundamental development of Industrial Dynamics has financially supported my research efforts since 1958. Second is the M.I.T. - I.B.M. Computation Center, which has produced all of the computer studies undertaken for this dissertation. Mr. Michael Solomita, of the Computations Center, has been especially helpful during the occasional moments of panic and deserves this individual note of appreciation.

Finally, the secretaries who toiled for months on the original drafts, revised copies, and final version of this volume have earned any laudits they desire. The original and revised text was typed by Miss Marie Lincoln, Mrs. Faith Richards, and Miss Jean Van Derlip. The final work has been done in part by Mrs. Richards and Miss Van Derlip, but the major effort has been faithfully and tirelessly performed by Mrs. Pattie Gregg. Her steadfast maintenance of the work during the final month of the term enabled this dissertation to reach completion before June.

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OMISSIONS

PAGE	LINE	INSERT
88	Footnote 8	William I. Thomas, "Control and Attention", in <u>Sociological Theory</u> , edited by Edgar F. Borgatta and Henry J. Meyer (New York: Alfred A. Knopf, 1956), pp. 441-442.
99	Line 9	(page 88)
99	Footnote 16	Vol. 6, No. 1....p. 29.
103	Footnote 17	p. 237.
103	Footnote 18	p. 57.
104	Footnote 20	<u>1958</u> (.....1961), pp. 32-35.
108	Footnote 24	pp. 359-360.
164	Footnote 13	Simon Marcson, <u>The Scientist in American Industry</u> (Princeton, New Jersey: Industrial Relations Section, Princeton University, 1960), pp. 112-113.
166	Footnote 16	...". <u>U.S. Air Force Project Rand Research Memorandum</u> , P-1288 (April 28, 1958), p. 7.

## INTRODUCTION

### THE NEED FOR RESEARCH ON RESEARCH AND DEVELOPMENT

#### The Problems of Research and Development

The importance of research and development to our national economy and to international security is universally acknowledged. However, its importance itself does not constitute sufficient reason for an extensive research study. There must be some demanding need for an investigation--a need which should manifest itself in vital problems plaguing the research and development industry and urgently requiring solutions. Such problems are apparent in the major difficulties experienced by firms doing research and development work aimed at new products, in the serious failures or flaws uncovered in our military research and development efforts (e.g., recently the Sputnik-Vanguard and Cosmonaut-Astronaut races), and in general in the over-all confusion and lack of understanding of the process of research and development management.

Looking first at industry,

although a definitive study on project failure rates has yet to be done, all available evidence points to a heavy mortality in research projects. For example, the average experience of 20 companies in the chemical industry shows that only one successful product results from every eight projects that go into research. Similar situations seem to be present in all industry.... Survey results covering more than 100 major companies show the median failure rate to be about 67%. (Failure here is defined as projects instituted and designed for market appearance that never reach the market place.<sup>1</sup>

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

An even more pessimistic view is put forth by the marketing manager of one large company's research division. He says, "Out of 500 bright ideas usually only one proves practical enough to reach the market as a finished product. Then, only one or two products in 10 are good enough to last more than two years in the market."<sup>2</sup>

In addition to the problems relating to this high failure rate of product research and development efforts, industrial managers find themselves faced with an extremely long lead-time before the initial research attempts can begin to pay off.

In the age of technological advance, a product (or service) can be created, can mature, and have its day in the economic sun, then can perish through obsolescence and competition. And while accelerating technology is tending to make the sales life of a product or service shorter, the complexity of this same technology is tending to make the research/development, or gestation, period longer---often up to 5 or 10 years in the case of advanced electronic, chemical, or pharmaceutical products.<sup>3</sup>

This long lead-time, creating a need for intelligent decision-making a decade prior to market release of a new product, is likely to be one of the factors producing the high product development failure rate mentioned above. In any event, the problems facing corporate management which must operate in this kind of environment seem obviously significant.

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<sup>2</sup>Louis R. Larsen, "New Product Development--Basis for Growth", Industrial Science and Engineering, Vol. 5, No. 6, (November 1958), p. 36.

<sup>3</sup>William J. Platt, "Pre-Testing Company Planning", Stanford Research Institute Third Annual Industrial Economics Conference, January 1958.

The second general problem area relating to research and development arises with respect to the military or quasi-military (i.e., A.E.C. or N.A.S.A.) requirements for research and development outputs. One aspect of the problem was very succinctly stated by Lt. General Arthur G. Trudeau, while he was serving as Chief of Research and Development of the U. S. Army. "The current lead-time", said General Trudeau, "from conception of a new weapon until its delivery is 7 to 8 years here in the United States. Russia does a comparable job in 5 years."<sup>4</sup> This comparatively longer lead-time is but one manifestation of the problems encountered in the management of military research and development.

Another sign of underlying difficulties is the fact that so many of our military developments seem obsolete, out-of-date, and devoid of purpose even before they leave the test site. In only a half-facetious vein one writer has "explained" this situation by the "Principle of Dynamic Obsolescence.....first formulated a number of years ago in approximately these terms. 'If we make a new system big enough and complicated enough, it will be obsolete before we can get it finished.'<sup>5</sup>

The author goes on to cite the cost implications of this problem, maintaining that

the costs associated with dynamic obsolescence in military work are becoming all too familiar. When we are in competition with an alert and inventive enemy, and forced to maintain an instant capability,

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<sup>4</sup>Electronic Industries, Vol. 19, No. 11 (November 1960), p. 4.

<sup>5</sup>Dr. Richard C. Raymond, "Avoiding Obsolescence in System Planning" (General Electric Technical Military Planning Operation, May 1959), p. 1.

we cannot afford to be caught with less than the highest performance weapon system which we can deploy. If we find that the life of a system is drastically foreshortened either through a change in technology or in operational requirements or through late deployment,....the cost per hour of operation of the system can become prohibitive.<sup>6</sup>

This obsolescence factor thus lessens the effectiveness of a relatively fixed national defense budget, or increases the costs without similarly improving the effectiveness, and thereby indicates a trouble spot in our research and development picture.

Thusfar we have pointed out some obvious major problems in both the areas of industrial new product development and military research and development. These factors would seem to demand thorough direct investigation if, indeed, these were the problems, instead of merely the outgrowth of other, more fundamental, needs. There seems to be good reason to believe that underlying all those apparent griefs is a not-so-apparent, but far more important, general lack of understanding of the entire process of managing research and development undertakings. One indication of this lack of know-how about research and development is the great effort put into debating and defining the meaning of the terms. This shows up in the variance in dollar measures of our nation's research and development inputs. The budgetary statistics on research and development are so poorly defined that "it can be said on the basis of published reports...that expenditures for military research and development in fiscal year 1959 are estimated at 2.2 billion dollars, or 2.4 billion dollars, or 3.3 billion dollars, or, if you like, as

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<sup>6</sup> Ibid., p. 2

much as 6.2 billion dollars."<sup>7</sup> This absence of reliable statistical data is perhaps sad commentary on whether or not those few people who talk about our "national research and development program" even know which program they are discussing.

But far more important than the inaccurate gross figures on the nation's research and development inputs is the major lack which exists in our understanding of what is the research and development process itself. Our newspapers abound with examples of the mystics of research and development: cancellation of a multi-billion dollar atomic plane project; Congressional demands for more emphasis on men-in-space programs: an announcement to stockholders of the forthcoming release of two-minute color photography; new heights reached by the stock price of a "glamour" research and development-based company, currently selling at eighty times earnings. Many of the phrases linked with research and development---stretchout, speedup, astrophysics, geophysics, computation, automation, bomber gap, missile gap---have become almost household words, yet fundamental understanding of what lies behind these words is almost nonexistent, even among our so-called experts. Why are so many of our weapon systems obsoleted so soon? What distinguishes the company whose market fortunes grow apparently unbounded on the basis of product innovations from one which bankrupts itself on ill-conceived and/or ill-conducted research ventures? What are the facts of research

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<sup>7</sup>National Science Foundation, "Methodological Aspects of Statistics on Research and Development Costs and Manpower" (Washington: United States Government Printing Office, 1959), p. 7.

and development life which cause the vast proportion of new product efforts to be scrapped before they even reach the testing grounds of the market-place? These questions carry far more than the fifteen billion dollar price tag that marks our current annual expenditures for research and development. For with their answers goes not only the key to our country's economic growth and military security, but also the cornerstone to fathoming much of the innovative world in which we live.

#### Sources of Misunderstanding of Research and Development

Since the main body of this work will argue that research and development is most effectively viewed from a systems perspective, it is worthwhile here to examine the sources of misunderstanding of research and development that arise from the usual non-system approach. Seven general factors are identified below, to which list no doubt others could be added.

1. The typical multi-department involvement of research and development highlights for each department its "special problems" while it obscures the key process common to all aspects of the involvement. Personnel sees the "special problems" of recruiting, training, evaluating, and retaining engineering and scientific manpower. Finance encounters the "special problems" of government contracting, research and development progress measurement, and project funds control. Manufacturing suffers from the "special problems" of the many change orders usually accompanying a new research and development output's entry into production, or from the exacting demands placed upon the manufacturing department's shops. Marketing views its "special problems" as relating to the relatively few sources of contracts, the need for



major technical-financial job proposals in areas of high uncertainty, or the too-often boom or bust nature of market participation. All of these "special problems" prevent or at least discourage managers from asking "What business are we in?", etc.

2. The large amount of random-like behavior masks the fundamental character of research and development activities. In any situation involving human actions and decisions at least some of the behavior is caused by random factors which introduce what engineers call "noise" into the observed system character. The process of invention seems intrinsically linked with creativity or genius or luck and is most often cited as causing the necessary uncertainty of research and development work. Yet, the invention process appears to be a good example of the case in which basic influences on behavior have much noise (or uncertainty) superimposed over the base. At least we act as if we believe such a statement, even if we do not in fact say such things. The very existence of organized research programs consuming fantastic expenditures of company and government funds shows the fundamental confidence of these groups in the inherent predictability of at least the pattern of results expected from these research and development efforts. Efforts seeking managerial understanding need to be directed toward such underlying patterns, rather than focused on the superficial random day-by-day events.

3. The intangible nature of many basic phenomena of research and development is a principal reason for lack of their explicit recognition. How, for example, does one measure engineering effectiveness, or

experience, or real accomplishment? One writer suggested that in general,

the variables that turn out to be of critical importance in mathematical models and the simulation of complex operations rarely have been recorded explicitly in practice. This appears to be particularly true in engineering and research work. In this area, we are concerned with the manner in which a research and development project transforms technical effort of scientists, engineers, and support personnel into increments of technological advance.<sup>8</sup>

Since neither the inputs nor the outputs seem readily measurable, perhaps it is not surprising that the transfer process between input and output is over-simply perceived.

4. The nonlinear aspects of research and development make still more confusion in the manager's mind. One clearly nonlinear part of the research and development process is the effectiveness of the engineering work force as a function of its size. Certainly no reader would be so naive as to claim that the hundred-man organization is ten times more effective than the ten-man core group which initiated the project. Yet, this kind of linear extrapolation of a basically nonlinear phenomenon is behind much of the chaos in project-estimating procedures. Another example in the same general area is the changed effectiveness of an engineering team as it becomes more familiar and experienced with its task. This "learning process" in engineering is most likely not a linear function either of time or of work output, but which research and development manager even attempts to take this nonlinearity into his thinking?

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<sup>8</sup>Peter V. Norden, "On the Anatomy of Development Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 34.

5. Many secondary problems in research and development often get an undeserved amount of public attention, removing the focus of management researchers from critical areas. With respect to one such attention-getter, the so-called engineer shortage, a Booz, Allen, and Hamilton survey reached this conclusion: "While it is true that many laboratories can use additional talent, especially of top-flight caliber, and that certain sections of the country have experienced a tightening in the supply of scientists and engineers, none of the [more than 100] companies in the survey considered the shortage of technical personnel a critical problem."<sup>9</sup> The shortage more likely exists in the number of properly utilized engineers and scientists and in the number of engineering managers who understand and can cope with this difficulty. And yet the public and professional press, university research studies, and government and trade association panels spent much time and effort on the nonexistent "quantity" problem, with almost no intensity of work devoted to the more vital phases of the manpower problem. Another secondary problem which for a time drew the major attention of research and development-oriented thinking is the surge in engineering salaries which began a few years ago. Eventually, usually after much turmoil, the wage increase which began in the college recruitment race was extended throughout the engineering organization, resulting in somewhat higher project costs. But effects of this nature are probably both insignificant and inevitable, and the manager's view of the basic research and development activity flows should not be obscured by the existence of such transients

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<sup>9</sup>Randle, op. cit., p. 130.

in flows.

6. The organization of research and development itself--the functional compartmentalization which exists---restricts the manager from recognizing any systematic character of research and development. This compartmentalization takes place in three ways. First, the research laboratory is generally separated, often even geographically, from the other company functions of marketing, manufacturing, etc. Secondly, within the research organization itself, one usually encounters the functional separation of engineering from marketing or from personnel, for example, or the project-phase separation of the proposal-preparation group from the advanced developers from the product design team from the production engineers. Finally, within the major engineering group are found samples of organization by discipline (such as physics or chemistry or mathematical analysis), or by product subsystems, (e.g. combustors or compressors, and memory devices or control systems), or by state-of-the-art (for example, a group labeled "Vacuum Tubes" with another called "Solid-State Components"). This fine breakdown of operations, though perhaps justifiable to those who worry about the economies to be derived from specialization, division of labor, or from still further decentralization, nevertheless does erect solid walls in the paths of managerial vision of the organization as a whole. Each research and development manager is thus given a very special pair of sunglasses for use in viewing the research and development process. Not only does each manager see whatever he observes with a special and individually-selected color, but also he has blinders placed on both sides to narrow the breadth of his possible perception. It is this mode of organizing

R and D (and, in fact, of organizing most large corporate activities) which has been one of the foremost restraints on management's efforts at understanding research and development.

7. Finally, the underlying belief by most people that the elements of research and development cannot be related by means of some basic framework has discouraged search in this direction. The apparent presumption that there is no orderliness to R and D keeps people from looking for it. If government and industry could be convinced that a framework basic to the research and development process does in fact exist, several alternatives would soon be discovered.

#### An Approach to Understanding Research and Development

The primary need in the research and development area thus seems to be a demand for a set of concepts that will enable research and development managers in both government and industry to:

1. place into perspective their current R and D headaches;
2. seek the underlying causal factors beneath the superficial layer of everyday events;
3. recognize the importance of at least considering some of the intangible or difficult-to-measure variables of the research and development process;
4. focus management attention on the permanent internal forces creating R and D success or failure rather than on such temporary external "crises" as manpower shortages and salary races;
5. uncover a unifying structure that ties together the dissected organizations of people contributing to a single research and development

effort; and thereby

6. provide for themselves a thought-and-action framework which they can effectively utilize in the management of R and D.

The following chapters constitute an approach to gaining the understanding of research and development which need has been outlined above. It proceeds on the theory that the heart of research and development activities is the research and development project. Whether formally recognized or not, every new product, process, or technique (consumer, industrial, or military) comes into existence by means of a project-type endeavor. The crux of understanding the research and development process then must lie in those factors which influence the life cycle of R and D projects, from the birth of the project activity through to the emergence of the final product form or to the earlier halting of this research-development process.

The most obvious projects which come to mind are those aimed at developing military or quasi-military products. These constitute the largest single area of research and development activity (over eight billion dollars in 1961 according to the figures cited previously), are most immediately important to our nation's well-being, and include the most easily identifiable and best publicized project entities. Moreover, the military research and development process is in some regards more simplified than other R and D forms, since any given project encompasses for all intents and purposes but a single customer, a very specific end product (at least after the early stages of research have been completed), and often but a single firm engaged in the development of that

product. For these reasons the emphasis will be placed primarily on research and development for military purposes, although the method of approach, the theory, and the conclusions are no doubt generally applicable to all research and development, including that directed at the industrial or consumer markets.

The general procedure that is used here is that developed in a new approach to the study of socio-economic systems called Industrial Dynamics. Industrial Dynamics

treats the time-varying (dynamic) behavior of industrial organizations....Industrial Dynamics is the study of the information-feedback characteristics of industrial activity to show how organization structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of an enterprise. It treats the interactions between the flows of information, money, orders, materials, personnel, and capital equipment in a company, an industry, or a national economy....It is a quantitative and experimental approach for relating organizational structure and corporate policy to industrial growth and stability.<sup>10</sup>

The several stages through which an Industrial Dynamics approach progresses form in effect the outline of this volume. The first phase is the identification of a key industrial or economic problem which appears to merit dynamic system-oriented investigation. The earlier part of this chapter showed the significance of the problems arising out of the lack of understanding of the research and development process. Furthermore, the heart of this process was identified as the research and development project, whose life cycle embodies the time-varying

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<sup>10</sup>Jay W. Forrester, Industrial Dynamics (Cambridge: The M.I.T. Press, and New York: John Wiley and Sons, Inc., 1961), p. 13.

interacting forces which can be treated by the Industrial Dynamics approach.

The second stage of an Industrial Dynamics study consists of the development of a verbal theory of cause-and effect interaction, an isolation of the "information-feedback loops that link decisions to action to resulting information changes and to new decisions,"<sup>11</sup> and a verbal description of the decision policies in effect in the system being studied. The chapters of Part I of this work will develop such a verbal synthesis of research and development, utilizing empirical findings, the descriptive literature, and personal experience and hypothesis where suitable or necessary to accomplish the integration.

The next phase of Industrial Dynamics study requires the construction of a mathematical model of the research and development system, the information generated about the state of these activities, and the use of such information in the decision policies of research and development managers.

This phase will be treated in the appendices to the chapters of Part I. Each appendix will develop in flow diagram form a visual treatment of the verbal material of the preceding chapter. The diagrams are intended both as an aid to understanding the model that follows, and as a take-off point for researchers desiring to utilize techniques other than the model-building methods adopted in this work. Following the diagrams will be the development of the mathematical model which is intended to add much precision, and hence enhanced understanding, to the descriptive and theoretical portions of this volume. This phase in itself is a major undertaking in both scope and content, being heavily

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<sup>11</sup>Ibid.



concerned with the intangible aspects of the real world, including problems relating to decision-making and human behavior. Although the model will be developed in a language and manner intended to be readily comprehensible to the intelligent layman, the reading of these appendices is not required for gaining most of the understanding of the remainder of the work.

The fourth phase of development of an Industrial Dynamics investigation is the generation over time of the behavior of the modeled system. Digital computer simulation techniques will be used for the study of the research and development model, results will be compared with available know-how about R and D projects, and the model will be revised until it seems acceptable for more intensive study of the actual system. The results of this initial exploration phase, as well as those of the more detailed simulation experimentation which constitutes stage five of a typical Industrial Dynamics study, will be described in Part II. The extensive studies will be aimed at determining which factors of the many included in the representation of the research and development process seem most important to the potential improvement of R and D behavior. The identification of such factors immediately contributes to the goal of increasing the basis for understanding research and development and provides clues to beneficial changes in organizational policies and structure of the actual R and D management system.

A sixth phase of research, also described in the chapters of Part II, involves incorporation into the model of redesigned system parameters or policies and experimentation with them to determine their effectiveness on altering the outcomes of research and development projects.

Finally, an Industrial Dynamics study of a real organization ought to attempt change of the real system in the improved manner indicated by the model experimentation. However, this study of research and development is of a general, rather than specific, nature and a different final phase of activity seems more appropriate. As a result of the extensive studies of project variables, the basis for general understanding of research and development will no doubt need redefining and restressing, and direction will have to be provided to the further research required before policy implementation can result. This summarization with suggestions for additional studies will be provided in the last chapter of this volume.

The Industrial Dynamics approach outlined above has been applied during the past five years to a wide variety of industrial and economic problems. In all these attempts success has been achieved at least with respect to the heightening of understanding of the managerial problem under investigation. While this study of research and development is by far the most complex Industrial Dynamics undertaking until now, treating as it must the elusive and intangible forces that bear so strongly on the R and D management process, there is good reason to believe that similar benefits to understanding can be achieved.

## PART I

## A GENERAL THEORY OF RESEARCH AND DEVELOPMENT

"Of all forms of mental activity, the most difficult to induce is the act of handling the same bundle of data as before, but placing them in a new system of relations with one another by giving them a different framework, all of which virtually means putting on a different kind of thinking-cap for the moment."

Herbert Butterfield  
The Origins of Modern Science

## PART I

Part I is divided into seven chapters. The first chapter presents a brief over-all description of the life cycle of research and development projects. The second through the sixth chapters discuss the various phases of activity of the R and D life cycle, describing in detail the factors that enter into the complete process of research and development management. The final chapter of Part I examines the detailed description to determine those factors which seem to critically influence the behavior that is produced by the R and D cycle. The flow diagrams and mathematical model equations which represent this verbal description are presented in the appendices of Chapters 1 through 7.

## CHAPTER I

### THE OVER-ALL DESCRIPTION OF A PROJECT LIFE CYCLE

Most attempts to discuss the process of research and development use a framework which hinders rather than aids understanding. The typical article breaks R and D activities into three or more phases of work, distinct in time and in character. One such approach designates the three phases as "preliminary", "design", and "hardware", and then breaks these down into twelve steps, going from "basic conceptualization and planning" to "system testing and debugging".<sup>1</sup> Another attempt conceives the phases of system design as falling into two categories, "pre-proposal" and "post-proposal", in turn subdividing these into: "1) initiation, 2) organization, 3) preliminary design, 4) principal design, 5) bread board, 6) prototype construction, 7) test, and 8) pre-production".<sup>2</sup> There is little question but that most R and D project life cycles can be viewed, at least after the fact, as having been composed of such segments. The question does exist, however, as to whether or not one has gained much from such an organizational frame of reference.

There are two primary faults to the type of approach toward describing or analyzing R and D that has been indicated above. The first is

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<sup>1</sup>Peter V. Norden, "Curve Fitting for a Model of Applied R and D Scheduling", IBM Journal of Research and Development, Vol. 2, No. 3 (July 1958), p. 234.

<sup>2</sup>Harry H. Goode, "Intracompany Systems Management", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 17.

that the dynamic essence of research and development is distorted. The emphasis is placed upon discrete sets of activities, separated in time, lacking any base of underlying common elements to bind them. The second fault is that the fundamental systems nature of R and D is ignored, with progress proceeding unidirectionally from preliminary to design to hardware and out, or from conceptualization through to preproduction, or what-have-you. The ever-present feedbacks that exist in all socio-economic systems are glossed over by such an approach, and writers convey their understandings through tentative definitions such as this: "A development project is a finite sequence of purposeful, temporally ordered activities, operating on a homogeneous set of problem elements, to meet a specified set of objectives representing an increment of technological advance."<sup>3</sup> This definition suffers from its overlooking of the significance of feedbacks between action, results, information, and new action, the very crux of change in R and D projects. It suffers also by laying emphasis on the finite set of activities rather than on the continuous ensemble of behavioral and decision-making characteristics which produce these activities.

The organizational approach to be taken in the following presentation is that the most effective way of studying any complex system, such as a research and development project, is to examine those underlying flows of activities which continuously interact to produce the economic behavior in the project. To be sure during the initial period of a

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<sup>3</sup>Peter V. Norden, "On the Anatomy of Development Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 41.

project life cycle some of these activities will appear in an ordered temporal sequence, e.g., the customer perceives the need for a product before he actually releases funds to the firm. But it will be the continuous changes over time of these underlying streams of activities which will establish the events within the life cycle. And perhaps most significant is the fact that these actions will continuously feed back upon the other decision areas of the project to induce still further changes.

The continuous activity phases that constitute a research and development project are described below, listed in the order in which they usually manifest themselves initially in a life cycle.

1. A project life cycle begins when the customer or the firm perceives the need for a new product. This perception of the need involves an estimate of what the product would be worth to the customer organization.

2. Once the need for a product has been recognized, the customer and/or the firm estimate the amount of effort that will be required to develop the product, attempting to take into account the manpower requirements and the associated materials, facilities, and equipment that will be needed to accomplish the end result.

3. Being cognizant of this effort estimate, the customer and/or the firm attempt to judge the total cost that will be required to develop the product.

4. The company now has two alternate and parallel paths available. In the first path the firm can prepare

and then submit to the customer organization a request for financial support.

5. The customer evaluates this request by comparing its estimate of the worth of the product to its estimate of the cost that will be necessary to complete the project. If the customer reacts favorably to the firm's request, after a long budgetary delay the customer will commit funds to the project.

6. The alternate path of action available to the firm is the decision to invest its own money in the project. This decision involves risk to the firm since it commits its own funds to the project before the customer has made such a commitment. These paths (4 and 6) are parallel in that both paths lead to the commitment of funds to the project. They are alternate in the sense that in any given project at any given time either one or both of the paths may be in active use.

7. As the firm obtains the funds from either internal or external sources the firm undertakes plans and actions which include the hiring of engineering personnel and their supporting elements.

8. The people who have been hired are employed on the job and accomplish some progress on the job.

9. Both the customer and the firm continuously attempt to assess the extent of the progress that has been made. They evaluate the state of completion of the job by comparing their



current interpretation of the results that have been accomplished with their current perception of the end results for the project that are desired.

10. This continuing progress evaluation creates a new estimate of work yet to be done on the project. The new estimate essentially reinitiates the closed-loop cycle that has been described above. That is, the firm and the customer both continue to estimate effort needed and cost required to complete the job. Similarly, the further accomplishment of progress on the job gives both the firm and the customer a better understanding of the project and allows them to make new better-informed estimates of the ultimate value of the project. On the basis of these newly obtained estimates of cost and value, new evaluations are made: 1) by the firm, as to whether continued investment in the project seems appropriate; and 2) by the customer, as to whether the continuance of the project itself is deserved.

11. This continuing cycle of activity leads to completion of the job when the desired results are achieved or to cancellation at some point prior to full completion of the project objectives.

This life cycle is diagrammatically represented in Figure 1-1, where one readily observes the closed-loop system character of research and development projects that was described above.

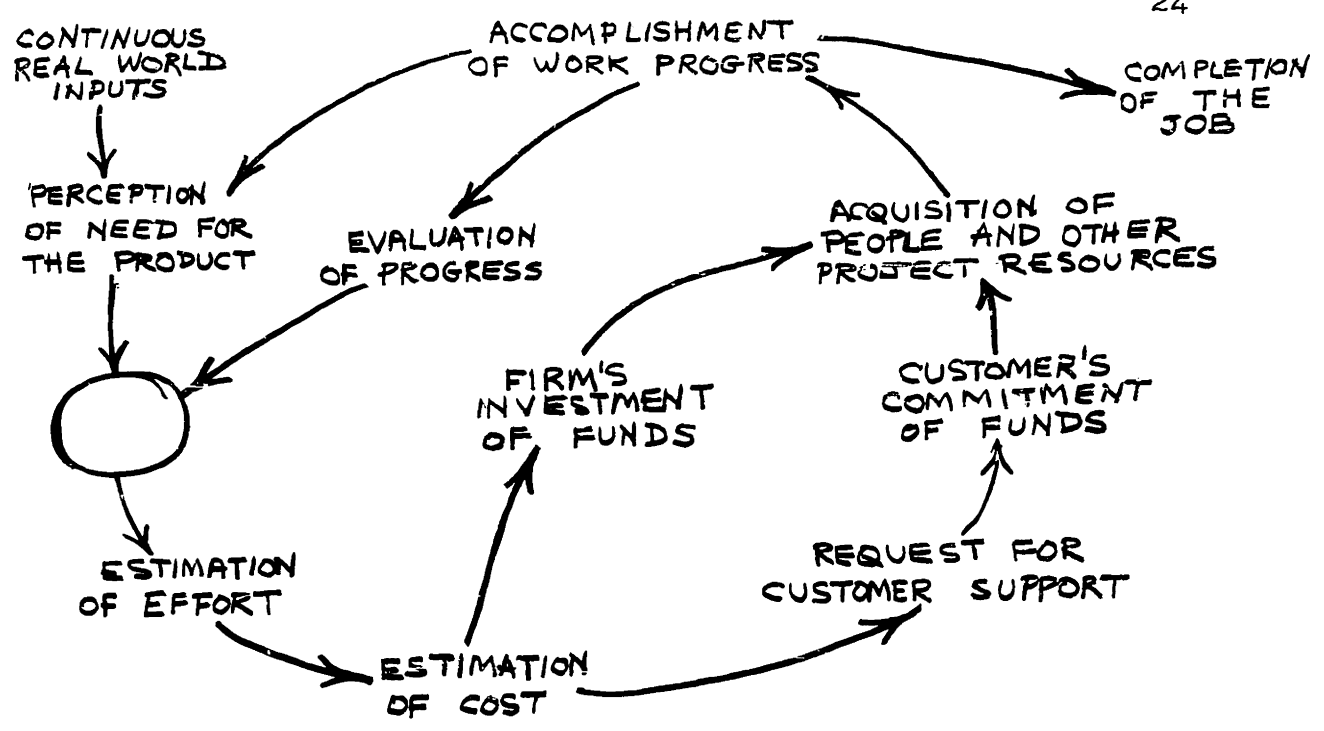


Figure 1-1 Dynamic System Underlying Project Life Cycles

These continuously occurring phases of research and development activities have within them the potential of producing all the facets of behavior that are commonly observed in research and development projects. This life cycle includes the possibility of successful completion of the job on schedule as well as the possibilities of late completion of the task, of stretch-out in the process of doing the job, of acceleration towards the completion of the task, and of failure to complete the end result itself. These various types of economic behavior can be observed not only in military research and development projects but in commercial new product development activities as well. R and D efforts encompass, at least on the over-all basis, the life cycle of activities that have been described above. Economic activities by R and D firms which exclude any phase included above will, upon close examination, be found to be part of some larger all-inclusive project entity.

## APPENDIX TO CHAPTER I

In the appendices to the next several chapters a mathematical model will be developed to correspond with the evolving general description of research and development project life cycles. The model will consist of a series of linear and nonlinear, algebraic and difference equations, corresponding in each appendix respectively to the phase of project activity discussed in the nonmathematical portion of the chapter preceding the appendix. The equations will be in a form required by the DYNAMO compiler and simulator program for the IBM 709 and 7090 computers.<sup>4</sup> The general format of these equations will be explained below. The model, when completed, is to be simulated on the digital computer by providing a set of necessary inputs and allowing the computer to calculate R and D project time histories, using the model equations for determining the desired calculations. "In general a model gives intuitive understanding of the object or system modeled. The mathematical model, therefore, serves the same function as the architect's model; it enables its user to grasp the important structure of a problem in a simple and efficient way."<sup>5</sup> This is our intended use of the research and development model.

The model equations will relate specifically to phenomena described in greater detail in the general chapter discussions. They will thus constitute a precise statement of aggregated relationships for typical

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<sup>4</sup>See DYNAMO User's Manual, The M.I.T. Press, 1961, by Alexander L. Pugh, III, for complete details, or Appendix A of Industrial Dynamics, by Jay W. Forrester for a general discussion.

<sup>5</sup>Albert H. Rubenstein and Chadwick J. Haberstroh, Some Theories of Organization (Homewood, Illinois: Richard D. Irwin, Inc., 1960), p. 10.

research and development projects. The equations will often be explicitly derivable from the flow diagrams which will also be used to represent the earlier verbal descriptions. Both the diagrams and the equations constitute at once a mode of abstraction and a mode of increased tangibility. To one extent they ignore details, qualifications, and conditions that will be present in the verbalization. This will be particularly true of the flow diagrams, in which often only the general relation between model variables is depicted. On the other hand, the diagrams and equations require a degree of specificity totally lacking in most word outlines. The diagrams visually present the set of variables considered significant, show the directions of causal relationships, often make clear overall interrelationships not otherwise readily determinable. The equations themselves are even more exact in their statements as to causal linkages, the forms of behavioral functions, and the values of system parameters. Many of these aspects are potentially testable, if only relevant data existed. But, in general, research that would produce sample data meaningful to this model is as yet nonexistent.

### Flow Diagrams

The type of flow diagramming which shall be used in these appendices is that developed by the Industrial Dynamics Research Group of the M.I.T. School of Industrial Management.<sup>6</sup> It is used to represent a set of relationships that can be conceived as falling into two categories-- levels and rates. The levels represent those aspects of the real world

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<sup>6</sup>See Chapter 8 of Forrester's Industrial Dynamics.

in which accumulations of resources exist--inventories of goods or ideas, balances of funds, pools of employees, accumulations of job progress. These will be represented in the flow diagrams by a simple block, labelled inside to indicate the contents of the level.

For example,

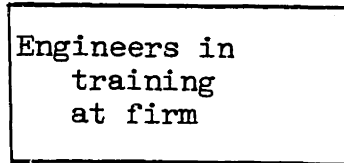


Figure 1-2 Level Symbol

The second category of variable type, the rate, includes all of the activities within the system--the flows of work effort and output, the streams of information, the actual payments for expenses incurred. Here one type of symbol is used to indicate the actual decision function which controls the rate, and a second set of symbols indicates the flows themselves.

Thus either

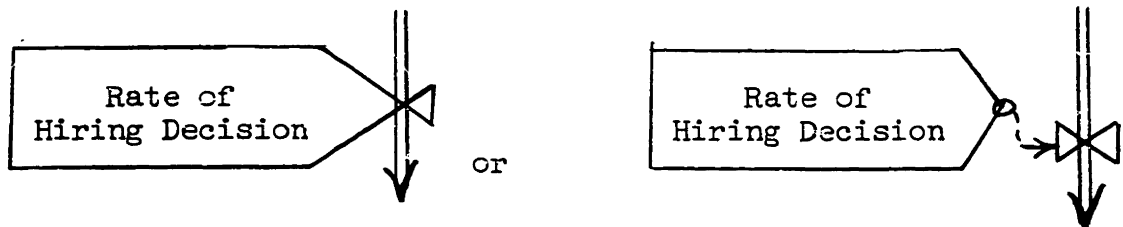
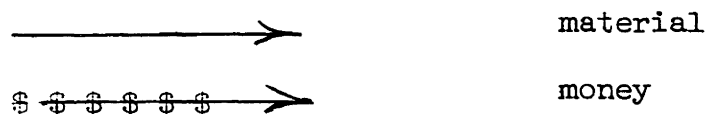


Figure 1-3 Rate or Decision Function Symbols

could be used to represent the decision as to the number of people to hire, whichever symbol fits more conveniently into the particular diagram. The actual flows resulting from such decisions are subdivided into six basic types and represented as follows.



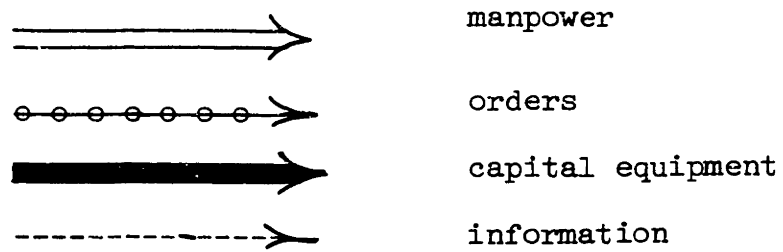


Figure 1-4 Flow Symbols

It is likely that not all of these flow symbols will be used in our R and D model diagrams.

Finally it will often be desirable for clarity and simplification that we break up a decision function into more elementary parts, called auxiliaries, and represented by a circle.



Figure 1-5 Auxiliary Symbol

The symbols shown thusfar might well be organized into a simple flow diagram, illustrating an engineering hiring sector.

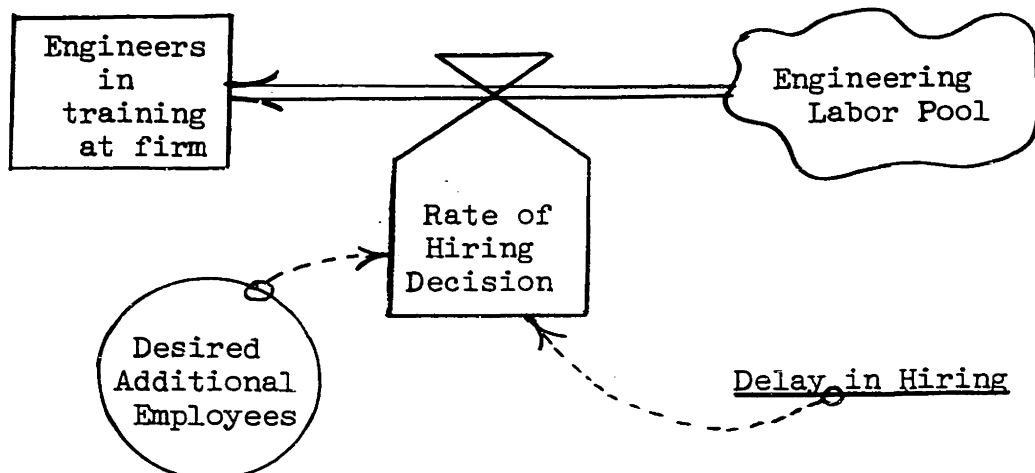



Figure 1-6 Simple Flow Diagram

The additional symbols used here are a cloud, , to indicate a source or sink for some flow, and a solid underlining of a parameter name, Delay in Hiring, to indicate a constant term.

### Equation Writing

The equations to be used in developing this model will use variable names corresponding as closely as possible to the described phenomena for the purpose of mnemonic significance. DYNAMO limits us to five letters or numeric characters in making these name designations. The time notation for the equations corresponds in a sense to the traditional difference equation subscript notation, but in a manner immediately admissible as input to a digital computer which has no facility for reading subscripts or superscripts. Let us illustrate the equation-writing techniques with an example of each basic equation type.

The equation below is a level equation written in the notation to be used in the model.

$$\text{ENITF.K} = \text{ENITF.J} + (\text{DT}) (\text{ENGHF.JK} - \text{ENLTF.JK}) \quad 1-1, L$$

ENITF--Engineers In Training at the Firm (men)

DT--Delta Time, the time interval between solutions  
of the equations (months)

ENGHF--Engineering Hiring rate at the Firm (men/month)

ENLTF--Engineers Leaving Training at the Firm (men/month)

The equation says that the number of engineers in training at the present time, .K, equals the number in training at the previous time, .J, plus the change in the number of engineers in training that has taken place between time J and time K. (The postscripts .K and .J correspond, respectively, to the subscripts t and t-1 in the traditional difference

equation notation.) ENGHF.JK indicates the monthly rate of engineering hiring which occurred during the time interval from J to K or .JK, and ENLTF.JK designates the monthly rate of engineering departures from training during the same period. DT is a constant supplied to the DYNAMO computer system to instruct it as to the time interval between calculations of the values of all the model equations. If DT = 1 month, the ENITF at the beginning of the current month, .K, equals ENITF at the outset of the previous month, .J, plus the net change caused by the difference between last month's rates of acquisitions and departures, ENGHF - ENLTF. However, DT may be selected as some value smaller than one month in order to insure numerical accuracy in the difference equations solutions, e.g., DT may equal 0.25 month, or about one week. In this case the equation will still be valid in the general form written above. For DT = 0.25 months, however, the computations will produce ENITF at the beginning of this quarter-month equals ENITF at the beginning of the previous quarter-month plus one-fourth the new monthly rate of change of ENITF. Finally, the designation 1-1, L at the extreme right of the equation shows that it is Chapter 1-Equation number 1, and that the equation is a level type (L).

We can check the dimensions of the terms in the above equation to provide a necessary but not sufficient condition for equation consistency.

$$\text{men} = \text{men} + (\text{months}) (\text{men/month} - \text{men/month})$$

$$\text{ENITF} = \text{ENITF} + (\text{DT}) (\text{ENGHF} - \text{ENLTF})$$

This reduces to the dimensional equality, men = men, to provide our initial check.

The second type of variable type, the rate equation, expresses the



rate of flow, determined at the present time, .K, which rate is to persist until redetermined at the next point in time, .L. Thus, rate equations compute values which are to exist during the interval .KL. Let us define the equation for the hiring rate to represent the fact that the firm hires a certain average fraction of the number of additional employees desired each month.

$$\text{ENGHF.KL} = \frac{\text{EADF.K}}{\text{DH}} \quad 1-2, R$$

ENGHF--ENGINEERING Hiring rate at Firm (men/month)

EADF--Engineers, Additional, Desired at Firm (men)

DH--Delay in Hiring (months)

During the next computation interval, the equation shows that the firm will hire at a rate equal to 1/DH times its present desires for additional workers. If the hiring rate were maintained at this value, DH months would be required to hire all the additional employees desired. The number at the extreme right of the equation, 1-2, R, shows that the equation is the second of Chapter 1 and is a rate equation (R).

Finally, let us specify an auxiliary equation to complete this set of sample equations. For this purpose assume that the number of additional desired at the firm is the gap between the total number of engineers needed and the actual number already available. Such an equation would then be:

$$\text{EADF.K} = \text{TEDF.K} - \text{ENGRF.K} \quad 1-3, A$$

EADF--Engineers, Additional, Desired at Firm (men)

TEDF--Total number of Engineers Desired at Firm (men)

ENGRF--ENGINEERs at the Firm (men)

The number indicates the above to be the third equation in Chapter 1,

and an auxiliary type (A). All auxiliary equations are used solely because of convenience or preference, not necessity. They can be substituted directly into the pertinent rate equations, omitting the need to define an auxiliary. For instance, the hiring rate equation could have been written as:

$$\text{ENGHF.KL} = \frac{\text{TEDF.K} - \text{ENGRF.K}}{\text{DH}}$$

The use of the auxiliary not only simplifies the initial rate equation but also usually separately labels a concept of significance, here the additional engineers desired. By using these auxiliaries with the previously illustrated level and rate equation types, we shall be able to define any phenomenon pertinent to our research and development system in simple equation form.

#### Computer Simulation

Once the basic model has been developed in the form just specified, it will be studied by digital computer simulation methods. Simulation has within the last few years begun to become a significant technique for use in studying economic problems at the levels of the firm, industry, and economy.<sup>7</sup> "Simulation is nothing more than the process of

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<sup>7</sup>The sources listed below contain discussions of the application of simulation techniques to a wide variety of industrial and economic problems: I. Adelman and F. Adelman, "The Dynamic Properties of the Klein-Goldberger Model", Econometrica, Vol. 27 (October 1959), pp. 596-625; Robert Dorfman, "Operations Research", The American Economic Review, Vol. L, No. 4 (September 1960), pp. 602-605; Jay W. Forrester, "Industrial Dynamics: A Major Breakthrough for Decision-Makers", Harvard Business Review, Vol. 36, No. 4 (July-August 1958), pp. 37-66; G. H. Orcutt et. al., "Simulation: A Symposium", The American Economic Review, Vol. L, No. 5 (December 1960), pp. 893-932; and Edward B. Roberts, "Simulation Techniques for Understanding Research and Development Management", IRE National Convention Record, 1959, part 10, pp. 38-43.

operating the model with selected inputs and recording the outputs. In a dynamic model the simulation proceeds sequentially...from one time period to the next for the duration of the computer run, with the inputs of one period carried over from the outputs of the previous period."<sup>8</sup> From such computer runs, graphs of project performance can be obtained quickly for many different assumed sets of underlying characteristics or decision-making policies. The effects of different factors can be separated. The dynamic behavior of the research and development system under changing conditions, which is impossible to visualize intuitively, can be quickly and easily studied.

To aid in these simulation efforts, the Industrial Dynamics Research Group has developed a compiler and simulator program for use on the IBM 709 or 7090 computers. This program, called DYNAMO (DYNAMIC Models) reads a deck of IBM cards on which have been punched the equations of the model, does extensive checking for certain classes of possible errors, produces a set of detailed machine instructions for computing the model's behavior, calculates the dynamic behavior of the model for the desired duration of the simulation run, then prints data and plots graphs of the requested variables.<sup>9</sup> This program's speed and flexibility makes very easy the task of obtaining computer results for the basic system under various sets of input and parametric conditions. The big task is rather in developing the basic system and in meaningfully

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<sup>8</sup>Stuart W. Cragin, Jr., et al., Simulation, Management's Laboratory (Cambridge: Simulation Associates, 1959).

<sup>9</sup>Complete instructions for program utilization can be found in the DYNAMO User's Manual by Alexander L. Pugh, III.

interpreting the results of the computer runs provided by DYNAMO

### Over-all Organization of the System Equations

The formal mathematical model of the research and development project system is developed in the appendices of the remaining chapters of Part I. As a preview of these appendices, Figure 1-7 shows the interrelationships between the various sectors of the system and the locations of the equations describing each sector. The full model will require about 250 variable equations, about 65 initial-condition equations, and approximately 70 constants defining this particular system.

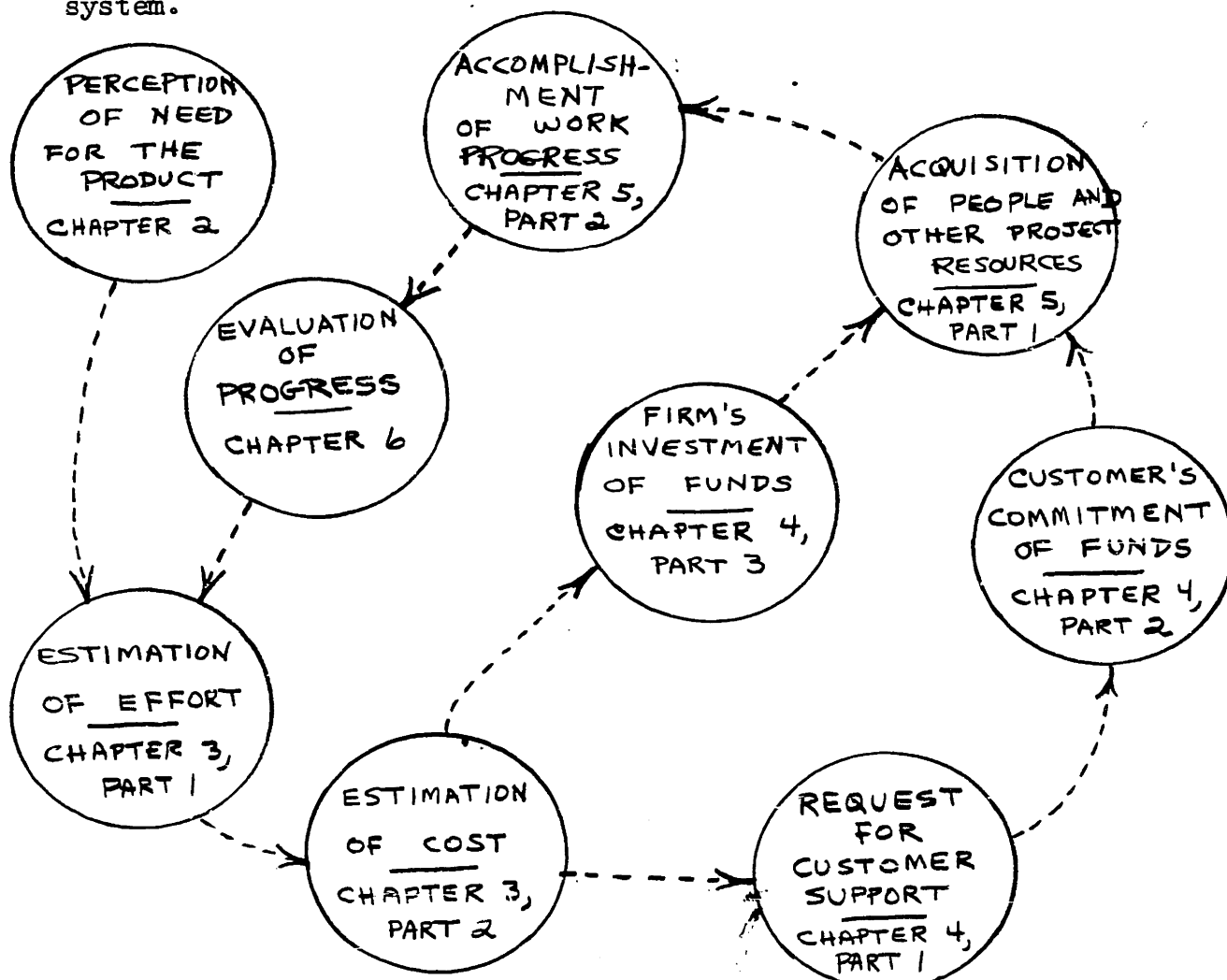


Figure 1-7 Over-All Organization of the System Equations

## CHAPTER II

### THE PERCEPTION OF THE NEED FOR AND VALUE OF A PRODUCT

The initial phase of the research and development life cycle consists of the birth of the product idea, that is, the initial perception of the need for some set of results, for a particular end product. Before one can adequately discuss the way in which the customer and the firm perceive the need for the product, this concept itself of the need for a product should be discussed and adequately explained.

#### The Underlying Need for a Product

In the consumer product area the concept of the need for a product is tied first to the satisfaction of the physical needs of individuals and then more generally to satisfying their psychological needs.<sup>1</sup> These psychological needs involve the problems of consumer wants and consumer tastes which in part may depend on the income or on the wealth of the individual and on other influences upon the psychological desires of people.

In the military area the concept of need for a product is basically quite similar, although by no means is it a simple matter to treat. In the military product market the need for a product is certainly still tied to the set of end goals and policies of the potential customers. Given the United States historical policy of nonaggression, however, the underlying needs

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<sup>1</sup>For a general discussion of this hierarchy of need relationships within the individual, see Douglas McGregor, The Human Side of Enterprise, New York: McGraw-Hill Book Company, 1960), pp. 36-42.

for military products in the United States are largely determined by the condition of world affairs and by the activities of those who are currently, or at least potentially, our competitors in military conflict. To be sure, the perceived needs for various products may be the resultant of other, perhaps political or economic, pressures. But for the moment we are concerned with those aspects of underlying need which relate to the required usage of the product for society's benefit. This implies, then, that at any given point in time the state of world affairs and the military preparedness and weapons of our enemies will in fact strongly influence the need for offensive and defensive weapons in our nation's arsenal. In turn, our preparedness and activities have the same effect on the underlying need for weapons of our military competitors. This creates the spiraling arms race, a feedback system which seems to have difficulty in reaching an "equilibrium" state of world power balance.

The usefulness of any particular product will vary over time. Prior to some point in time there will be little or no need for a particular product. This need may increase as world tensions in a given area increase, and finally the need for the product may later decrease again as its usefulness begins to diminish in the world arena. Thus the need for a product, in terms of its basic usefulness to society, or in terms of the satisfaction it could potentially provide through an omniscient military organization's use of the product, is illustrated by a curve of the type

shown in Figure 2-1. The gradual rise, the period of relatively unchanging mature value, followed by a decline in the need for the product is characteristic of the life cycles of all product types.

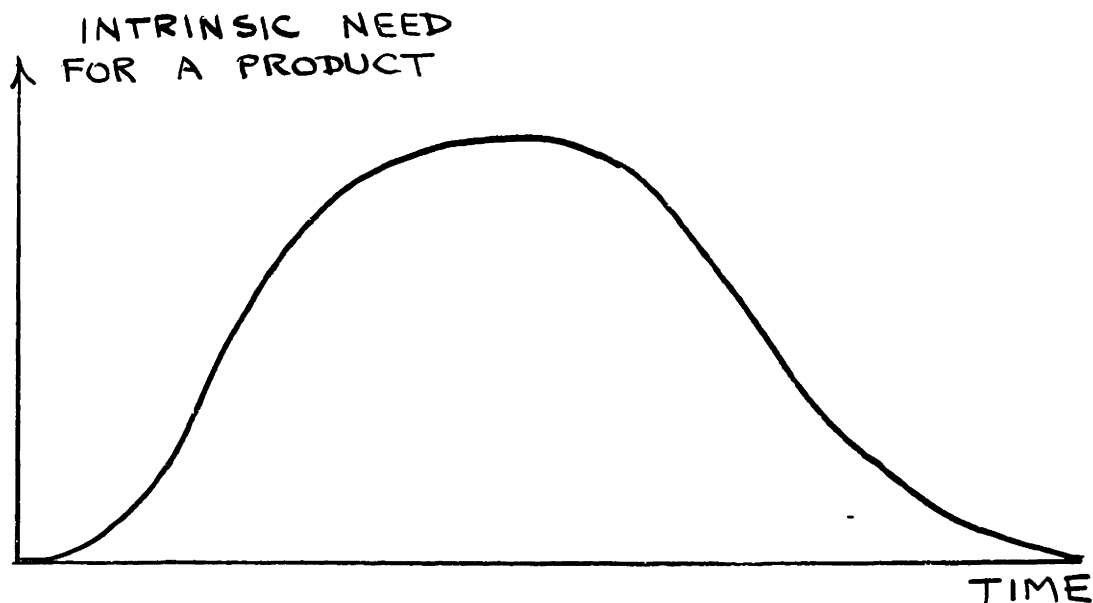


Figure 2-1 Time-Path of the Underlying Need for a Product

Thus far, this description of product need has been non-quantitative, but in fact there certainly are quantitative characteristics that are applicable to any discussion of the need for various products. Individuals and organizations recognize that one product is needed more than another, thus implying a ranking in terms of the significance of different products. But even more than this is implied by the way in which organizations and individuals deal with their need for different products. People are willing to exchange things which they value for other products which they need or desire. In our moneyed economy individuals exchange money for products. Consumers pay for the products that they want to acquire. The amount that people are willing to pay

to acquire a given product is an indication or measure of the extent to which the individual recognizes his need or desire.

The same is true in the military market. Different products are more or less able to satisfy the needs of the military. Therefore the military ought to be willing to pay more or less money corresponding to the extent to which the product can satisfy the needs of their organization. Thus a basic characteristic of any product is its ability at different points of time to satisfy the needs of the potential using organization to the extent that the user ought to be willing to pay a certain dollar amount to acquire the product at that point in time. This characteristic of the product's built-in ability to satisfy the user's needs we shall refer to as the "intrinsic product value".<sup>2</sup>

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<sup>2</sup> "Intrinsic product value" is obviously a measure of the product's "utility" characteristics. The author does not choose to involve himself at this point in the historic controversy in the economics literature regarding the nature of an individual's attitudes towards the comparative utilities of more than one product. There are some (ordinalists) who assume only that an individual can rank product choices as to preference. Others (the cardinalists) assert that the individual can associate some magnitude of utility measure to the various products under consideration. More significantly, both approaches to utility theory have led in the traditional literature to the definition of conditions by which the decision-maker maximizes his personal utility in the making of any economic decision. While theoretically decision-makers might attempt such maximization or optimization of profit-like variables, their conduct of research and development in the real world does not take such a simple but impracticable form. A more thorough discussion of the actual bases for research and development decision-making will be postponed to the chapters describing the individual decision functions.



Now that the concept of intrinsic product value has been introduced, we can discuss the fact that the existence of a product at any point in time can have negative as well as positive attributes. Many products require maintenance in order to preserve their existence. The use of nearly all products involves costs of operation. Moreover, some products have dangers or hazards associated with them which require special precautions and added costs which begin as soon as the owner possesses such a product. The old phrase, "holding a lion by the tail", describes just such a phenomenon. The possession of a lion requires building or buying a cage or the use of some other measures of restraint. Ownership and use of a nuclear reactor, for instance, necessitates the disposal of radioactive waste with the large costs associated with this activity. It may very well be that the technology of acquisition of many products has developed more rapidly than the technology of disposal or control of the product. Thus, for such products, to have is in fact to be burdened. This class of products is therefore characterized by the fact that during some phase of time the value of actual possession of such a product is negative--the utility of ownership of such a product would then be less than zero. This characteristic is true of many products during that phase of time when the potential customer's need for the product is either nonexistent or is very small. The negative attributes of the product then outweigh the little positive benefits that can be derived from the product to produce a net negative value associated with that product entity.

Of course, if the product is to become meaningful, it must at some time of its life have a positive utility or value. In other words the amount of positive satisfaction that a product can provide by satisfying certain needs of the customer must be able at some point in time to outweigh the negative attributes of possessing such a product. This means that during the phase of positive net value of the product, fully-informed rational customers should be willing to pay a positive price to gain the use or benefits of the product. Any product worth a name, therefore, has a potential phase of existence of positive value. In fact, many products as we know them probably pass from the zero value to the positive value phase and back eventually to zero value, entirely omitting the negative value phase described above.

#### The Actual Perception Process

To this point we have been discussing the intrinsic product value concept, defined as the inherent worth of a product to society if that product existed at any point in time. Of course, only an omniscient and all-sensitive being could respond to this intrinsic value of the product. In actuality, decision-makers are far from all-knowing and are not at all fully sensitive to the nature of either the environment or of potential products within that environment. Decision-makers possess knowledge to the extent that they receive, accept, and understand information. This information in itself is delayed, noisy, and even biased and/or distorted. The reception or perception, acceptance, and understanding processes of the decision-maker may similarly be characterized in terms of

delays, noise, bias, and distortion. In addition, decision-makers have lags in their sensitivity or responsiveness to new understandings--they delay in translating their new understandings into new actions or decisions. Thus we ought to now turn to the problem of describing how the actual decision-makers involved in research and development processes, the decision-makers in the organizations of the customer and of the developing firm, do in fact perceive the need for a product and the value of the product.

In trying to describe the way individuals or organizations perceive the need for or value of a product, we should first recognize that we are dealing with the entire psychological concept of perception as here applied to a particular area of product evaluation. In Leavitt's text on managerial psychology, he very simply defines the distinction between the perceptual world and the real world.

Most of us recognize that the world-as-we-see-it is not necessarily the same as the world-as-it-"really"-is. Our answer depends on what we heard, not on what was really said. The housewife buys what she likes best, not what is best. Whether we feel hot or cold depends on us, not on the thermometer. The same job may look like a good job to one of us and a sloppy job to another.<sup>3</sup>

We can continue in the same vein as Leavitt to say that what might look like a good product to one may not look like a good product to another. In general, then, it is important that we recog-

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<sup>3</sup> Harold J. Leavitt, Managerial Psychology (Chicago: The University of Chicago Press, 1958), p. 27.

nize that what we perceive, particularly here as related to the perception of the need for and value of a product, is determined not solely by the external facts of the real world environment, but rather it is determined jointly by these external conditions and by the expectations, the past experiences, the needs, and the goals of the decision-makers and their organizations.

It is most difficult for a military organization to establish product need or value, particularly in economic terms. "The military strategist has no such single quantitative measure of military worth as industry profits. He must evaluate his programs in qualitative terms, such as national survival, or minimizing the risk of war by preparedness measures."<sup>4</sup> But regardless of these difficulties the military does establish not only priorities but also budget limitations on the funds it is willing to provide for the attainment of various new product objectives. Let us then be specific about the kinds of phenomena which bear upon an organization's perception of the need for and value of a particular military product. First of all, this perception depends upon the intrinsic product value that was spoken of earlier. This intrinsic product value is manifested in the real world events which are continuously occurring. These events may consist of statements by leaders of the foreign countries or military actions by our enemies,

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<sup>4</sup> Richard B. Foster and Francis P. Hoerber, "Cost-Effectiveness Analysis for Strategic Decisions", Journal of the Operations Research Society of America, Vol. 3, No. 4 (November 1955), p. 485.

or the testing of some new device by us or our adversaries. All of these real world events and many other events of a similar nature bear within them the information that discloses, at least potentially, the current value of a given product.

But, of course, the things which take place in the real world are only potentially an input to the decision-maker's perception of the need for a new product. Before the decision-makers of the customer or the firm can at all be affected by these new real world events, they must receive information about them. This means that one of the influential determinants of the timing of the perception of the need for a new product and, hence, of the value of the new product is the delay in acquiring the information regarding these events. In part, problems of industrial security and military secrecy determine the length of the delay in transmitting and/or acquiring such information. But also the time to acquire such information at least in part depends upon the magnitude of the information or of the events themselves. That is, the more significant the occurrence, the greater the likelihood that people will find out about it sooner.

However, the mere transmittal of information regarding the events does not in and of itself lead to the perception of a new product, that is, of the need for or the value of such a product. An additional delay enters into the perception process, this delay being the time that it takes to absorb the new information and therefore to recognize the current value of the product. This absorption delay largely depends on the technical and managerial

ability of the firm or of the customer; that is, on their ability to comprehend the significance of the information about the events which have taken place. The length of this comprehension delay depends particularly upon the familiarity of the customer or the firm with the specific (or with some related) technical area in which the events have taken place.

The above factors largely serve to determine the level of recognized current value of a new product. However, the decision to invest in a research and development enterprise is based not on an estimate of the current worth of a new product, but rather on an estimate of what the product will be worth at some future time, when it is expected that the project either will be available or could be made available through the research and development process. Both customer and firm estimate the future value of the product based in part on their estimates of the current product value. Thus the estimate of the current worth serves as a foundation upon which the customer and/or the firm may extrapolate changes or trends.

The second influence on the organization's perception of the future value of a new product idea is the rate at which information about new events is becoming available. The famous Mr Parkinson (author of Parkinson's Law) appropriately remarked, "When the problem is one of dispatching a spaceship to (say) the moon, news of progress in Russia leads to frantic efforts in the United States; and the news of these efforts leads to fresh exertions in Russia."<sup>5</sup> When

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<sup>5</sup> C. Northcote Parkinson, "Haste and Waste in Science", Think, February 1960, p. 27.

the state of affairs is changing rapidly, the organization tends to extrapolate this rate of change into the future. As opinions begin to shift in terms of the perceived value of a product, a positive feedback effect commonly known as "climbing on the bandwagon" usually occurs. This phenomenon acts to induce mental extensions of the changes one believes have been occurring into the future. Thus the rate of change of the organization's current estimate of product worth is a strong determinant of its estimate of future value of the product.

A third factor which influences the estimate of the future worth of a product idea is the organization's delay in revising its estimates. This implies that even though the organization may have new information upon which it can base an estimate of the current or future value of a product idea, it does not necessarily immediately respond to such information. Instead, a delay occurs in revising the estimates of the organization. This delay may in fact largely depend on the extent of the organization's commitment to the earlier estimation. Thus the organization may very well be faced with a conflict situation--on the one hand, it has a commitment to an earlier estimate that it has made; on the other hand, it can at least subconsciously recognize the fact that the new information it has received demands a change in the estimates already made. The conflict inheres in the fact that personal motivations tend to demand the maintenance of the earlier estimations to which the organization has been committed, whereas dedication to meeting the goals of the organization demand the recognition of the new facts of life. Thus

a psychological pressure gap exists, the magnitude of this pressure being dependent on the difference between the previous commitment of the organization and the estimation to which new facts would lead the organization. This pressure gap will be a key determinant of how long it takes the organization to face up to the new facts that (correctly or incorrectly) it perceives.

The final influence on the organization's estimates of the future value of a product is the time duration over which the organization looks ahead. It is insufficient to talk about an estimate of future product value without specifying how far ahead in the future. The organization which makes decisions on the basis of its estimate of the future value ten years hence is in fact going to make different decisions than the organization which bases its actions on its estimates of the value one year hence. Thus the time horizon or duration over which the organization projects the expected changes in the value of the product is a determinant of the organization's perception of the future value. In part, the length of this time horizon depends on the willingness of the organization to take chances, since the further ahead the organization projects itself in making estimates of the worth of a product, the less certain is the state of the world on which the organization can base these estimates.

In review, we find that the problem of perception of the need for or the value of a product is not at all a simple matter. In the first place, the state of world affairs determines the intrinsic value of the product, but only an omniscient organization would



really "know" this intrinsic value. "Real world" organizations do not have access to knowing what this intrinsic value is. Real organizations make their estimates on the basis of the information that they receive about what is taking place in the world. This information may be gained by various formal and informal sources of communication. By whatever means the information is obtained, there are nevertheless delays involved in acquiring, absorbing, and responding to this information. The organization not only estimates the current value of the product, but it also attempts to anticipate the value of the product at some later point in the future, particularly at a point in the future when it believes that the product can be made available to the potential users. Many different kinds of factors influence the firm and the customer in making such perceptions, including such influences as their own past experiences, present goals, and present needs. These influences on perception not only present bias or distortion to the estimates, but also determine the length of time that it takes for the organization to respond to new and different information regarding the need for and, hence, the value of a new product. Psychological factors seem to be quite important in determining the behavioral characteristics of the firm and of the customer. Despite the fact that many of these notions are still unexplored areas of psychological research, we must recognize the kinds of influence these psychological factors have on the decisions, and the direction of these influences, and we must attempt to assess the magnitude of importance of these factors.

Fast Experiences in Value Estimation

The problem of properly estimating the value of products proposed for development is not a new one. In a recent article Dr. Eberhardt Rechtin cited an early example of this difficulty.

More than one hundred years ago, Michael Faraday was demonstrating his electromagnetic equipment to a British government committee in the hope of obtaining government support. One member admitted he was fascinated, but asked Faraday, "What practical benefits can we expect?" "I can't answer that question," Faraday replied, "but I can tell you that one hundred years from now you will be taxing something like this." <sup>6</sup>

It is similarly easy to point to many more recent examples in which the United States has shown lack of ability to estimate properly the value of new developments, both those of political strategic nature and those of military strategic nature. For one example of a continuously changing value estimate that we have made in the political area, we can readily point to the fact that the United States or at least the Congress of the United States saw little value in the League of Nations as an institution itself, or at least in our participation in such an institution. It took until about twenty years later before the United States did perceive the value of an institution of such nature. Of course, the intrinsic value of such international institutions has not yet been determined, nor will it be determined for some time, if ever. As another example of the change in our estimates of values in the

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<sup>6</sup> Dr. Eberhardt Rechtin, "Why the Space Race?", I.R.E. Student Quarterly, Vol. 7, No. 4 (May 1961), p. 46.

political area, we can point to the fact that at the end of World War II the United States wanted Germany to cease being an industrial state and to become an agricultural state. Yet by 1946 we had already begun changing this value perception. Today the value we see in West Germany is one of a very strong industrial and military strength in the Western European Alliance. In another area of political strategy we recall that the United States felt that there was great value to being able to move security questions out of the United Nation's Security Council and into the General Assembly. Our leaders failed to recognize for a long time that with the many newly emergent countries in the United Nations there would come a time that the General Assembly could in fact vote against the United States. Thus the perceived value of this particular strategy move has changed in our own eyes.

But let us now move on to areas that are more closely related to the problems of research and development. In 1937 a highly appointed presidential committee under Harold Ickes on technology and natural resources made no mention of jet engines in its evaluation of transportation. Yet the Germans were flying jet aircraft only seven years later. In the jet engine field the United States was not the only nation to demonstrate its inability to correctly assess product value.

The only radical innovation during the period [prior to World War II] in aircraft engines, the turbojet, was backed in the early stages neither by the government nor by an established engine producer. This was so in England and Germany as well as in the United

States. The first successful turbojet design was that of RAF flying officer Frank Whittle. He was unable to interest the government in a program to test his engine design and eventually obtained financial backing through a rather irregular arrangement with a small English investment banking firm.....It is interesting to note that Whittle's only suggestion as to an immediate practical use for his engine was for long-range mail planes.<sup>7</sup>

In the area of nuclear energy the Ickes report had made no mention of the atom, but two years later fission was achieved. In that same year, 1939, Einstein wrote a letter to Franklin D. Roosevelt, seriously discussing the potentiality of an atomic bomb. It was not, however, until two and one-half years later, after Pearl Harbor forced a change in the bases of our value estimates, that the United States really got going on the problem of developing an atomic bomb. This same nuclear weapons area provides good examples of a poor ability of the United States to estimate the future military position of our enemies. This lacking has caused us to seriously misjudge the value of certain weapons. For instance, we underestimated the ability of the U.S.S.R. to develop the atomic bomb by five years. Even after this lesson we were still wrong by three years in our estimate of when Russia would be able to develop a hydrogen bomb.

In the area of missiles there are many examples wherein the United States has revised its estimates of the value of some development on several different occasions and where we have shown extremely

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<sup>7</sup>Richard R. Nelson, "Invention, Research, and Development: A Survey of the Literature", U.S. Air Force Project Rand Research Memorandum, RM-2146 (April 15, 1958), pp. 40-41.

poor perception of the values of other developments. For instance, although we even knew that Russia was going ahead on the development of missiles during the entire post-war period, the United States did not adequately perceive the value of such a weapon. In part this was because of the fact that certain key pieces of information were kept from the decision-makers. From 1945 to 1951 the knowledge on atomic weapon development was kept from many military men. Therefore they thought that tremendously accurate guidance ability would be needed to have a long-range ballistic missile destroy a target. In 1952, however, the hydrogen bomb was "discovered" as a weapon, giving us a power of major magnitude despite poor guidance systems, for ballistic missiles. The development of these smaller hydrogen weapons and the recognition that radioactive fall-out itself was a major retaliatory weapon changed our entire perception of the value of ballistic missiles. Further in the missiles area the potentiality of the solid fuel rocket was not recognized early enough, nor, as has been very well documented, was the value of the atomic submarine recognized without much long and bitter struggle. Continuing in the area of missiles the value of the Sidewinder air-to-air missile was underestimated for an extremely long period of time. The development of this missile was strictly a bootlegged project, being able to continue for a long period, largely because of the fact that its development within a Navy laboratory was kept secret from the funding agencies of the Navy.

Most of the foregoing examples relate cases wherein we have

initially seriously underestimated the value of the product. But the many weapons which are obsolete when ready for use lend evidence to possible errors in the other direction too. The "traditional process has...produced a great number of prototype aircraft that have cost large sums of money and much highly skilled manpower but which were never produced in significant quantities, if at all. Presumably, in someone's opinion, these were unsatisfactory or unwanted aircraft....Historically, these aeronautical curiosities far outnumber the airplanes that have received full implementation."<sup>8</sup> These were no doubt cases of initial gross overestimation of the worth of some aircraft configuration. Thus it seems that the errors in our product value perception process have been both of underestimation and the overestimation varieties.

And finally, before closing this discussion on the way in which people have perceived value in the military product market, let us mention the nuclear-powered bomber. Here is a case where the first real attraction of the possible weapon, that is the basis for the perception of value of this product, in at least some areas of Congress, was that it was inexpensive--believed to be far cheaper than the maintenance of our foreign air bases. Now, after having spent many hundreds of millions of dollars on the design and development of a nuclear bomber, we have finally decided to leave the development stage and go back to the research stage. Thus, here again, the basis of the perception of value was completely

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<sup>8</sup> Robert A. Bailey, "Application of Operations-Research Techniques to Air-Borne Weapon System Planning", Aeronautical Engineering Review, Vol. 13, No. 11 (October 1954), p. 74.

wrong, as was perhaps the magnitude of the value perceived itself.

This preceding chapter has pointed out the fact that one can do more than just make theoretical arguments as to the nature of the perception of the value of military products. It has been easy to point out, despite the general secrecy and lack of public documentation which characterize military research and development projects, that one of the notable problems in the management of military R and D is the perception of value of various potential products. The United States historically has had difficulties not only in the military product development area but also in recognizing and properly perceiving the value of various political and strategic developments. Some of the reasons for these mistakes have been pointed out earlier. The psychological factors, the delays that are inherent in the large military organizations, and many other factors all contribute to the problem of adequately perceiving the value of some new and major development. But yet the perception of the value of a new product is only one of the several continuously on-going sets of activity that underlie a research and development project. As discussed earlier, several other areas of activity exist in all such projects, and before we can gain a full understanding of the problems of managing research and development, we must look into these other areas of activity.

This appendix includes the flow diagrams and equations which describe the perception of the need for and value of the product by both the research and development firm and the sponsoring government agency or customer. Figure 2-2 shows the over-all relationships described in the foregoing chapter. The diagram is, of course, an abstract of the information which was presented in the verbal description in the chapter, and represents one mode of aggregation of that detailed material. A diagram of this sort will help us to focus upon the major variables which must be included in the model of research and development projects, which model is to be developed in the following appendices, even though the model equations themselves will require some greater degree of detail for producing mathematical completeness and precision. The numbers in the diagram symbols refer to equations or other figures used later in this appendix.

Briefly following through the diagram we see represented the fact that the nature of the real world environment defines the changes in the intrinsic product value of any product under consideration. Information as to the intrinsic product value is always in the process of being communicated to those interested, particularly to the potential customers and to the potential research and development firms. The diagram here represents either or both the firm and the customer, since the process of perception of product need and value is common to both of them. The first number listed in each block refers to the detailed information for the firm and the second refers to the customer. The rate of recognition of product value is dependent both upon the actual informa-



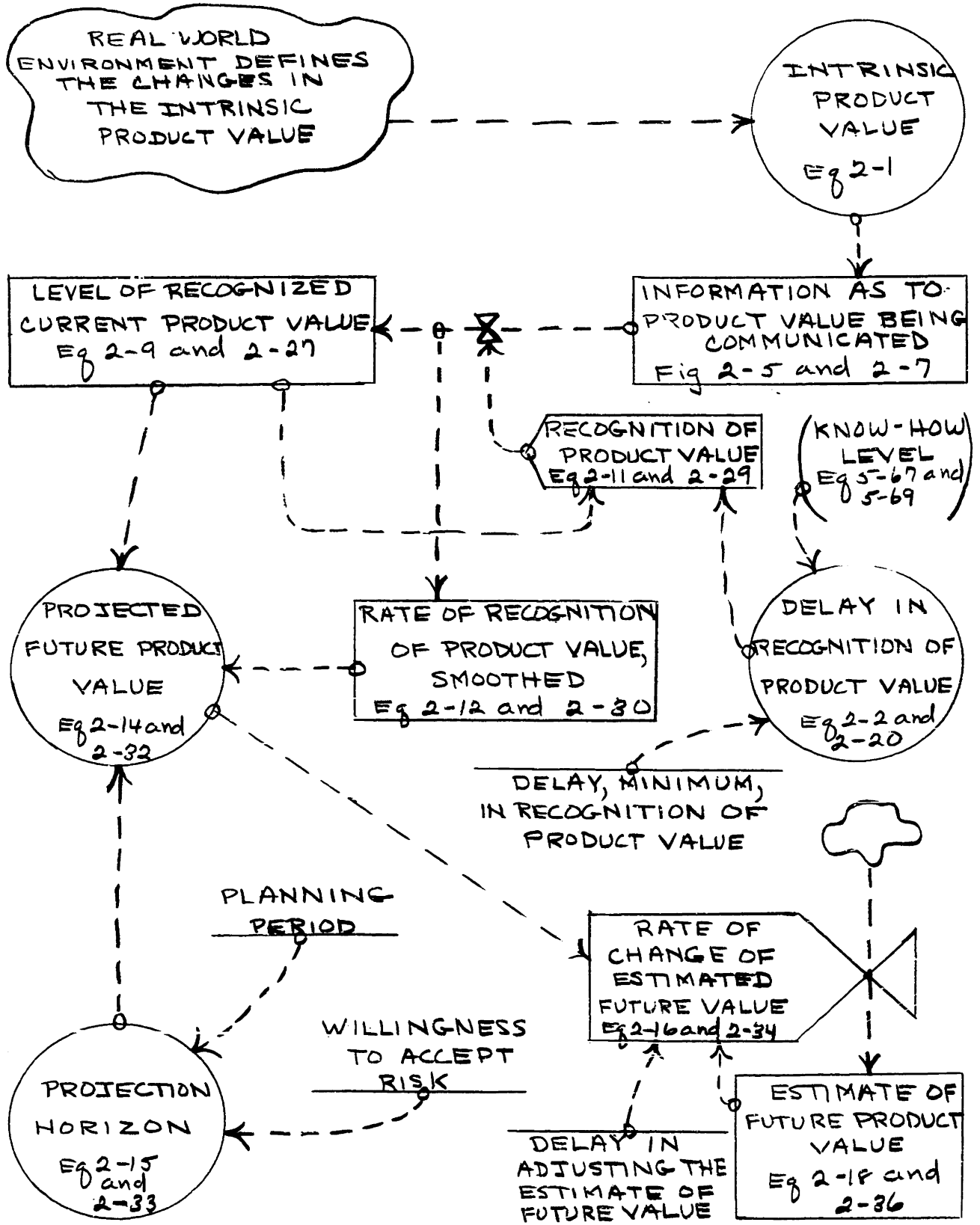


Figure 2-2 Perception of Product Value

tion as to product value which is being communicated, and on the delay in recognizing this information. The diagram further shows that this delay in recognition is dependent both on some minimum delay in recognizing such information about product value and upon the level of related know-how of the potential receiver of the information. As the new information about product value is received it builds up the level of product value currently recognized by either the customer or the firm. In addition to affecting this, the customer and the firm take cognizance of the average (or smoothed) rate of recognition of the product value. That is, they are aware not only of what they currently believe the product to be worth, but also of how this belief has changed over time. These two influences primarily produce a projection of the future product value. This projection depends upon the trend in changes of value (i.e., the rate of recognition of product value, smoothed) and on the extent of time that the firm or the customer is projecting this trend ahead. This extrapolation time has been labeled in the diagram as the "projection horizon". The projection horizon in turn is shown as depending upon the basic planning period of the organization and its willingness to accept risk, a measure of risk-taking propensity or conversely of the conservatism of the organization. As the projected future product value changes, this begins to build up an influence on the organization to change its actual estimate, held for decision-making purposes, as to what the future product value will be. The rate of change of this estimate depends upon what the current estimate of future value is,

and what the current projected information would produce as an estimate. The gap between the two is the strong influence to revise the estimate, this influence being modified by some normal delay in adjusting this estimate of the future product value.

Now that the diagram has been described, let us go on to the writing of the actual equations needed to represent the model. The first equation written, Equation 2-1, is for a basic input to the research and development model, the intrinsic product value. Here in a table of constants are stored the numbers which over time represent the intrinsic product value of the particular product under consideration in the research and development project. From one computer simulation run to another, we may change this table of values to see what effect different product value environment considerations would have upon the project life cycle. The equation for selecting the product value from this table of stored numbers is:

$$IPV.K = TABLE(PVTAB, TIME.K, 0, 180, 6) \quad 2-1, A$$

IPV--Intrinsic Product Value (dollars)

TABLE--a notation used by the DYNAMO compiler to indicate the fact that a set of tabular values will be utilized to provide the specific number for the variable IPV

PVTAB--Product Value TABLE, the name of the table of input values for IPV (dollars), in which values have been inserted at 6-month intervals from TIME = 0 to TIME = 180 months

TIME--the simulated project time starting from time = 0 and proceeding until the end of the computer run (months)

Although this intrinsic product value input shall be varied later to determine its effect upon the research and development

project outcome, we shall start by providing a set of values for the product value table which seem to be a plausible and reasonable set. As specified in the equation for IPV, this table will contain values stored at six-month intervals from month 0 to month 180. We will then be able to make computer simulation runs for this entire period of time, the equivalent of 15 years duration. Figure 2-3 pictures the initial input specified by the product value table below the graph. In the constants listed below the graph, the

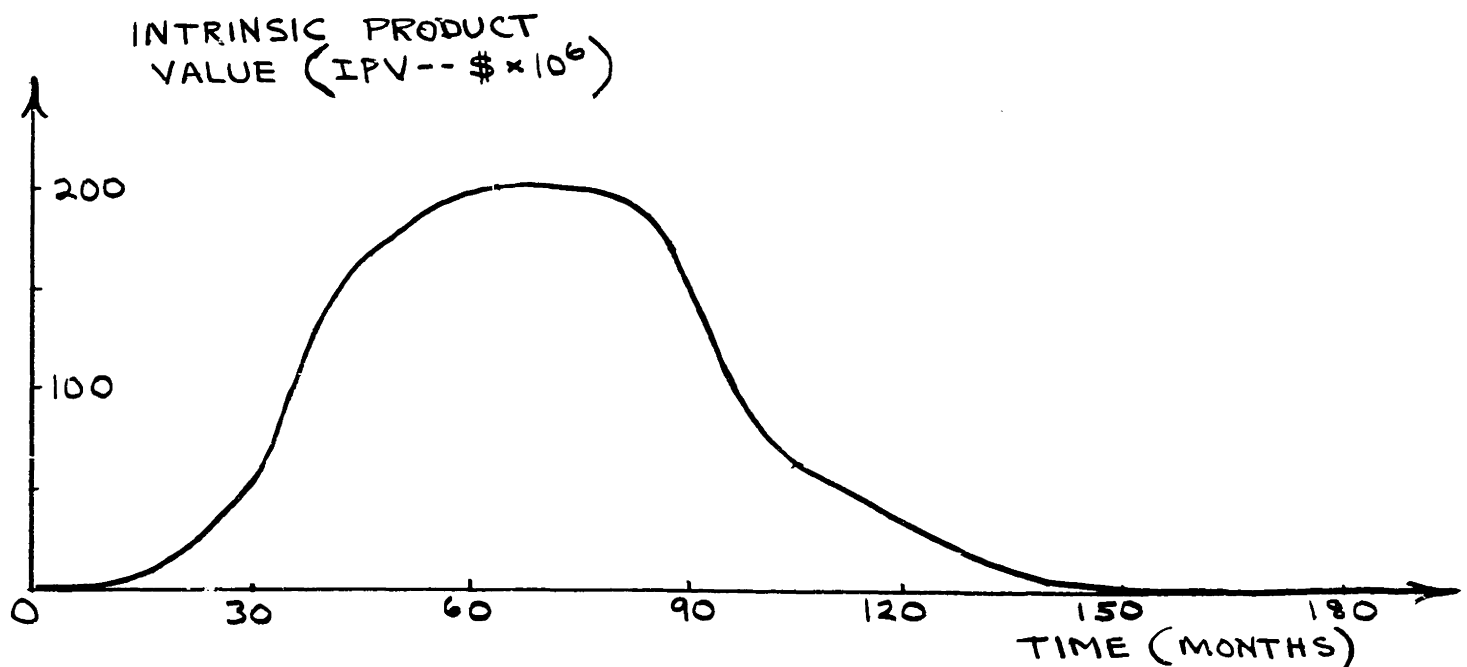


Figure 2-3 Intrinsic Product Value

PVTAB\* = 0/0/1E6/10E6/30E6/60E6/100E6/150E6/170E6/185E6/200E6/200E6/  
 200E6/200E6/190E6/150E6/100E6/70E6/50E6/40E6/30E6/20E6/10E6/1E6/  
 0/0/0/0/0/0/0

E-form stands for ten's exponent. Thus, 10E6, for instance, equals  $10 \times 10^6$  or 10 million. All of the constants in the PVTAB table

are in dollar amounts.

This information as to the intrinsic product value becomes recognized over a period of time by the organization and incorporated into its level of recognized current product value. This delay consists of two basic parts: first, the constant minimum delay which is a function solely of the process of communication or the nature of secrecy related to the particular product; secondly, a variable delay which probably depends upon the basic know-how and understanding of the organization attempting to receive the information as to the product value. Figure 2-4 pictures a relationship for such a delay which seems feasible.

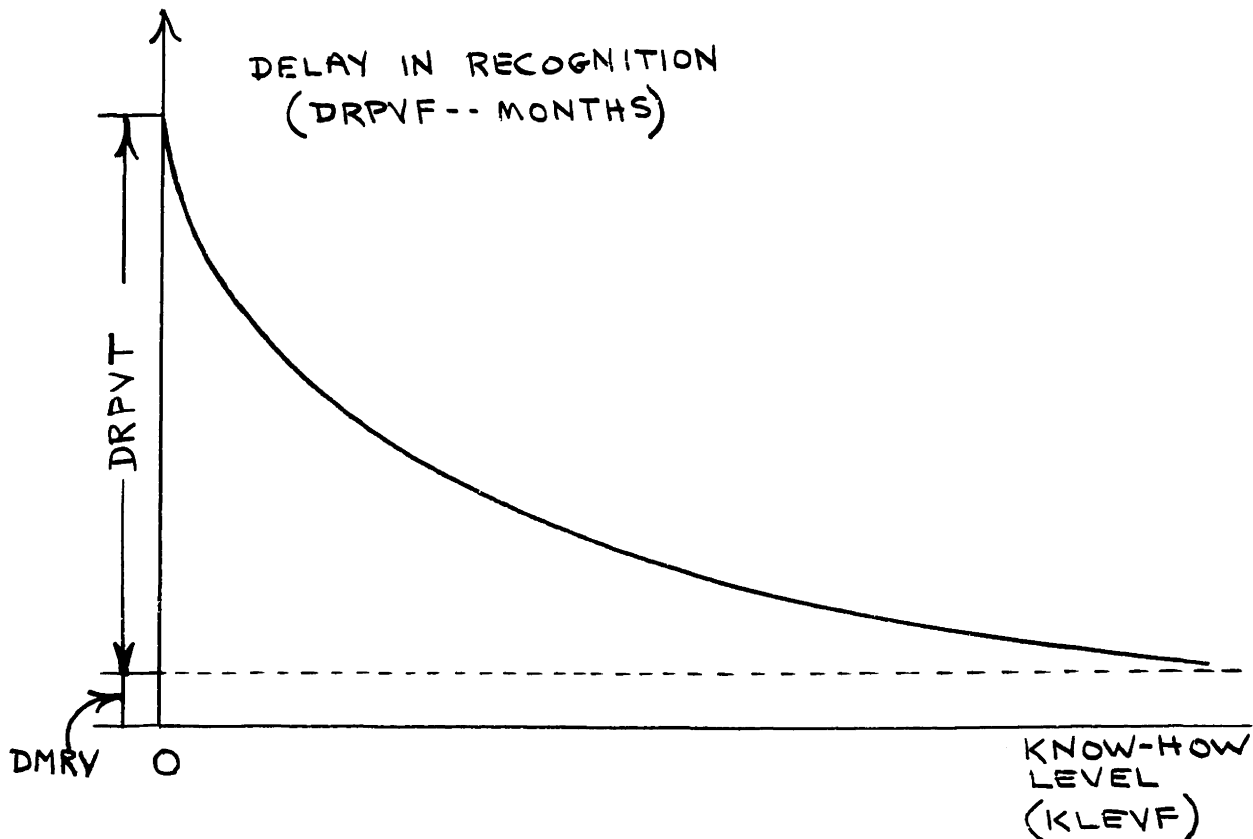


Figure 2-4 Delay in Recognition of Product Value  
At the Firm

Here what we see pictured, at the extreme left of the diagram, is the fact that with no knowledge relevant to the product area, the delay in transmitting the information as to the product value will be extremely large. As the related know-how increases, the delay in receiving appropriate information of this sort steadily decreases. With a large amount of effective knowledge relevant to the product area this delay in product value information transmission decreases to the minimum level illustrated in the diagram. Two equations are used to represent the delay described above. The first equation (Equation 2-2) indicates that the delay in recognition of product value at the firm is equal to the minimum delay in recognizing such information plus a variable additional delay in the firm's recognition time. This variable additional delay (Equation 2-3) declines exponentially from its maximum value as the firm's related product know-how increases. This added delay becomes approximately zero when the level of the firm's knowledge becomes large.

$$\text{DRPVF.K} = \text{DMRV} + \text{DVRVF.K} \quad 2-2, \text{ A}$$

$$\text{DVRVF.K} = (\text{DRPVT}) e^{-\text{KLEVF.K}/12} \quad 2-3, \text{ A}$$

DRPVF--Delay in Recognition of Product Value at the Firm  
(months)

DMRV--Delay, Minimum, in Recognition of product Value  
(months)

DVRVF--Delay, Variable, in Recognition of product Value  
at the Firm (months)

DRPVT--Delay in Recognition of Product Value, Time  
constant (months)

e--base of natural logarithms, equals 2.7183---

KLEVF--Know-how LEVel of the Firm (effective man-months  
of effort)

In setting the values of the two constants used in the above equations, we shall follow the practice of using parameters which seem to be plausible for the system being described. We shall not concern ourselves with whether these particular numbers apply to any specific company, customer, or project. We can at any time, by simply changing the values selected, determine the effects of such changes upon system behavior through the use of the simulation runs. Taking into account how long information in the military product area requires for transmission and also the delay in actually attributing value to the information received, we shall set the constants as:

$$\text{DMRV} = 6 \text{ months}$$

$$\text{DRPVT} = 60 \text{ months}$$

These constants say that in the absence of related product knowledge, 66 months will be required for the firm to receive and interpret information about changes in the world situation which create corresponding changes in the intrinsic value of the product. This time delay, a period of 5 1/2 years, is longer, for example, than the lag in United States information about the Soviet progress in developing their first atomic bomb or regarding the U.S.S.R state of preparedness in the long-range missile area. But no doubt there are some cases in which this maximum product value information delay may rise to as much as 240 months or 20 years. At the other extreme, the DMRV constant indicates that even if the firm possesses a very substantial amount of information in the related technical area, a minimum time of 6 months is still required for

taking account of the potential value of the product which is indicated by new information received. The reader's experiences and tastes may prefer longer or shorter constants for either of these two numbers; but for the purpose of our demonstration runs, we shall proceed with the selected values.

We would now like to be able to describe the level of recognized current product value at the firm as merely some delayed function of the intrinsic product value, utilizing the delay just defined above. Specifically, we would like to assume that this recognized value is a third-order exponential lagged relationship of the intrinsic product value.<sup>9</sup> However, a technical restriction in the DYNAMO program which will be used to study the research and development project model prevents the use of a variable delay, such as DRPVF, in a third-order delay equation. Therefore, we shall create a set of three subordinated first-order delays to create the desired third-order result for the recognized product value. This situation is shown in Figure 2-5.

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<sup>9</sup> The distinctions between the various forms of lagged relationships of the exponential delay form are explained in Chapter 9 of Forrester's Industrial Dynamics.



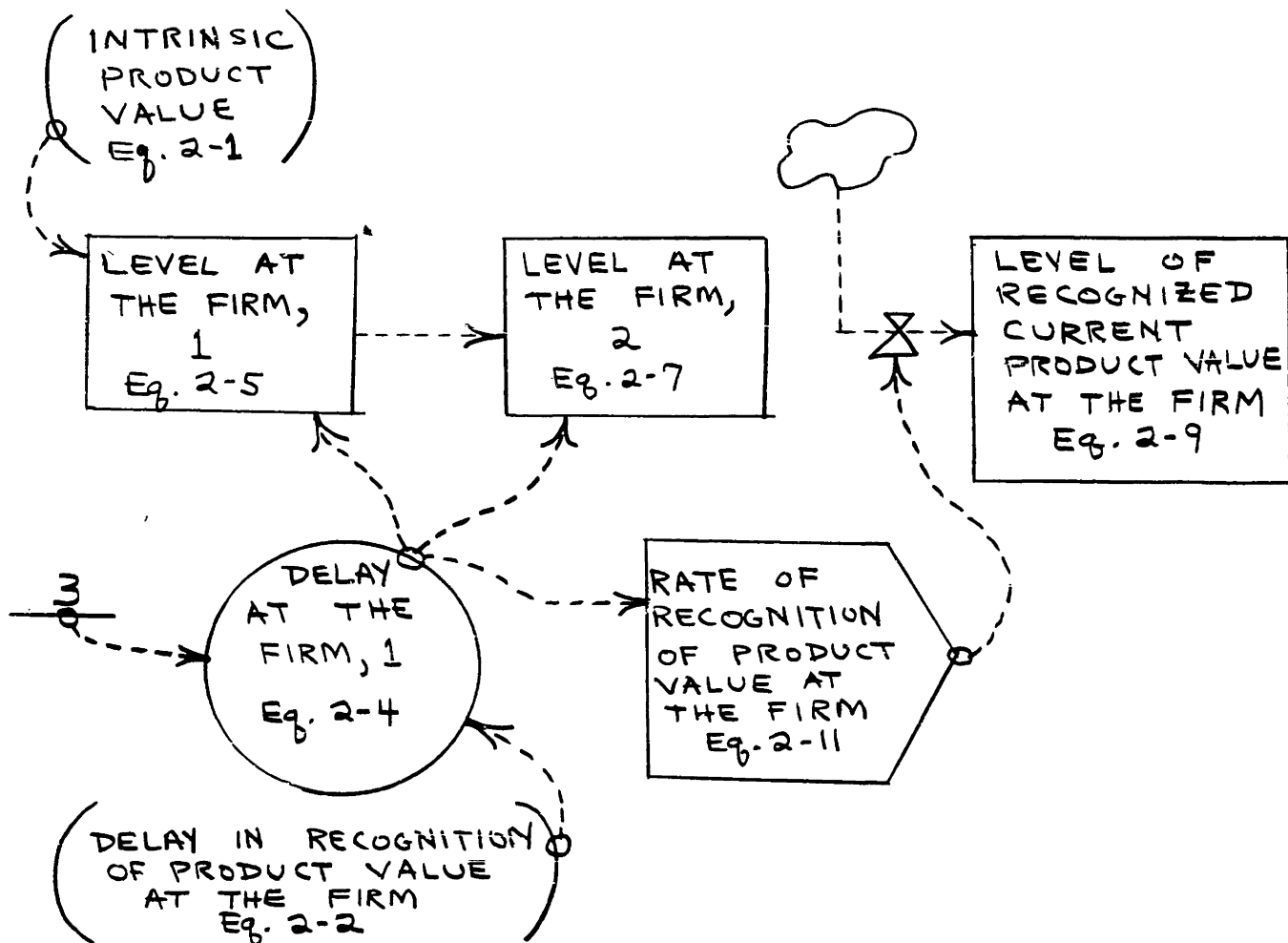


Figure 2-5 Information as to Product Value Being Communicated to the Firm

Thus, the first thing that shall be done is to define a variable which is equal to one-third of this above defined delay, DRPVF, and utilize this new auxiliary variable in our technically required equations.

$$DF1.K = DRPVF.K/3$$

2-4, A

DF1--Delay at the Firm, 1 (months)

DRPVF--Delay in Recognition of a Product Value at the Firm (months)

We can now define the three level equations which will be necessary to create the third-order lagged effect of the IPV term. Each equa-

tion produces a first-order smoothing of the input variable.

$$\text{LEVf1.K} = \text{LEVf1.J} + \left(\frac{\text{DT}}{\text{DF1.J}}\right)(\text{IPV.J} - \text{LEVf1.J}) \quad 2-5, \text{ L}$$

$$\text{LEVf1} = 0 \quad 2-6, \text{ N}$$

$$\text{LEVf2.K} = \text{LEVf2.J} + \left(\frac{\text{DT}}{\text{DF1.J}}\right)(\text{LEVf1.J} - \text{LEVf2.J}) \quad 2-7, \text{ L}$$

$$\text{LEVf2} = 0 \quad 2-8, \text{ N}$$

$$\text{LRPVf.K} = \text{LRPVf.J} + (\text{DT})(\text{RPVf.JK}) \quad 2-9, \text{ N}$$

$$\text{LRPVf} = 0 \quad 2-10, \text{ N}$$

LEVf1--LEVEL at the Firm, 1 (dollars)

DT--Delta Time (months), the time interval between computer solutions of the equations

DF1--Delay at the Firm, 1 (months)

IPV--Intrinsic Product Value (dollars)

LEVf2--LEVEL at the Firm, 2 (dollars)

LRPVf--Level of Recognized current Product Value at the Firm (dollars)

RPVf--Rate of recognition of Product Value at the Firm (dollars/month)

Since we shall be interested in the rate of change of the firm's recognized current product value, Equation 2-9 above which defines the level of recognized value has been written in a slightly different manner from that used for the two intermediate level equations. The level of recognized current product value at the firm is written as the summation of all previous changes in this level, and the rate of change itself is defined in Equation 2-11 below. The N-type equation after each level above provides the initial value for the level. Here we are beginning from a state of absence of any perceived product value by the firm. Hence, all of the levels are initially set equal to zero.

The input to the final output level, the level of recognized product value of the firm, LRPVf, is defined by the next equation for

RPVF:

$$RPVF.KL = \frac{LEV2.K - LRPVF.K}{DF1.K} \quad 2-11, R$$

RPVF--Rate of recognition of Product Value at the Firm  
(dollars/month)

LEV2--LEVEL at the Firm, 2 (dollars)

LRPVF--Level of Recognized current Product Value at  
the Firm (dollars)

DF1--Delay at the Firm, 1 (months)

This equation in effect makes LRPVF of the same form as LEV1 and LEV2. All are first-order information delays with time-constants equal to one-third of the over-all delay in recognition of product value at the firm, DRPVF. The three delays in sequence form a variable third-order delay with time-constant DRPVF.

In each of the three level equations above, the constant DT, Delta Time, was used to specify the time period between calculations of solutions of the equations of this model. This is a parameter of the computer solution procedure rather than of the research and development system itself. The value for this should be specified not on the basis of personal taste but rather on the technical requirements for mathematical accuracy in our equation system solution. As illustrated in Appendix D of Industrial Dynamics, the solution interval should be less than one-sixth of the smallest length of time represented in any third-order delay in the system. Since we are going to use a third-order delay constant as short as two months in the research and development system, the solution time interval shall be:

$$DT = 0.25 \text{ months}$$

This means in essence that the computer will be solving the equa-

tions of the entire system approximately every week. Such frequent computer solution will insure numerical accuracy of the results without introducing any significant computational errors.

Returning now to the definition of equations for the firm's perception of product value, we next take account of the fact that over a period of time the firm becomes aware of the average trend in its own recognition of product value. We assume that in using this mental averaging process, the firm weights more heavily recent changes in its product value recognition and gradually forgets about changes which have taken place further back in the past. This assumption is readily incorporated into a first-order exponential smoothing (or averaging) equation, which smoothed variable is appropriately labeled the "Rate of recognition of Product Value, Smoothed, at the Firm".<sup>10</sup>

$$RPVSF.K = RPVSF.J + \left(\frac{DT}{DSRPV}\right)(RPVF.JK - RPVSF.J) \quad 2-12, L$$

$$RPVSF = 0 \quad 2-13, N$$

RPVSF--Rate of recognition of Product Value, Smoothed, at the Firm (dollars/month)

DSRPV--Delay in Smoothing Recognition rate for Product Value (months)

RPVF--Rate of recognition of Product Value at the Firm (dollars/month)

As explained above this average rate of change of the recognized product value takes into account all previous changes in the firm's

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<sup>10</sup> This first-order smoothing approach is explained in Appendix E of Industrial Dynamics.

estimates of current product value, most heavily weighing the recent changes made in this estimate.

The typical near-sightedness of the firm leads it to respond rather quickly to changes which it in fact has already recognized. The firm tends to forget quickly the recognized events of the past and both judges the present and guesses the future by the recognized events of the most recent few months. Thus, the smoothed rate of recognition of product value is assumed to depend primarily on the latest three-month period's recognized occurrences, and therefore:

$$\text{DSRPV} = 3 \text{ months}$$

This does not imply that the firm recognizes a basic market change in so short a time. That delay in recognition (Equation 2-2) ranges between 6 and 66 months. Rather this constant means that whatever the firm does recognize soon causes it to change its beliefs as to the future value expectations for the product area. In the situation characterized by much short-term random and conflicting pieces of information, such a short smoothing period would potentially produce relatively short-term swings of the firm's confidence in the merits of any given product area. Such behavior is commonly encountered in research and development companies.

Companies basically recognize that for them to be effective in the research and development business, they must at least try to anticipate the future demands of their customers. Thus, using its perception of the current level of recognized value as a baseline, the firm projects ahead the trend in its own beliefs as to

changing product value to form an initial projection of the future value of the product.

$$\text{PFPVF.K} = \text{LRPVF.K} + (\text{RPVSF.K})(\text{PHF}) \quad 2-14, \text{ A}$$

PFPVF--Projected Future Product Value of the Firm (dollars)  
 LRPVF--Level of Recognized current Product Value of the Firm (dollars)  
 RPVSF--Rate of recognition of Product Value, Smoothed, at the Firm (dollars/month)  
 PHF--Projection Horizon of the Firm (months)

The "projection horizon" of the firm determines how far ahead the firm is willing to project this trend that it has detected in order to anticipate the future product value. This projection horizon depends not only on the normal planning period for the firm, but also on the basic conservatism or, conversely, the willingness to accept risk that characterizes the firm. The basic planning period expresses the maximum amount of time over which the firm would normally make such a projection, whereas the willingness to undertake risk indicates the extent to which the firm is willing to guess that far into the future in making a value estimate upon which it is going to base important decisions. Thus the firm's willingness to accept risk determines that fraction of its maximum planning period which it will use to project the recognized value changes.

$$\text{PHF} = (\text{PLPF})(\text{WARF}) \quad 2-15, \text{ N}$$

PHF--Projection Horizon of the Firm (months)  
 PLPF--Planning Period of the Firm (months)  
 WARF--Willingness to Accept Risk by the Firm (percentage)

The firm probably ought to work on programs based on needs

very distant in the future. But in fact very few firms even "venture beyond their front pastures" in considering the implications of changes in the current world situation. For the maximum planning period of the firm we shall select a value of four years, probably much longer than that period used by most companies.

$$\text{PLPF} = 48 \text{ months}$$

The effective projection horizon of the firm is determined not solely by this planning period, however. The firm's willingness to accept the risks of basing its decisions on estimates that are highly uncertain also constrains the projection horizon of the company. Initially, we shall represent a firm with maximum risk-taking propensity, and later vary this parameter to determine its effect on project behavior. Thus the company's risk-taking propensity is set at 100%, or:

$$\text{WARF} = 1.00 \text{ (decimal percentage)}$$

We now return to a discussion made far more extensively earlier in this chapter; namely, that the projection of this trend would ordinarily lead the firm to one estimate, namely the projected product value. However, the firm has already made a commitment to a different estimate of the future product value. The gap between these two values, the projection and the previous commitment, constitutes pressure on the firm to change its actual estimate of the future product value. This change decision and its result are incorporated in the following set of equations. The first equation below (Equation 2-16) indicates that the firm gradually recognizes

a fraction of the difference between its value projection and its previous future value estimate. The fraction recognized depends on the average response time of the firm to such gaps in the estimates; i.e., the longer the firm takes to respond to the influence of the gap in its estimates, the smaller will be its rate of modifying its previous commitment.

Before using the value projection, however, we will check to see if we have encountered the condition under which this linear trend extrapolation produces a negative future value estimate. This will be done for two reasons. First, it is actually unlikely that military products today pass into this negative value region. They more likely get retired to some secondary usage, but maintain a small, positive value. This fact indicates that the extrapolation should be a nonlinear one, rather than the linear formulation which produces this difficulty. Secondly, and perhaps of greater current importance, projecting the product value into the negative region produces possible technical problems with the existing model formulation. Thus the convenience is adopted here of restricting the range of the projection to non-negative values only. This is a weak model-building practice to follow, but it is unlikely to affect the over-all dynamic system behavior in this particular case. Thus Equation 2-17 below produces a usable projection value that is positive only.

$$RCEVF.KL = \frac{UPPVF.K - EFPVF.K}{DAEVF} \quad 2-16, R$$

$$UPPVF.K = \text{MAX}(PFPVF.K, 0) \quad 2-17, A$$



RCEVF--Rate of Change of Estimate of future Value  
at the Firm (dollars/month)  
 UPPVF--Used Projection of Product Value at the Firm  
(dollars)  
 EFPVF--Estimate of Future Product Value at the Firm  
(dollars)  
 DAEVF--Delay in Adjusting the Estimate of Value at  
the Firm (months)  
 MAX--a notation used by DYNAMO to indicate that the  
maximum of the two parameters named within the  
parentheses shall be taken and used to determine  
the value of the variable, UPPVF  
 PFPVF--Projected Future Product Value of the Firm (months)

The firm's delay in resolving the difference between its projected estimate and its previous value estimate commitment can conceivably vary greatly between different companies and different situations. No data exists to help define this delay numerically. We will adopt a constant of six months duration (possibly somewhat on the lower end of the feasible range) and test the model later with a much longer delay in the firm's adjustment of its product value estimate. Thus, at least temporarily,

$$\text{DAEVF} = 6 \text{ months}$$

The rate of change of the estimate of value produces, in a cumulative fashion, the level equation for the currently held estimate of future product value of the firm. This equation for the future product value estimate completes the description of the firm's process of perception of the need for and value of the product.

$$\text{EFPVF.K} = \text{EFPVF.J} + (\text{DT})(\text{RCEVF.JK}) \quad 2-18, \text{ L}$$

$$\text{EFPVF} = 0 \quad 2-19, \text{ N}$$

EFPVF--Estimate of Future Product Value at the Firm  
(dollars)  
 RCEVF--Rate of Change of Estimate of future Value at  
the Firm (dollars/month)

A similar set of equations to those of Equations 2-2 through 2-19 also describes the behavior of the customer. There is no reason to believe that the customer's process of perception of product value is any different from that of the firm with the exception of the particular parameters or coefficients which might fit into the appropriate equations. The first aspect of the customer perception to be described is the customer's delay in recognition of the current product value. This delay is a function of the customer's level of related product know-how, the delay decreasing exponentially as the customer's knowledge increases. Figure 2-6 corresponds to Figure 2-4 which showed the delay function for the firm.

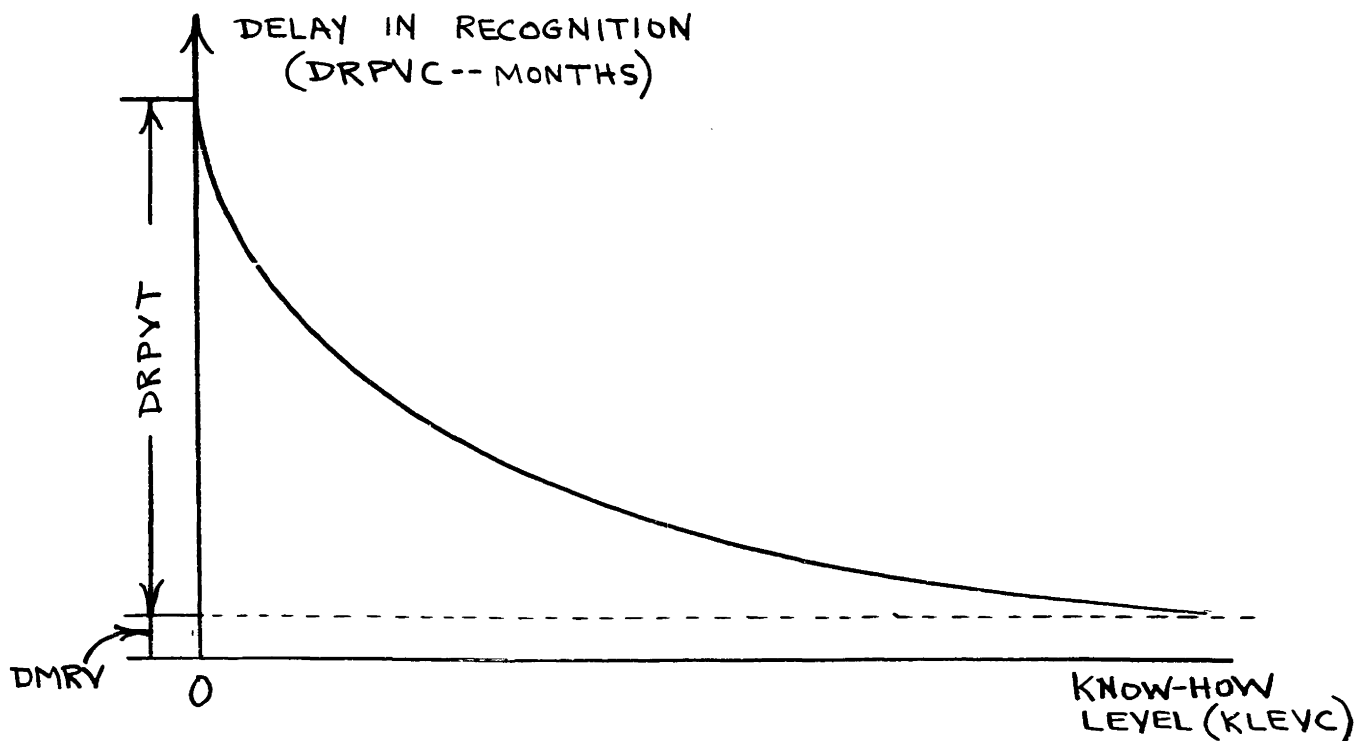


Figure 2-6 Delay in Recognition of Product Value  
At the Customer

The two equations needed to describe the above curve correspond to Equations 2-2 and 2-3 which described the delay in recognizing the product value information for the firm.

$$\text{DRPVC.K} = \text{DMRV} + \text{DVRVC.K} \quad 2-20, \text{ A}$$

$$\text{DVRVC.K} = (\text{DRPVT})e^{-\text{KLEVC.K}/12} \quad 2-21, \text{ A}$$

DRPVC--Delay in Recognition of Product Value at the Customer (months)  
 DMRV--Delay, Minimum, in Recognition of product Value (months)  
 DVRVC--Delay, Variable, in Recognition of product Value at the Customer (months)  
 DRPVT--Delay in Recognition of Product Value, Time constant (months)  
 e--base of natural logarithms, equals 2.7183---  
 KLEVC--Know-how LEVel of the Customer (effective man-months of effort)

The values of the two constants in these equations were defined earlier in this appendix. DMRV equals 6 months and DRPVT = 60 months. This makes the maximum delay in the customer value perception process be 66 months and the minimum be 6 months. These figures are exactly the same as those used for the firm.

The customer's recognition of current product value is represented as a third-order lagged relationship of the intrinsic product value. Figure 2-7 shows the three first-order delays used to achieve this relationship, given DYNAMO's restriction against the use of variable third-order delay time-constants. This diagram is similar to that of Figure 2-5 used to represent the firm's recognition process.

The equations which correspond to this diagram are similar to Equations 2-4 through 2-11 used for the firm. The first equation

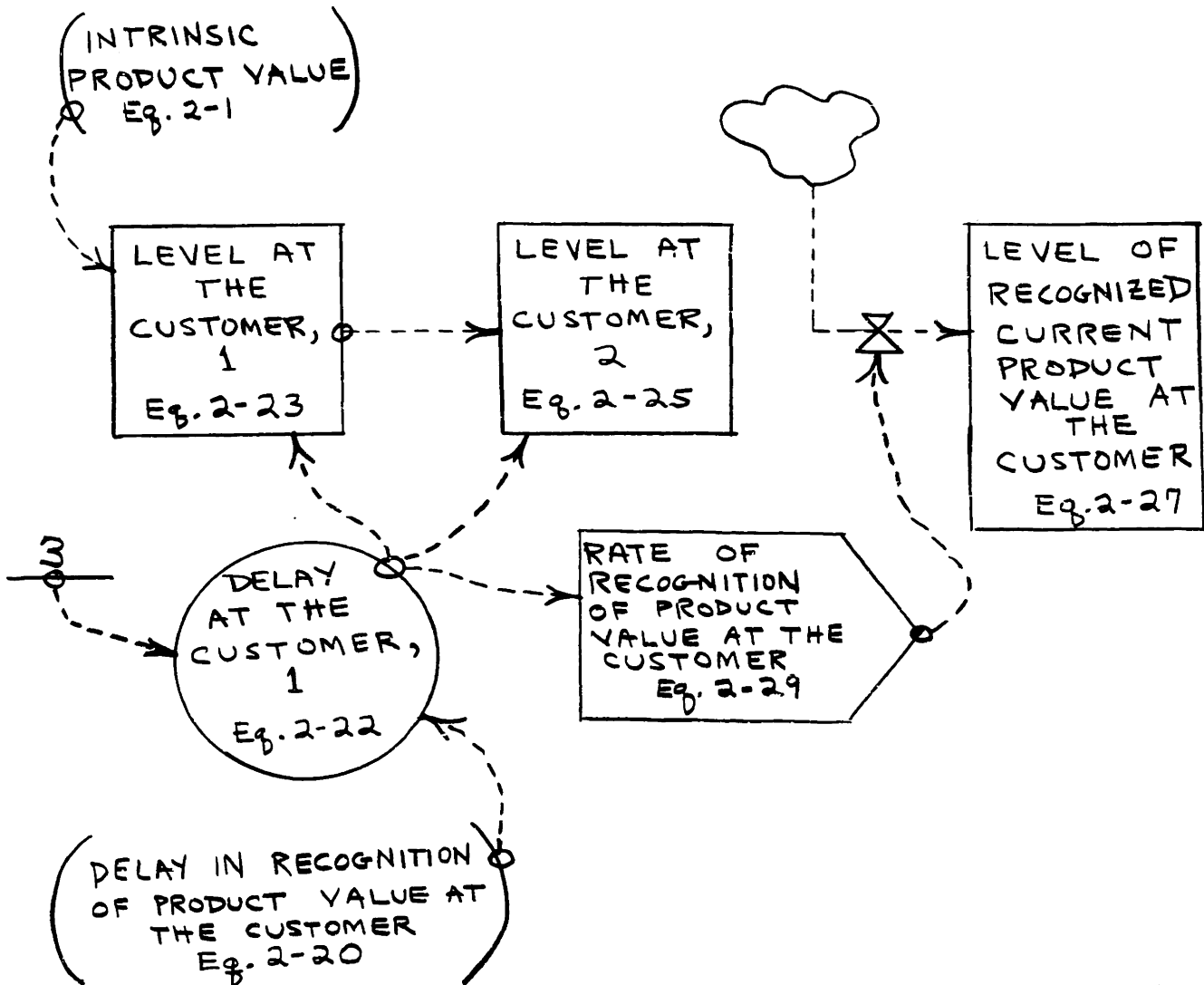


Figure 2-7 Information as to Product Value Being Communicated to the Customer

below takes one-third the value of DRPVC (Equation 2-20) for use in the three first-order information delays.

$$DC1.K = DRPVC.K/3$$

2-22, A

DC1--Delay at the Customer, 1 (months)

DRPVC--Delay in Recognition of Product Value at the Customer (months)

We can now define the three level equations needed to produce

the third-order lagged effect.

$$\text{LEVCl.K} = \text{LEVCl.J} + \left(\frac{\text{DT}}{\text{DCl.J}}\right)(\text{IPV.J} - \text{LEVCl.J}) \quad 2-23, \text{ L}$$

$$\text{LEVCl} = 0 \quad 2-24, \text{ N}$$

$$\text{LEVc2.K} = \text{LEVc2.J} + \left(\frac{\text{DT}}{\text{DCl.J}}\right)(\text{LEVCl.J} - \text{LEVc2.J}) \quad 2-25, \text{ L}$$

$$\text{LEVc2} = 0 \quad 2-26, \text{ N}$$

$$\text{LRPVC.K} = \text{LRPVC.J} + (\text{DT})(\text{RPVC.JK}) \quad 2-27, \text{ I}$$

$$\text{LRPVC} = 0 \quad 2-28, \text{ N}$$

LEVCl--LEVEl at the Customer, 1 (dollars)  
 DCl--Delay at the Customer, 1 (months)  
 IPV--Intrinsic Product Value (dollars)  
 LEVc2--LEVEl at the Customer, 2 (dollars)  
 LRPVC--Level of Recognized current Product Value at  
 the Customer (dollars)  
 RPVC--Rate of recognition of Product Value at the  
 Customer (dollars/month)

The rate of change of the recognized current product value at the customer makes LRPVC a first-order smoothing of LEVc2.

$$\text{RPVC.KL} = \frac{\text{LEVc2.K} - \text{LRPVC.K}}{\text{DCl.K}} \quad 2-29, \text{ R}$$

RPVC--Rate of recognition of Product Value at the  
 Customer (dollars/month)  
 LEVc2--LEVEl at the Customer, 2 (dollars)  
 LRPVC--Level of Recognized current Product Value at  
 the Customer (dollars)  
 DCl--Delay at the Customer, 1 (months)

The customer also becomes aware of the trend in his own recognition rate of new product value and takes this into account in his projection of the future value of the product under consideration. This is described below in Equations 2-30 through 2-33 which in turn correspond to the earlier Equations 2-12 through 2-15 which described these activities for the firm.

$$RPVSC.K = RPVSC.J + \left(\frac{DT}{DSRPV}\right)(RPVC.JK - RPVSC.J) \quad 2-30, L$$

$$RPVSC = 0 \quad 2-31, N$$

$$PPFVC.K = LRPVC.K + (RPVSC.K)(PHC) \quad 2-32, A$$

$$PHC = (PLPC)(WARC) \quad 2-33, N$$

RPVSC--Rate of recognition of Product Value,  
           Smoothed, at the Customer (dollars/month)  
 DSRPV--Delay in Smoothing Recognition rate for Product  
           Value (months)  
 RPVC--Rate of recognition of Product Value at the  
           Customer (dollars/month)  
 PFPVC--Projected Future Product Value of the Customer  
           (dollars)  
 LRPVC--Level of Recognized current Product Value of  
           the Customer (dollars)  
 PHC--Projection Horizon of the Customer (months)  
 PLPC--PLanning Period of the Customer (months)  
 WARC--Willingness to Accept Risk by the Customer  
           (percentage)

The above equation set shows that the customer projects the changes in his own beliefs as to product value into the future. He uses his level of recognized current product value as a base-line and extrapolates the smoothed average of his own rate of change of this recognition. The extrapolation period, or the projection horizon, of the customer is that fraction of his maximum planning period which his risk-taking propensity influences him to utilize.

The time period of reacting to changes in the customer's recognition rate, DSRPV, is taken as 3 months, just as was done for the firm. This means that the customer tends to respond to his recent perceptions and to quickly forget his earlier experiences. The customer is accustomed to having long lead-time requirements. His planning period therefore might well be longer than that of the firm. It is chosen here as being five years. Therefore,

$$PLPC = 60 \text{ months.}$$

Of course, the customer does not really commit himself to programs based on estimates that distant. His conservatism or relative unwillingness to accept risk, influences the customer to restrict his vision to nearer sights. The customer will be regarded as relatively cautious initially, suggesting a 50% value for the customer's willingness to accept risk.

$$\text{WARC} = 0.50 \text{ (decimal percentage)}$$

The projection of the trend in the customer's rate of recognition of product value leads to a different figure than the customer's previous estimate of future value. The customer therefore undergoes the same type of pressure as the firm to change his convictions as to the estimate of future product value. The gap between the projected value and the customer's previous commitment to an estimate of future value constitutes the force which will create the rate of change of the customer's commitment. As was done with the firm, the projected value is first limited to a positive range only before being used as an influence upon the rate of change of the customer's estimate of future product value. The fractional part of the gap between the projection and the previously committed estimate which enters as a change in the customer's estimate is determined by the customer's average delay in adjusting this value estimate.

$$\text{RCEVC.KL} = \frac{\text{UPPVC.K} - \text{EFPVC.K}}{\text{DAEVC}} \quad 2-34, \text{ R}$$

$$\text{UPPVC.K} = \text{MAX}(\text{PFPVC.K}, 0) \quad 2-35, \text{ A}$$

RCEVC--Rate of Change of Estimate of future Value at the Customer (dollars/month)  
 UPPVC--Used Projection of Product Value at the Customer (dollars)  
 EFPVC--Estimate of Future Product Value at the Customer (dollars)  
 DAEVC--Delay in Adjusting the Estimate of Value at the Customer (months)  
 MAX--a notation used by DYNAMO to indicate that the maximum of the two parameters named within the parentheses shall be used to determine the value of the variable, UPPVC  
 PFPVC--Projected Future Product Value at the Customer (dollars)

Due to the greater organizational complexity of the customer, relative to the firm, it is likely that his delay in adjusting value estimates is probably somewhat longer. We shall select a value of eight months, reserving the right, as before, to test the model with a much larger value later. Thus,

$$\text{DAEVC} = 8 \text{ months}$$

The final variable to be specified in this chapter is the actual estimate of future product value at the customer. This level is a simple integration of all the estimate changes which have taken place from the earliest embryonic phase of the project onward.

$$\text{EFPVC.K} = \text{EFPVC.J} + (\text{DT})(\text{RCEVC.JK}) \quad 2-36, \text{ L}$$

$$\text{EFPVC} = 0 \quad 2-37, \text{ N}$$

EFPVC--Estimate of Future Product Value at the Customer (dollars)  
 RCEVC--Rate of Change of Estimate of future Value at the Customer (dollars/month)

This completes the specifications of the model equations and parameters which correspond to the Chapter 2 text.



## CHAPTER III

### THE ESTIMATION OF PROJECT EFFORT AND COST

The second phase of activity to appear in research and development projects is the estimation of the effort required to complete the job. Following the procedure used in discussing the perception of the value of a product, this chapter shall proceed by first treating the underlying situation as related to the effort required to do the job. Then it will describe how the decision-makers in a research and development project, that is the customer and the developing firm, make their estimates of the effort needed.

#### The Underlying Determinants of Project Effort

Again, similar to the concept of intrinsic product value that was introduced in the earlier discussion, we shall now introduce the concept of the intrinsic size of the job. By this we mean that inherent in the development of any new product is some set of tasks, whose magnitude is defined by the nature of the product itself. There are, of course, many aspects to the product which create this magnitude of the job. They include the physical size of the job, the complexity of the product, the stringency of environmental requirements as demanded of the product, including of course the reliability that is expected of the product. The magnitude of effort required for an R and D project is reflected in the time needed for development. For example,

From conception to operational status in quantities, the time required for an entirely new aircraft design may vary from 4 to 8 years, depending on complexity and urgency. Fighters, for example, might reach

combat wings ready for combat in 4 years, whereas medium and heavy bombers may take as long as 8 years or more to reach operational status in quantity.<sup>1</sup>

In addition, whereas the intrinsic size of the task increases as complexity increases, the steady trend in military research and development has been towards heightened complexity. The curve below indicates the number of electronic parts being used in modern aircraft.<sup>2</sup> This indicates the trend in the sizes of research and development jobs.

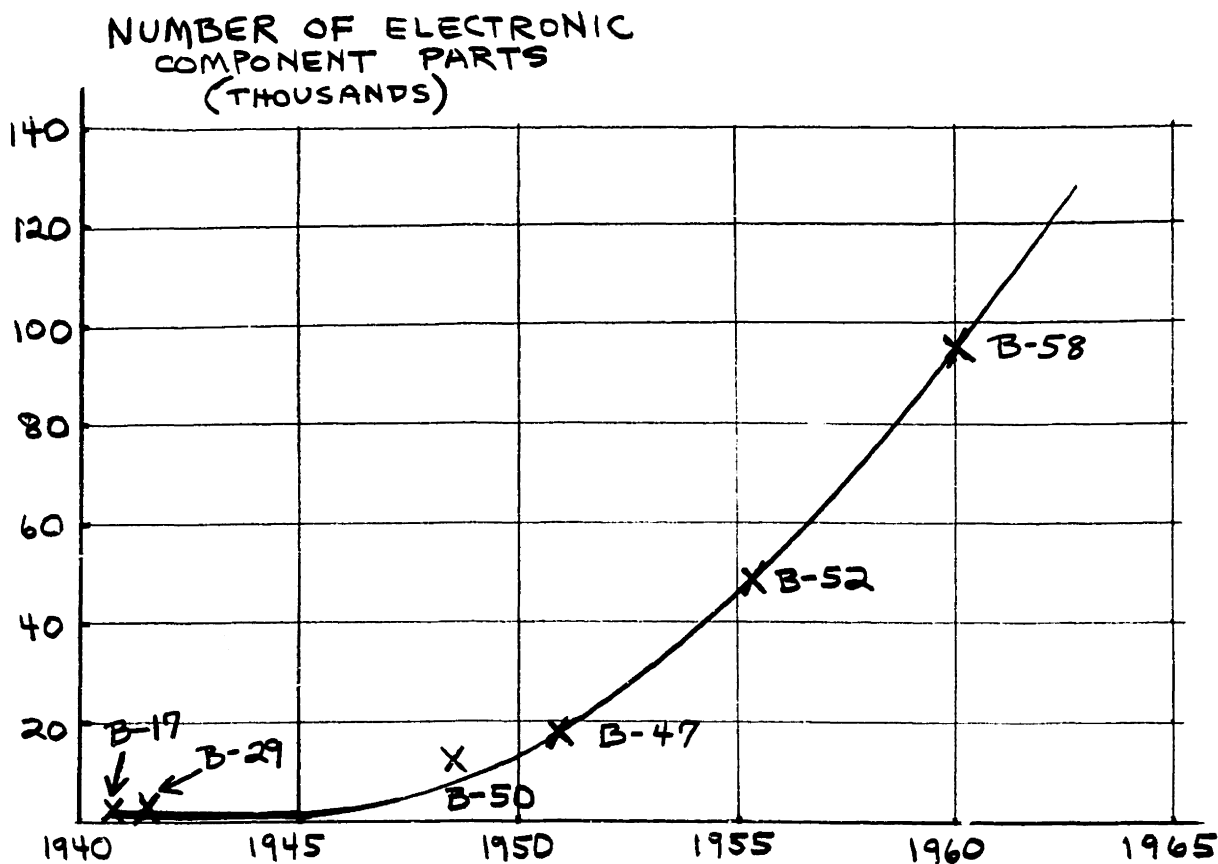


Figure 3-1 Trend in Product-Complexity

<sup>1</sup>Robert A. Bailey, "Application of Operations-Research Techniques to Air-Borne Weapon System Planning", Aeronautical Engineering Review, Vol. 13, No. 11 (October 1954), pp. 73-74.

<sup>2</sup>John E. Hickey, Jr., "What Price Reliability?" Electronic Industries, Vol. 20, No. 9 (September 1961), p. 142.

But given these factors as describing the nature of the end product desired, there is in fact a magnitude of task inherently associated with the nature of this job. This magnitude effectively describes the amount of efficient effort that would be required to translate existing know-how in the technical area of the product into an equipment design for the product. We ought to immediately recognize that one basic characteristic of the job is the amount of effort that would be required to design the end product even if all the product know-how needed to do this design were already in existence. But in fact, in the usual course of events in the research and development process, not only is it necessary to translate existing know-how into an equipment design but in fact, it is also necessary to develop the know-how itself.

This brings us to the second basic characteristic that determines the amount of effort that is optimally needed to develop a new product. The second characteristic is the available technological effectiveness, otherwise known as the state of the art. The state of the technological art at any given time is the amount of the then-available know-how which is necessary to design the product. The amount of effort that a firm has to invest into the accomplishment of the end result is dependent upon the extent to which it can make use of available technological know-how. Looked at from the opposite direction, the effort required of the firm depends on the extent to which it has to develop the technological know-how itself.

In the activity of invention, as in most goal-directed activities, the actor has a number of alternative paths amongst which he must choose. The greater his knowledge of the relevant fields the more likely he will be eventually to find a satisfactory path, and the fewer the expected

number of tried alternatives before a satisfactory one is found. Thus the greater the underlying knowledge, the lower the expected cost of making any particular invention.<sup>3</sup>

The important dynamic characteristic, therefore, that determines how much effort will have to be invested to develop a new product is this changing state of the technical art. The state of the art in any technological area is always changing in an increasing fashion, and as it changes the potential technological effectiveness of engineers working on the job is increasing. Figure 3-2 below illustrates what two different curves of potential technological effectiveness might look like. Each corresponds to what might be a different rate of growth of the

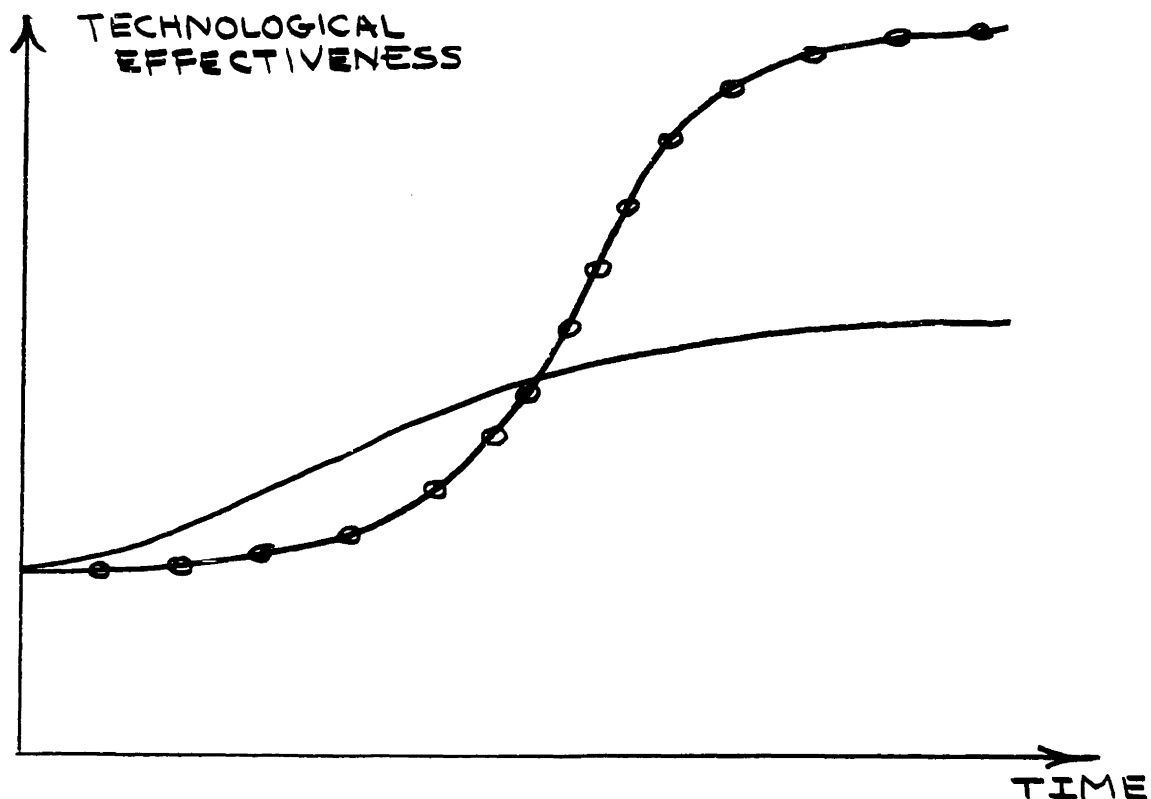


Figure 3-2 Comparative Curves of Technological Growth

<sup>3</sup>Richard R. Nelson, "The Simple Economics of Basic Scientific Research--A Theoretical Analysis", U.S. Air Force Project Rand Research Memorandum, P-1288 (April 28, 1958), pp. 6-7.

technological state of the art curve in the technical area related to the product under development. In the computer industry, for instance, the state of the art of computing technology apparent in the new products which became available to the computer user improved between 1950 and 1960 by an average factor of ten each year. These changes can be measured, for example, by the changes in cost per million arithmetic operations which accompanied the successive release of such machines as the IBM 604, 650, 701, 704, 709, and 7090. These advances in the end product reflect earlier changes in the state of the art of design knowledge available to the engineers who were working on the development of these new computers.

One can similarly point to the changes in the state of the art of any other technological area as factors reducing the effort requirements for new developments. Examples from two different fields were specified in recent testimony to the United States Senate Committee on Aeronautical and Space Sciences. In the general area of materials the Assistant Director of Research of NASA pointed out: "The next chart (...Progress in Strength of Materials) shows how the strength of materials has been improved over the years....Since, in most cases, we are talking about materials having a constant density, the weight of the material is inversely related to the strength of the metal--if we double the strength, we can cut the weight in half. Thus these new high-strength materials appear to be very attractive."<sup>4</sup>

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<sup>4</sup>Richard V. Rhodes, NASA Scientific and Technical Programs, Hearings before the Committee on Aeronautical and Space Sciences, United States Senate, February 28 and March 1, 1961 (Washington: U.S. Government Printing Office, 1961), pp. 421, 424.

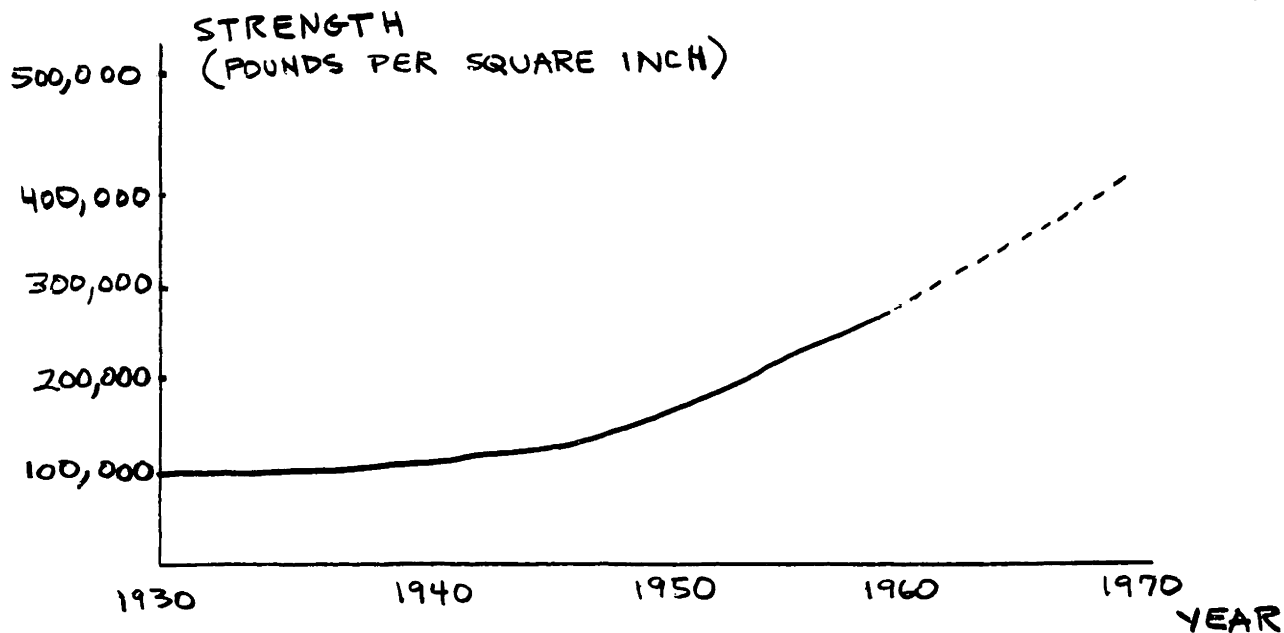


Figure 3-3 Progress in Strength of Materials

Their use can reduce the propulsion requirements of the booster vehicle or make the task of the design engineers less difficult by easing the weight restrictions on their configurations. A second participant in the hearings testified as to the increased payload capabilities expected from new more powerful rocket engines being developed. This technological advance in propulsion ability was said to have influence on reducing development effort required for payload designs. "This increase in payload size and weight capability will greatly assist the payload designers in their efforts to improve reliability, lower costs, and still include essential functions in their payloads."<sup>5</sup> Thus the level of technological effectiveness available in the existing state of the art is seen to be a dynamic factor which apparently is significant in all technical fields of product development.<sup>6</sup>

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<sup>5</sup>Col Donald H. Heaton, NASA Scientific and Technical Programs, Hearings, op. cit., p. 327.

<sup>6</sup>Here one of the distinctions between the real world and that world which is described by the traditional microeconomics appears very

The technological effectiveness potentially available in a given area of product development is of course dependent upon the accumulation of the previous growth of the state of the art, external to the firm that is itself doing the development of the new product. However, a lengthy delay is encountered by any firm in determining and then utilizing the current available level of technological know-how. First there is the delay in transmitting the new knowledge from the firms that have developed it to the firm which is in the position of applying it to a particular product development activity. This delay in transmitting new information is in part due to the secrecy or security restrictions on such communication, and is in part due to the desires of companies to preserve their own rights to information they have

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clearly. One of the fundamental notions of microeconomics is that of a static set of technological capabilities of the firm, which are represented by what is known as the firm's production function. This production function shows as a static quantity the maximum amount of product that a firm can produce given various quantities of production inputs. But in fact research and development activity in the real world is the process of developing the technological datum of the firm i.e., the technological basis of the firm's production function, to the point where a firm is effective enough to be able to produce products acceptable to the customer in terms of the cost and time required. In the same vein, the traditional microeconomics again ignores the fundamental basis of research and development and of technological effect in its usual treatment of the concept of technological external economies. In Bishop's text, he maintains, "Technological external economies are apt to be rather isolated and trivial."<sup>7</sup> And yet, in the field of research and development, the activities of one firm in a development project produce new know-how that in itself is used by other firms in their later development projects. The cost to develop new products is constantly being affected by the technological external economies which come about because of changes in the level of knowledge in a technological area or in a given industry. Here the effects of the external economies of the technological type are certainly not trivial nor are they isolated. They are the essence of every day life in the research and development area.

<sup>7</sup>Robert Bishop, Economic Analysis (unpublished manuscript of textbook), Book Two, Chapter I. p. 29.

developed. With respect to the problems due to secrecy, over-classification hampers progress because people are restricted from communicating with each other, thereby making the delay in transmitting new know-how much longer. The problem of "need to know" also hampers such transmittals. Many different agencies of the government may be requesting research and development work on projects which are essentially related in a technological fashion. But restriction of communication to only those people who have "need to know" on the particular project very often constrains engineers and scientists who are technologically in the same area, even within the same company, from communicating with each other. This often prevents the flow of developmental information which could improve the technological effectiveness of either or both of the parties to the potential communication.

A second, perhaps more important, influence on the delay in transmitting and using know-how developed outside of the firm's own activities is the "N.I.H. factor". The device or technique that was "Not Invented Here" inevitably seems to have basic flaws to the engineer or scientist working on the project. Resistance to change, reluctance to give up the old way of doing things, hesitation to accept a new approach, all relate to the psychological barriers which delay the communication and use of an advanced technology.

In addition to these two sources of delay, the delay in receiving information about changes in the state of the art is in part dependent upon the decision to allocate effort for acquiring such new knowledge. This decision tacitly manifests itself in the company manager's attitude toward permitting or encouraging workers to perform searches of the



literature before undertaking development activity in a new area. It shows up in the manager's willingness to allow his engineering personnel to attend scientific conferences in their areas of activity, and in his enthusiasm (or lack thereof) for having his engineering personnel take refresher courses at universities, participate in industrial symposia, or take part in other professional engineering societies and activities. The attitude of the manager towards using outside consultants also in part reflects his policy towards attempting to acquire outside technological know-how for application to the development of a new product. The engineer's own attitudes also determine his willingness to take time to learn from the outside. This time-allocation decision is influenced not only by rational considerations of the alternatives, but also by the individual's personal educational objectives, his ego, and by the N.I.H. factor mentioned above. These manifold policies and pressures determine in part the delay in acquiring for use in the company's R and D projects the new knowledge that has been developed outside of the firm's internal activities.

In addition to the delay in transmitting and receiving the new knowledge, there exists the usually much longer delay in absorbing the new know-how, in developing competence in the techniques, or experience with the new knowledge. To illustrate this in a simple fashion, we quickly recognize that it is totally inadequate to have read a book containing all the elements of good driving (either automobile or golf) skill. For before we can accomplish the driving we must absorb the knowledge that the book includes by developing experience in working with these particular skills. And so it is in the technological area of

developing new products. It takes a long time to adequately develop competence in handling something like solid fuels or in "growing" crystal materials. This type of "skills" information is extremely hard to transmit. The "art" is more difficult to acquire than the "science" and is not well conveyed by words. Thus, there is the lengthy time span from the initial development of a new idea in a technological area through to the time when that idea is ready for applicability. In fact each portion of this time period, the time delay for transmitting the knowledge, absorbing the knowledge, and acquiring experience in areas related to the knowledge, is usually quite lengthy.

Thus for a task with a given intrinsic job size, the key factor influencing the achievement of the end product is the accumulation of related know-how. With this as a background, it is easy to understand the discussion by Borgatta and Meyer of the nature of invention:

it is just to attribute important movements in inventions to individuals only in a qualified sense. The extraordinary individual works on the material and psychic fund already present and if the situation is not ripe neither is he ripe. From this standpoint we can understand it is almost never possible to attribute any great modern invention to any single person. When the state of the science and the social need reach a certain point, a number of persons are likely to solve the same problem.<sup>8</sup>

In a similar vein, Dr. Eberhardt Rechtin has said:

it is true of science in one sense that no great discoveries are made until the technology is ready

for them; and when that time comes, the discoveries are often made independently by a wide number of researchers. The underlying principles of physics presumably always have been the same; and yet, discovery of motions of the solar system had to await development of the telescope. Formulation of the laws of electromagnetism had to await development of simple electrical components first. Now the amount of science which can be accomplished in space must await the launching of larger and larger pay loads, better and better communications, guidance, control, etc.<sup>9</sup>

Finally, in still further concurrence with these viewpoints is a statement made by Karl Taylor Compton while he was President of M.I.T. "Anyone familiar with scientific literature realizes the enormous number of contributions, most of them small and not very significant, but each and all gradually raising the level of understanding in the storehouse of knowledge until finally the stage is reached at which a great scientific discovery or a mighty practical application can be made."<sup>10</sup>

In brief summary, all of the foregoing indicates that the amount of effort needed to accomplish a significant research and development task is dependent not only on the intrinsic size of the job, but also upon the available technology. As the technological state of the art increases, the ability of engineers and scientists to apply new knowledge to their particular development project increases; hence, their technical effectiveness increases, and the development effort required is reduced.

#### The Actual Estimation Process

Let us now turn to a discussion of how research and development

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<sup>9</sup>Dr. Eberhardt Rechtin, "Why the Space Race?", I.R.E. Student Quarterly, Vol. 7, No. 1 (May 1961), pp. 47-48.

<sup>10</sup>Karl Taylor Compton, A Scientist Speaks (Cambridge: M.I.T. Press, 1955), p. 62.

managers both in the developing firm and in the organization of the potential customer and user, go about estimating the amount of effort required in a particular research and development undertaking. This discussion will be broken into three basic areas. We shall first take up the problem of how the initial estimate of the size of the job is made, then we shall discuss the initial estimation of technological effectiveness on the job, and finally we shall discuss how revisions in both these estimates are made during the course of the project life.

### The Initial Estimate

In a recent report by McKinsey and Company, one of the nation's largest consulting firms, to a major government research and development sponsoring agency, the consulting firm said the following about the problem of estimating project effort requirements: "No unerring formula can be used to estimate the total number of man-years required to carry out a given project in terms of (a) supporting research, (b) development of subsystems and components, (c) staffing of project-management teams, and (e) technical and administrative support for each of these activities."<sup>11</sup> This kind of general statement reflects the inherent nature of research and development. The exact character of an R and D task is indefinite, the specific technical requirements are uncertain, and the abilities of people to perform in areas of advancing technology are even less specifically known. Thus the initial estimates of the amount of effort required to do a research and development job

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<sup>11</sup> McKinsey and Company, Inc., An Evaluation of NASA's Contract Policies, Organization and Performance (Washington: National Aeronautics and Space Administration, 1960), p. 2-19.

are largely determined by factors other than the "real underlying facts of the situation", regardless of the degree of detail used in outlining the project tasks or the planned milestone accomplishment, or even in defining elements of the so-called "development network" for use with currently popular techniques, such as PERT.

In making its initial estimate of the intrinsic size of a research and development task, the firm and/or the customer is influenced by the relationship of its previous job experience to the size of the project under consideration, as well as its general overall managerial and technical ability. Enlarging on the first influencing force, we should recall that each job has been defined as having an intrinsic underlying job size. The company whose experience has included jobs of this magnitude will be far more capable of estimating correctly the scope of the anticipated undertaking than will other firms which have not had any experience with this size of job. To the extent that the experience of the customer or the firm has been with larger or smaller jobs than the one under consideration its initial estimate of the scope of the R and D task will be biased. That is, the company which has on the average handled larger jobs in the past will probably from its experience tend towards over-estimating the size of the current job. This is inherent in the estimation process because of the indefinite nature of research and development contracts.

"Traditionally, R and D estimates have been made by comparing the job at hand with jobs previously completed."<sup>12</sup> If a company's past experience

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<sup>12</sup> Peter V. Norden, "Curve Fitting for a Model of Applied R and D Scheduling", IBM Journal of Research and Development, Vol. 2, No. 3 (July 1958), p.

has lead it to believe that a certain method of approach of managing the job has turned out to be successful, it will generally think that this same method of approach should be applied to future projects. The company which has handled large jobs will have acquired experiences in which for the most part the degree of planning and organization for the conduct of activity tends to be large. Such a company will regard other jobs as being best managed by the same approach. The firm will thereby attribute as part of the effort the need for a major planning and organizational activity. If the actual job under consideration is intrinsically smaller than those which the company has handled in the past, one which does not require the same degree of planning and organization, then the company will tend towards over-estimating the size of the job. In fact, if the company is granted the contract, the way in which it will go about managing the activity will no doubt produce a job that in fact is larger in its total effort outlay than was necessary.

The same kind of behavior is true of the customer organization. An old armed forces adage said that in running an operation you needed cooks for the drivers and drivers for the cooks". A highly placed expert on the DEW (Distant Early Warning) line said that the Air Force had estimated the cost of an early warning system at forty billion dollars. Such a cost might in fact have been realistic for the Air Force's staffing estimate of 300 men per base. However, a specially-convened summer study group in 1952 recommended that the DEW line be staffed with twelve men per base. The system actually ended up utilizing fifteen men per base. The Air Force's experiences, or perhaps the traditional practice

to which the adage above referred, led it to this major over-estimation of job magnitude and cost.

Similarly, a company whose experiences have largely been with jobs that are much smaller in size will have a tendency due to its experience of underestimating the overall scope of the job. Such a company will probably have difficulty in recognizing the magnitude of the task before them. It will probably not understand the necessary requirement of initial organization and preplanning which is characteristic of a large undertaking. Thus the company whose experiences have been with smaller jobs in the past will be influenced to underestimate the size of the job.

Another variable affecting the nature of bias in effort estimations, more general than the influence of the company's past experience, is an overriding tendency to underestimate all jobs. This comes about due to the motivations of the customer to see a job as being relatively inexpensive, that is to recognize the job as being within the realm of economic feasibility. It comes about because the firm has a tendency to underestimate the scope of the job in its hopefulness that the customer will undertake the task and that the firm itself will be able to acquire the contract. On the basis of its pioneering attempt to analyze the results of twenty-two Air Force contracts, the Rand Corporation reported the following opinion as to the reason for these underestimations.

The optimistic bias is not hard to understand. Contractors are anxious to have their proposals accepted by the military, and the military itself is anxious to have developmental proposals supported by the Department of Defense and Congress. The incentive to make optimistic estimates is thus very strong. On the other hand, the contractual

penalties for having been over-optimistic are generally small.<sup>13</sup>

Thus we might say that before the job has been started there is a general tendency for both the contractor and the military agency to underestimate the over-all scope of the job. On the other hand the relative experience of the company and of the customer, in terms of the sizes of the jobs that they have undertaken in the past, will add a further bias to the nature of their initial estimates of the size of the job.

Interacting with both of these tendencies towards distortion of the estimation of the intrinsic job size is the managerial and technical quality of the firm or customer itself. Despite the fact that tendencies exist towards biasing estimates of job size in one direction or another the competent firm is by definition less likely to be swayed by these tendencies. Influenced by the same basic tendencies due to general psychological considerations and/or previous job-size experience, the less competent firm will tend to be further off in its estimates of the job size than the company whose managerial and technical capabilities are high.

One writer comments on this factor as follows:

Some persons wishing to "look good", consciously or unconsciously, inevitably underestimate the potential value of their proposed project. On the other hand, there are incurable optimists who think that they can produce results worth millions, at very low cost, in a very short time. A successful research and development executive is someone who

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<sup>13</sup>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.



can take the estimates given him by his staff, and by knowledge of the individuals, of the type of work to be undertaken, etc., can derive a "truthified" version (in view of later, actual results) of the estimates.<sup>14</sup>

These three factors then combine to produce the initial estimate of the size of the job: 1) the general over-all tendency to underestimate the job size; 2) the relationship of the previous job-size experience of the firm or the customer to the current project's intrinsic job size; and 3) the over-all managerial and technical quality of the firm or customer agency.

This estimate of the intrinsic size of the job is only one of the two inputs to the initial estimate of the total amount of effort that will be needed to get the job done. Earlier discussion pointed out the importance of estimating the amount of technical effectiveness that is currently available or which will potentially become available for application to the job. This means that the estimating organization has to attempt to evaluate how efficient or effective their engineers and scientists will be on the particular research and development project being considered. To do this the organization must not only think about the amount of technical knowledge that is currently available. It must also assess the rate of growth of the technical state of the art and try to guess at the future growth of know-how which will be available for application to the job under consideration.

In initially estimating the current effectiveness of engineers

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<sup>14</sup>Raoul J. Freeman, "A Stochastic Model for Determining the Size and Allocation of the Research Budget", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 3.

working in the firm, there are two principle influencing forces at work. First of course is the actual effectiveness of the producing engineers and second is the attitude of optimism or confidence of the firm or of the customer. The actual effectiveness of engineers working for the firm will be discussed in a later chapter discussing engineering productivity. Initially, i.e., before work on the project as a project has begun the engineering effectiveness of relevance here is that of engineers believed to be available within or outside of the R and D company. The principle task to be discussed now is the estimation of the effectiveness of engineers in the contemplated project. Thus we are discussing how people estimate the effectiveness of applying men of given initial skills and knowledge to solving unknowns in the anticipated research and development tasks. The estimators no doubt start with an aura of uncertainty as to what is the state of technology in the related problem area. This lack of certainty regarding the exact details for solving the particular R and D problem leads most estimators to underestimate the technology that is initially available, especially within the available work force, and hence leads to underestimating the current technological effectiveness of the engineers. Of course this underestimation (or alternately, overestimation) depends on the degree of optimism of the firm or customer and upon the confidence in the firm's engineering talents. Thus while we earlier maintained that in general a strong tendency exists to underestimate existing engineering effectiveness in the contemplated problem. The two hypotheses act in opposite directions and would tend, in and of themselves, to cancel each other out. We will soon see how

other factors contribute to the errors commonly observed in R and D effort estimates.

The second factor determining the initial estimate of technological effectiveness is the estimate of the future changes in the state of the art which will be able to be used in the contemplated project. This is largely dependent on the related technological progress observed by the customer or firm and the organization's relative optimism as to the continuation of this progress rate. If, for example, a firm is considering a project in an area where break-throughs and advances in techniques have been occurring steadily, it no doubt will assume that such events will continue. Thus it will estimate the future technological effectiveness of its engineering force as being much greater than the engineers' current capabilities in the new product area under study.

A good example of this typical practice of progress curve extrapolation is shown in a thorough discussion in 1953 of British aircraft engine development. "There is [pictured] a series of curves showing British progress in the last decade and what may be expected by 1960.... These curves are self-explanatory, indicating a steady improvement in engine performance during the last 10 years."<sup>15</sup> Several of the curves depicted are shown below. What is of particular interest is the obvious fact that in no case does the anticipated technology do other than extend the trend lines of past progress--no radical departures in the rate of advance of state or art, not even any signs of nonlinearities due to such commonplace effects as diminishing rate of returns. These curves

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<sup>15</sup>F. R. Banks, "The Birth of an Engine", Aeronautical Engineering Review, Vol. 12, No. 6, (June 1953), pp. 40-41.

SPECIFIC WEIGHT (LB. WT./LB. THRUST)  
and  
FUEL CONSUMPTION (LB./LB. THRUST/HR.)

98

THRUST  
(LBS.)

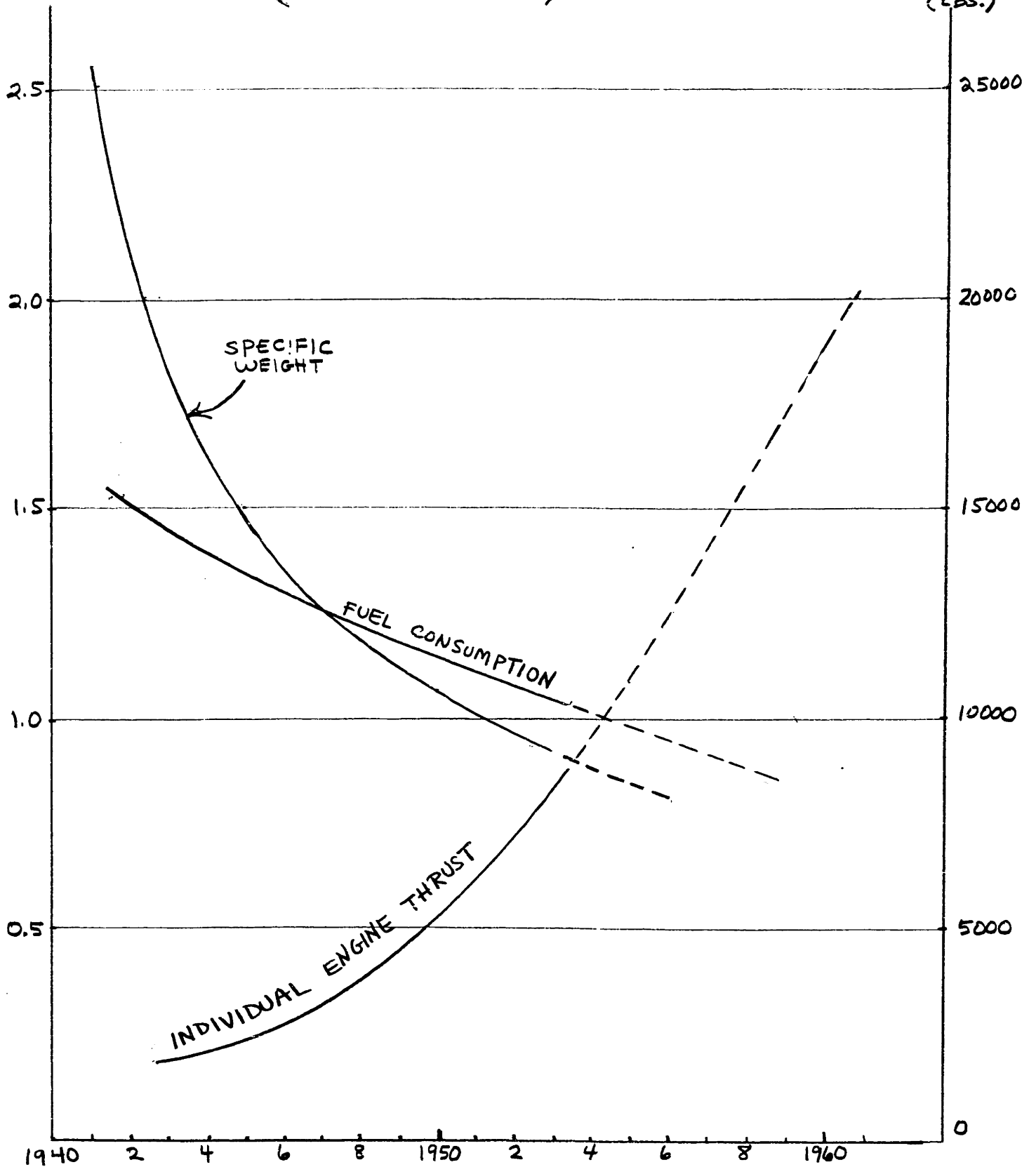


Figure 3-4 Extrapolated Technological Progress Curves

lend weight to the assertion that the usual practice in forecasting technological effectiveness is that of continuing the observed or believed progress trend lines. Ellis Johnson, a veteran of many studies of military planning problems, confirmed these observations. He said, "The technical forecast...for any particular time frame is based on existing trends in their relation to the values and objectives chosen, and it makes a prognosis of situations that may arise in a future period if these trends continue."<sup>16</sup> The extrapolation shown in the curve of Figure 3-3 (page ) still further supports this contention. Only in cases of extreme optimism or pessimism does it seem likely that deviations would tend to occur in such estimating methods.

Let us now summarize this discussion on the initial pre-start determination of estimates of effort required to do an R and D project. It was pointed out that the estimate of effort is based on (1) an estimate of job size and (2) an estimate of technological effectiveness. The prime influences on the firm or customer's ability to estimate job size correctly were a general psychologically-based tendency towards underestimation, the relatedness of previous job-size experience to the contemplated project, and the over-all managerial and technical quality of the organization. The estimate of the technological effectiveness that engineers will be able to apply during the project life cycle is based on the believed current "efficiency rating"

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<sup>16</sup>Ellis A Johnson, "The Crisis in Science and Technology and its Effects on Military Development", Operations Research, Vol. , No. (January - February 1958), p.

of the engineers and the expected changes in this efficiency. These factors in turn depend upon the actual level and historical rate of progress of the applicable technology and the optimism and confidence of the customer and/or the firm in the ability of the engineers to utilize these potentialities and in their expectations of continuation of progress advancements.

#### Revisions in the Effort Estimates

All of the above has described the process of effort estimation which takes place prior to the firm's initiation of much engineering work on the project. But the passage of time and the new experiences produced by the work process provide new inputs to both firm and customer, upon which information they base their revisions in the estimates of effort requirements. This section will look into the factors determining these estimate revisions during the project life. Let us look at the reasons behind modifications in the estimates of the first input to the effort requirements, namely, the basic size of the job. Based on their assumptions of the technical capabilities of the engineering staff, the customer and the firm establish an estimated schedule of completion of tasks, problems, milestones, program elements, or what-have-you within the over-all project. Thus for the assumed effectiveness level, the total engineering effort applied up to any point in time had an expected and scheduled percent-of-job completion. In addition to referring to this previous schedule, however, both organizations continually assess the progress actually made up to that point in time. (The way they estimate the project progress is discussed in Chapter 6.) To the extent that an organization can recognize its

anticipated schedule as deviating from its current beliefs as to actual progress on the job, the organization can modify its earlier estimate of the size of the job. An important question is whether the organization responds to such a gap quickly or not. Usually the degree of responsiveness is a function of how far along in the project the organization is or believes it is. In the early phases of the project not only is it difficult to determine the existence of gaps between the scheduled and the believed actual progress, but moreover it is easier psychologically to blame the gap on "initial organizing problems" or on some other excuse than it is to revise the estimate of job magnitude. However, later in the job such gaps in progress begin to become more obvious, and are harder psychologically to ignore. Thus as the project evolves in time the significance of these estimation errors becomes greater. Recognition of their significance results in changed size-of-job estimates.

But if this recognized gap between scheduled and believed actual progress causes revisions in the estimates of job size, what other factors cause revisions in the estimates of the technological effectiveness that will, in the course of the project, be applied to getting the job done? First, of course, are the observed changes in related technology and the attitudes towards expecting the continuation of such advances. These two factors were discussed thoroughly in earlier pages which described the initial estimate of future technological effectiveness, and the arguments need not be repeated here. More important is the contribution to revisions of the effectiveness estimates that results from belated recognition of the gap between believed accomplishment and actual accomplishment. Note the difference in concepts between

this paragraph and the preceding one. Typically at some mid-point of the project life cycle, we could argue that the scheduled (or anticipated) progress exceeds the believed (or currently estimated) progress, which in turn probably exceeds the actual progress. The gap between the first two measures was discussed in the last paragraph on job-size estimates, while it is here maintained that the gap between the latter two factors influences revisions in the estimates of engineering effectiveness. When something happens in the project to demand recognition of this gap between the believed and the actual level of project achievement, e.g. the missile engine blows up on the launch pad, both firm and customer are influenced to revise their previously-held estimates of the technological effectiveness of the engineering work-force. The delays in making these revisions, too, are dependent on the organization's characteristics, and on how far along in the project they are. The argument made earlier holds here, also, since during the early stages of a project it is extremely difficult to become aware of gross technical errors which might stimulate revisions in the effectiveness estimates. The product model-building, fabrication, pilot assembly, or testing, all of which occur during later phases of a project life, produce the tangible evidences which usually force recognition of unexpected inefficiencies (or much less likely, vice versa).

#### Cost Estimation

The preceding portion of this chapter has concerned itself with the bases for effort requirements in an R and D project and with the way in which these requirements are estimated by the firm and the potential



customer. But in making a decision as to the advisability of a particular research and development undertaking, the customer explicitly takes into account the expected dollar cost of the project, if for no other reason, because the budgetary limitations on the contracting agency are expressed in dollar terms. Thus, it is necessary at all stages of an R and D project to go from the effort requirement described earlier to a cost requirement. However, despite the fact that inputs other than labor, e.g. materials, machines, facilities, enter into the productive process of research and development, the prime ingredient, even from a dollar viewpoint, is engineering and scientific manpower. After analyzing several R and D projects at IBM, Norden reported, "Costs of materials, tools, test equipment, and purchases, etc., do not seem to have a functional relationship to the difficulty of the project."<sup>17</sup> Furthering this finding is Asher's report of a Rand study.

Materials cost in the case of engineering [i.e., the R and D phase for an aircraft project] is usually small. Engineering cost is essentially the labor cost of engineers, draftsmen, and other skilled technical personnel and the overhead necessary to support these people. In the case of cost-plus-fixed-fee (CPFF) contracts [the usual R and D contractual arrangement],...the contractors are reimbursed for overhead cost...by applying the negotiated fixed overhead rates to the actual direct-labor dollars charged to the contract.<sup>18</sup>

Both of these references point to the effort requirement as being

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<sup>17</sup>Norden, "Curve Fitting for a Model of Applied R and D Scheduling"; op.cit., p.

<sup>18</sup>Harold Asher, "Cost-Quantity Relationships in the Airframe Industry", Project Rand Report, R-291, July 1, 1956, p.

the major determinant of project cost. This conclusion seems to have been found also in many economic surveys of research and development activities in various industries. These studies almost uniformly summarize their findings as to R and D cost by citing an average annual dollar R and D cost per engineer. For example, the following situation was acted by two engineers in their report on R and D cost estimation practices:

Past experience has shown this company that all engineering facilitating activities (computers, draftmen, supplies, test equipment, etc.) may be prorated and considered in the cost of one engineer. For example, on the average, in this company it costs approximately \$30,000 per year for one engineer and all of the facilitating activities that are required for his support.

It is interesting to note that the figure \$30,000 was developed intuitively from experience. However, another large corporation which is known to the writers and which does hundreds of millions of dollars of work for the government each year uses the same system. Their figure is derived from detailed cost analysis and is correlated with current economic indicators. Their figure for the same time period was \$27,000.<sup>19</sup>

This type of "dollars-per-man" assumption seems adequate for most purposes in project budgeting, and this practice is apparently used extensively in industry.<sup>20</sup> Thus some average relationship between effort

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<sup>19</sup>Vernon L. Lambert and Hubert F. Sackett, "Research and Development Cost Estimation", IRE Transactions on Engineering Management, Vol. EM-6, No. 1 (March 1959), p. 10.

<sup>20</sup>See, for example, the report of the Booz, Allen, and Hamilton field surveys on research and development activity: Wilson C. Randle, "The Problems of R and D Management", Harvard Business Review, Vol. 37, No. 1, (January-February 1959), p. 132. The National Science Foundation has collected information on the costs of R and D on this "per-engineer" basis for the various industries in the United States. A good reference source for this data is: National Science Foundation, Funds for Research and Development in Industry, 195 (Washington: United States Government Printing Office, 196 ), p. .

required and cost is utilized both initially, prior to the project's "formal" start, and throughout the project life cycle. The cost estimates are of course subject to the same kinds of errors that were indicated in the discussion of effort estimation: the "natural" tendency to underestimate, the effect of previous experiences with projects of similar scope; and, modifying these other influences, the fact that all the estimates necessarily reflect subjective evaluations whose accuracy depends on the managerial and technical ability of the organization. Lambert and Sackett, quoted above, report from their survey study, "All the companies contacted had one thing in common in their engineering cost estimation procedure, this being judgment based on experience. All organizations interviewed agreed that the ability of the men who do the actual estimating is of prime importance."<sup>21</sup> To be effective the estimators at least have to possess reasonably valid beliefs as to the nature of the problems to be encountered, the extent of difficulty involved in their solution, and the approximate number of people, materials, computer time, etc., required to achieve the solutions. This task requires extraordinary competence combined with elements of strong intuitive insight and applicable experience.

The cost estimates thus formed are held internally by the customer and the firm separately, and may differ noticeably from the cost figures used in the contracting process. But this problem is better discussed in the next chapter.

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<sup>21</sup>Lambert and Sackett, loc. cit.

### Past Experiences in the Estimation of Effort and Cost

This chapter has thus far pointed out (1) the underlying determinants of optimal effort and cost in a research and development project, and (2) the main factors influencing the way individuals make estimates of the real resource need for such a job. The demand for such a discussion of the fundamental aspects of resource requirements in research and development arises from the problems which exist in this estimation area. One need not go far to find evidence of this kind of problem in research and development projects. First of all any research and development manager can speak from his own experiences of the great difficulties improperly estimating the amount of effort which will be required to successfully complete the development.

On a less subjective basis, some tangible evidence exists to back up this above statement about the general experiences of R and D managers. A Rand Corporation report cited earlier documented a major effort which attempted to gather data on and analyze the military's experiences in product development.<sup>22</sup> On each of twenty-two major items of Air Force equipment the authors calculated the ratio of the latest available estimate of the average cost of production of such equipment to the earliest such estimate that could be found. Of the twenty-two projects examined, two were found in which the predicted average costs were correct. The other twenty projects incurred costs which differed from their initial estimates by amounts ranging from 20 per cent to 5,760 per cent greater than the initial cost

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<sup>22</sup> Marshall and Meckling, op. cit., p. 11.

estimate. Examining the figures by class of project, in nine aircraft fighter development projects the cost estimates were found to be off by an average of 240 per cent. In three bomber projects the estimates were off by 450 per cent. In four projects aimed at developing and producing cargo and tanker aircraft the average estimate was off by a mere 30 per cent. Finally, in six missile projects the estimates were found to be off by 1,710 per cent. In this last case even if one excludes the particular exceptional project mentioned earlier which was off by a factor of 5,760 per cent in its cost estimation, the other five missile projects still erred in their estimates by 900 per cent. In summarizing their analysis of this data, the authors said,

The data presented above are neither as comprehensive nor as unambiguous as one would like. Nevertheless, they do give a reasonably accurate picture of recent experience with predicting the outcome of development projects. The truth is that estimates have been quite inaccurate. Cost increases on the order of 200 per cent to 300 per cent and extensions of development time by a third to a half are not the exception, but the rule. In addition, the size of the error in estimates has varied widely from one weapon to another.<sup>23</sup>

Reporting a similar RAND study of slippages in development schedules, Klein and Meckling stated:

Out of thirteen [aircraft] engines studied, four passed the 50-hour [acceptance] test 2-4 years later than the date estimated when development was begun; another four were 1-2 years late in passing the test; while five completed the test within twelve months of the estimated time of completion...The development of electronic equipment appears to be even less predictable than the development of aircraft engines. Types of airborne electronic equipment whose development initially

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<sup>23</sup>Ibid., pp. 21-22.

appear to present the same order of technical difficulty are not uncommonly 3-5 years apart in reaching an acceptable standard of operational usefulness and reliability.<sup>24</sup>

To further support this already strong evidence produced by the RAND Corporation, a former Chief Scientist of the United States Air Force said in a recent informal talk that a 1955 survey of 300 military research and development projects pointed out the fact that only one contract out of the 300 had been done in the initially estimated time. More than 50 per cent of the contracts took over twice the initial estimated time to complete, more than a third took over three times as long to do as had been earlier anticipated, with the data consistently indicating this type of pattern extending out to projects which required ten times as long to complete as had initially been estimated. He further remarked that the record of costs incurred in such projects showed a similar relationship to their initial estimates as did these records of the completion times.<sup>25</sup>

The records thus speak out very clearly--we have historically found major difficulties in estimating the amount of effort that will be required to successfully complete a project undertaking. The data sighted here is even biased to the extent that it generally comes from projects which were in fact completed, excluding the many projects which have never reached completion. Of course many of these latter

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<sup>24</sup>Burton Klein, and William Meckling, "Application of Operations Research to Development Decisions", Operations Research, (May-June 1958), p

<sup>25</sup>Guyford H. Stever, informal talk to M.I.T. Seminar on Research and Development for Military Purposes, February 15, 1961.

cases were cancelled because of the exorbitant cost and effort that was discovered to be required for completion of the project goal. Such awakenings often take place after much time and money have already been spent to develop the end product with but little or no side benefits to compensate for such expenditures.

The phases of underlying project activity considered in these past two chapters, the perception of value, and the estimation of effort and cost requirements, have dealt largely with influences provided intrinsically from the product environment; and from the psychological and experience-based characteristics of the R and D firm and customer organizations. Many problems for research and development management have already been described. The next chapter will begin to recognize how the more overt policies by the customer and firm combine with these other characteristics to make still more complex the inter-relationships between research and development activities.

## APPENDIX TO CHAPTER III

As was done in the Appendix to Chapter II, we shall in this appendix indicate the appropriate flow diagrams and equations which describe the material covered in the preceding text. The first diagram, Figure 3-5, includes those factors related to the development of the estimate (by either the firm or the customer) of the job. At the top of the diagram, we see indicated the fact that the real world product requirements define the intrinsic size of the job, i.e., that level of advanced know-how which is needed for the development of the product. This is a basic input to the initial job size estimate of either the firm or the customer. We have labelled this estimate the "believed needed know-how for the development of the product". However, both organizations in their estimating procedures are influenced by factors other than the real job size. These other factors include the estimation bias due to their past experiences, the general tendency to underestimate the complexity of a job, and the technical and managerial ability of the organization, all of which affect the initial estimate of job size. This initial estimate then provides a starting point for the organization's continuous redetermination of job size, i.e., needed product know-how, throughout the life cycle of the product. During the project life cycle, changes are made in this initial job-size estimate as required by the organization's response to gaps which it detects in the scheduled engineering accomplishment. These gaps exist between the scheduled percentage completion of the job, as based upon the amount of engineering effort that has been put into the task and the organization's estimate of the current



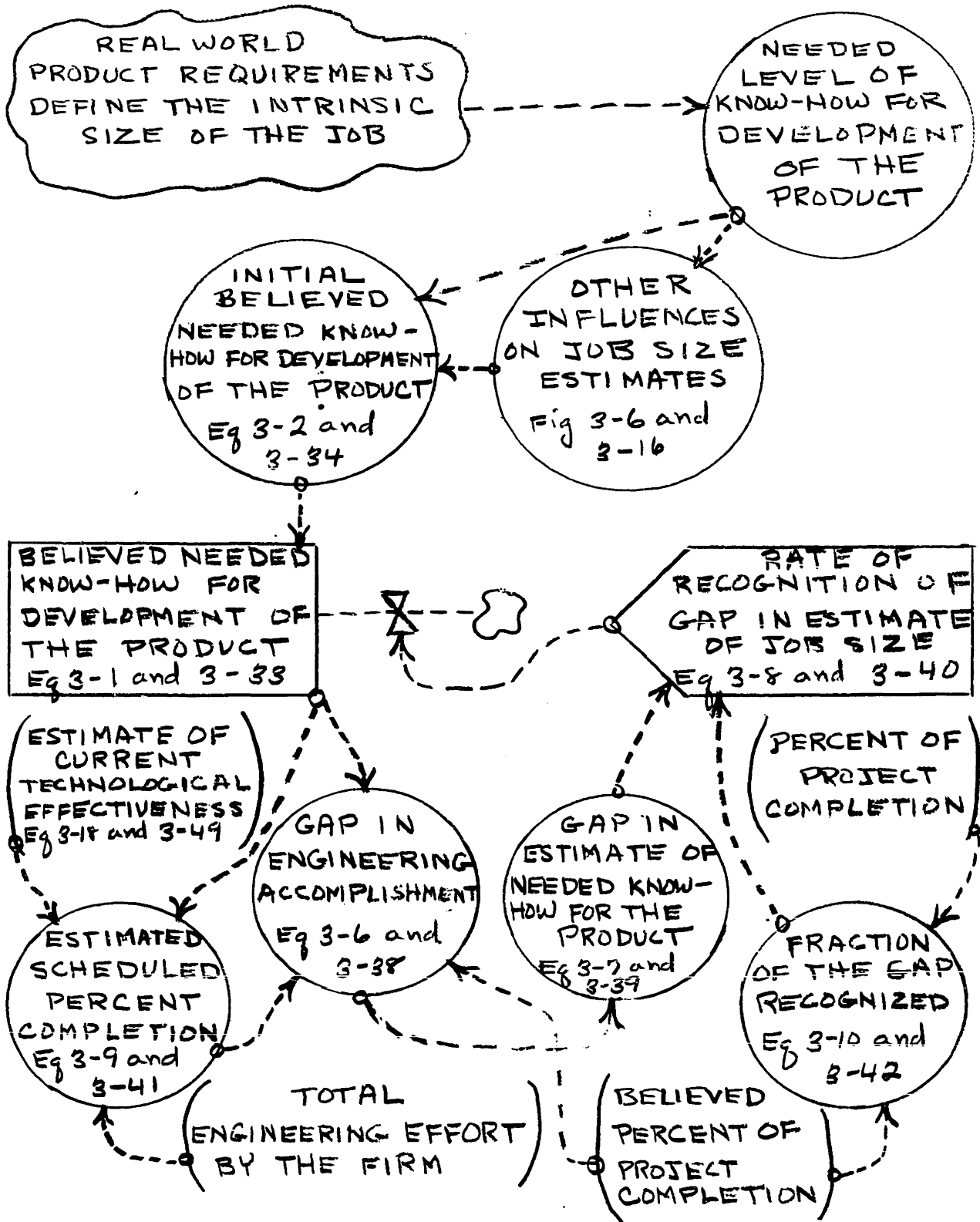


Figure 3-5 Estimate of Job Size

effectiveness of this effort, and, contrasted to this, the organization's over-all estimate of the believed percentage completion of the project to date. The fraction of this gap which is recognized at any time and taken into account in changing the existing estimate of job size is dependent upon the stage that the project is in. As was explained in the earlier parts of this chapter, during the early phases of the project it is very difficult to recognize any errors in the schedule. This task, however, becomes somewhat less difficult as the project advances towards completion.

We shall begin by listing the equations for the firm. Its estimate of the job size may be described by a level equation. This equation states simply that the firm's current belief as to the know-how needed for development of the product is what it believed before plus any changes from its previous estimate.

$$\text{BNKPF.K} = \text{BNKPF.J} + (\text{DT}) (\text{RGEJF.JK}) \quad 3-1, \text{ L}$$

BNKPF--Believed Needed Know-how for development of the Product by the Firm (effective man-months of effort)

RGEJF--Rate of recognition of Gap in Estimate of Job size at the Firm (effective man-months/month)

Initially, before the firm's experiences on the project have become the key determinants of this job-size estimate, other factors create the firm's beliefs. These influences determine the extent to which the firm's initial size estimate will err from the intrinsic size of the product development job. Thus the initial condition equation below states that the believed needed know-how for the product is the intrinsic needed know-how multiplied by a modifying factor, discussed on the next page, which includes the error-producing effects of such factors as experience, ability,

and environment.

BNKPF = (MSEF) (NLKP)

3-2, N

BNKPF--Believed Needed Know-how for development of the Product by the Firm (effective man-months of effort).

MSEF--Modifier of the job Size Estimate of the Firm (percentage)

NLKP--Needed Level of Know-how for development of the Product (effective man-months of effort)

The constant NLKP specifies for any given project simulation the amount of effective engineering effort required to develop the product. This is an input characteristic of the product and will of course be changed in many simulation runs to test the effect of different job sizes on project outcomes. NLKP is the measure of built-in scope and complexity of the job. It is stated in terms of effective effort rather actual effort. If, for example, engineers working on the project average a twenty percent effectiveness, then the actual total effort needed to complete the project will be five times NLKP: an average effectiveness of fifty percent will require twice NLKP, and so on. Initially let us start with NLKP = 6000 effective man-months of effort. This means the job size calls for 500 effective man-years of engineering work. Figuring, for instance, on an average effectiveness of 25 percent, 2000 man-years of engineering would be needed to complete the product development. At an average of \$30,000 per engineering man-year of work (including supporting personnel), a cost requirement of about 60 million dollars is indicated. This gives a "ball-park" idea of the size undertakings that are to be considered in this undertaking.

The factors which cause the firm to make errors in its attempts to estimate NLKP are shown in the next diagram. Figure 3-6 indicates

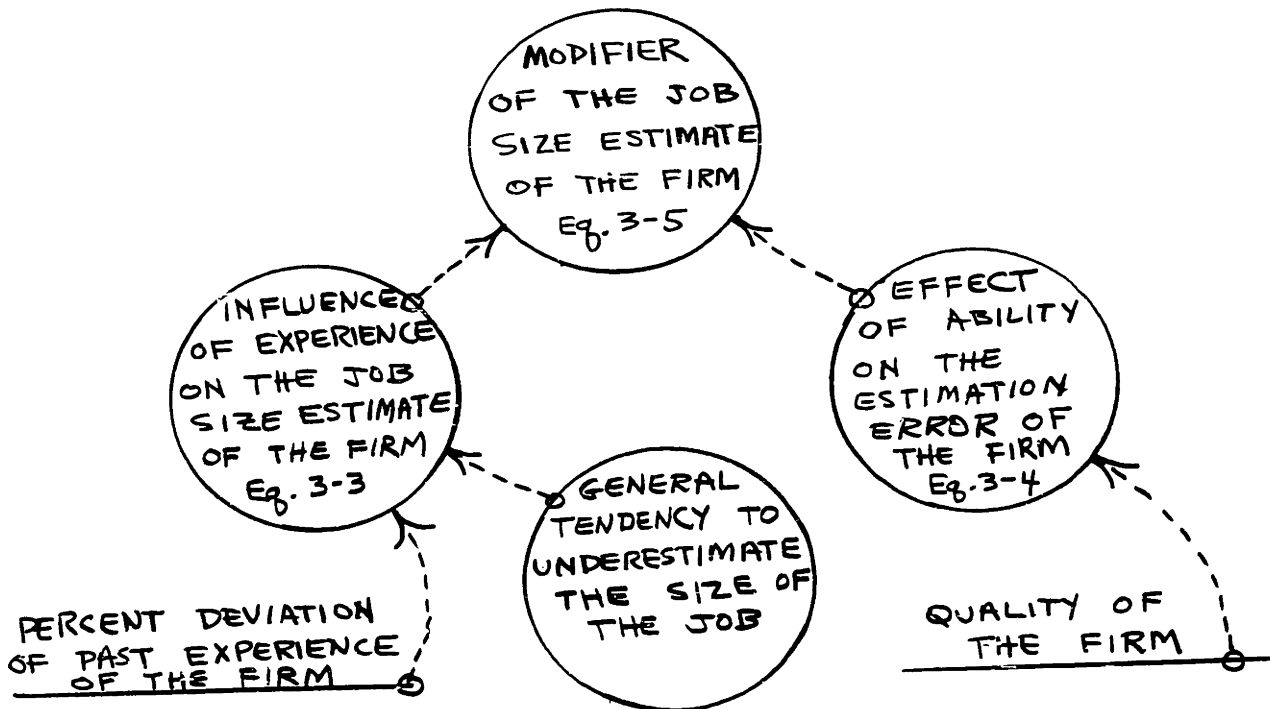


Figure 3-6 Other Influences on the Job Size Estimate of the Firm

that the past experience of the company (relative to the intrinsic size of the present task) combines with a general tendency to underestimate job size to produce one influence on the firm's belief as to the amount of know-how needed for development of the product. This influence is in turn modified by the over-all ability of the firm, based on the theory that the more capable the firm, the smaller the error in its job size estimate.

These influences are incorporated in the two curves and several equations that follow. The first curve combines the effects of the previous experience and the general tendency to underestimate the size of research and development tasks. On the horizontal axis we have the percentage difference between the average job size handled in the past by the company and the size of the present job being simulated. The vertical axis presents the percentage estimating error that would tend result from this experience, ignoring for the moment the modifying effect

of the firm's over-all capability. The general tendency toward under-estimation is shown by the fact that even with the average size of its

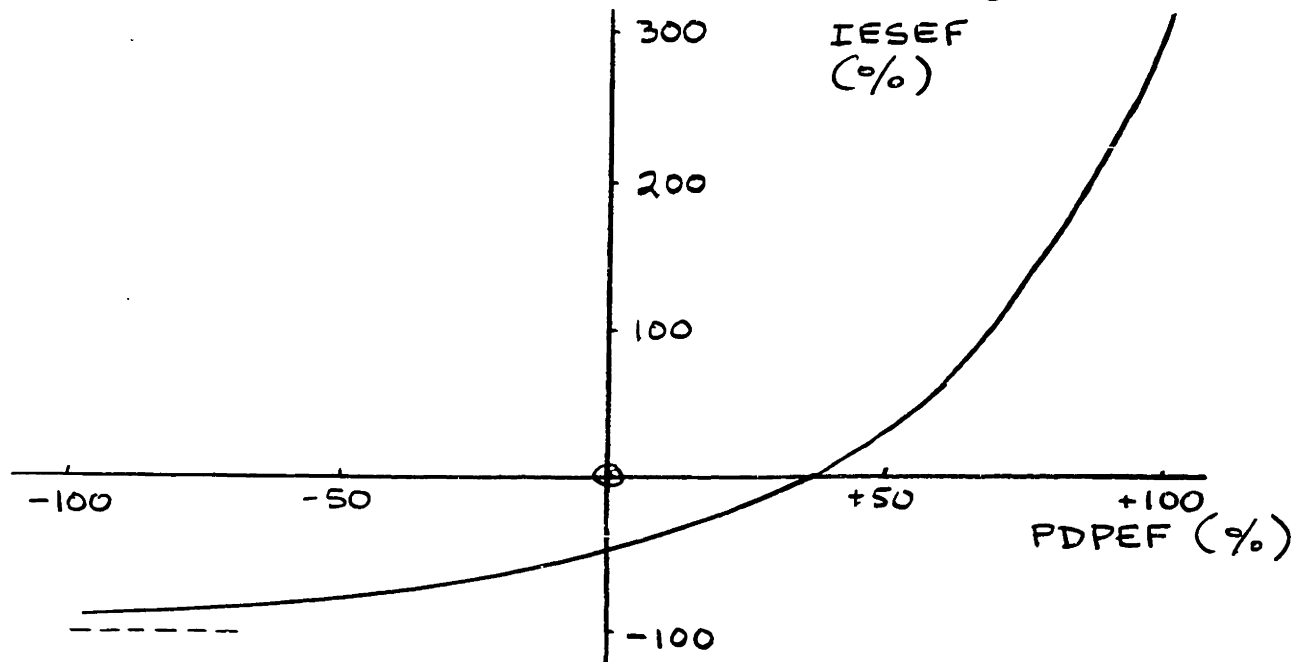


Figure 3-7 Influence of Experience on the Job Size Estimate of the Firm  
 IETAB\* = -0.95/-0.90/-0.83/-0.75/-0.65/-0.50/-0.25/0/1.6/3  
 previous jobs being exactly the same as the size of the present job  
 (PDPEF = 0) the firm would tend to initially underestimate the job size  
 by 50 percent. The table of constants below the curve shows the error  
 percentages at intervals along the curve separated by 20 percent incre-  
 ments in the previous experience gap.

The equation for this effect on the job size estimate is:

$$\text{IESEF} = \text{TABLE} (\text{IETAB}, \text{PDPEF}, -1, +1, 0.2) \quad 3-3, N$$

- IESEF--Influence of Experience on the job Size Estimate of the Firm (percentage error)
- IETAB--Influence of Experience TABLE, a table of stored input numbers which will produce the appropriate value of IESEF for a given value of PDPEF
- PDPEF--Percent Deviation of Past Experience of the Firm (percentage)

The table of values for IETAB is shown immediately beneath Figure 3-7.

As an initial input describing the firm we shall assume that the average

size of the jobs that the firm has handled in the past is 25 percent smaller than the job being considered currently. Thus

$$\text{PDPEF} = -0.25 \text{ (decimal percentage)}$$

This constant will be changed in later simulation runs.

It is reasonable, however, that the firm with more capable management will not err as greatly in its job size estimation as the firm with poor managerial ability. The effect of the general quality of the firm is taken into account in the curve below.

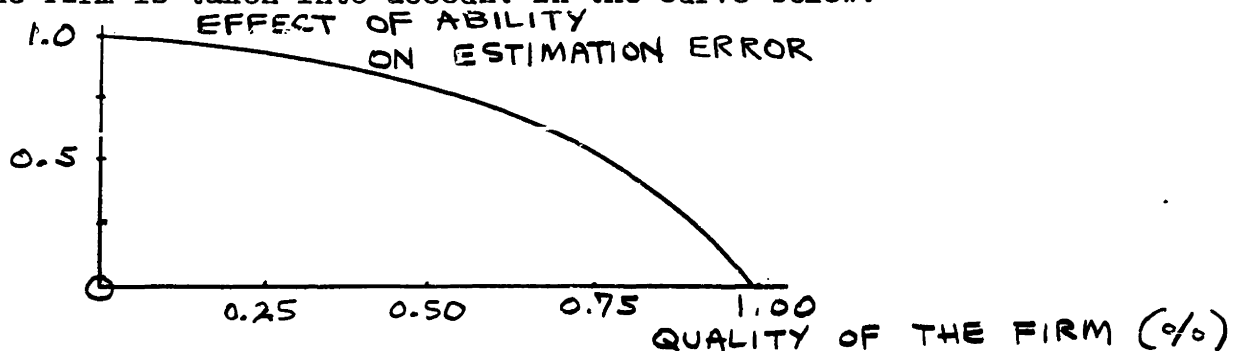


Figure 3-8 Effect of the Firm's Ability on its Estimation Error

When the quality of the firm is at its maximum possible value ( $QF = 1$ ), the previous size of job experience of the firm produces no additional tendency to err in its initial estimates of the job size. When the quality of the firm is 0, the full effect of the previous experience (from equation 3-3), shows up in the estimation error. When the quality of the firm has any intermediate value between 0 and 1, a part of the effect of IESEF is felt as a modifier of the size estimate of the firm. The particular value is selected from Figure 3-8 by use of a DYNAMO table hook-up function in the equation:

$$\text{EAEEF} = \text{TABLE} (\text{EAETB}, \text{QF}, 0, 1, 0.1) \quad 3-4, \text{ N}$$

EAEEF--Effect of Ability on the Estimation Error  
of the Firm (percentage)

EAETB--Effect of Ability on estimation Error, Table,

a table of stored constants, shown under Figure 3-8, which produce the appropriate value of EAEEF for a given value of QF.

QF-----Quality of the Firm (percentage)

Initially the firm will be assumed to be extremely able, and will be assigned a 100 percent quality measure. Thus,

$$QF = 1.00 \text{ (decimal percentage)}$$

This value will cancel out the firm's initial estimation error. In later simulations, QF will be set at other values between 0 and 1, thus varying the effectiveness of the potential estimation error and also modifying the firm's behavior in other ways, not yet discussed.

Both the experience and the ability effects come together in determining the estimation error, which acted to modify the intrinsic job size constant in the initial value equation for BNKPF (Equation 3-2).

$$MSEF = 1 + (EAEEF) (IESEF) \quad 3-5, N$$

MSEF--Modifier of the job Size Estimate of the Firm (percentage)

EAEEF--Effect of Ability on the Estimation Error of the Firm (percentage)

IESEF--Influence of Experience on the job Size Estimate of the Firm (percentage error)

This completes the specification of equations needed to provide the initial condition for BNKPF, the Believed Needed Know-how for development of the Product by the Firm.

As Equation 3-1 shows, the job size estimate continuously changes during a project in response to the rate of recognition of errors in that estimate. The estimation error which is gradually recognized, is here called the gap in engineering accomplishment, GEAF, and indicates the percentage deviation between the estimated schedule and the believed progress to date in terms of percent completion of the project. This

This percentage deviation is multiplied in Equation 3-7 below by the believed size of the job, BNKPF, to produce the gap in the estimated size of the job, GENKF, in consistent units of man-months of effort. This term then is multiplied by FOGRF, which indicates the percentage of that error gap which the firm recognizes in any month, to produce the rate of change of the firm's previous commitment as to the estimate of the job size, RGEJF (Equation 3-8).

$$\text{GEAF.K} = \frac{\text{ESPCF.K} - \text{BPPCF.K}}{\text{BPPCF.K}} \quad 3-6, \text{ A}$$

$$\text{GENKF.K} = (\text{GEAF.K}) (\text{BNKPF.K}) \quad 3-7, \text{ A}$$

$$\text{RFEJF.KL} = (\text{GENKF.K}) (\text{FOGRF.K}) \quad 3-8, \text{ R}$$

GEAF--Gap in Engineering Accomplishment at the Firm (percentage error)  
 ESPCF--Estimated Scheduled Percent Completion of the project at the Firm (percentage completion)  
 BPPCF--Believed Percent of Project Completion by the Firm (percentage completion)  
 GENKF--Gap in the Estimate of Needed Know-how at the Firm (effective man-months of effort)  
 BNKPF--Believed Needed Know-how for development of the Product by the Firm (effective man-months of effort)  
 RGEJF--Rate of recognition of Gap in Estimate of Job size at the Firm (effective man-months/month)  
 FOGRF--Fraction Of Gap Recognized by the Firm (percentage of gap recognized/month)

The scheduled percentage completion takes into account the actual amount of effort that has been put forth, the believed effectiveness of this effort, and the believed amount of total effective effort which would be necessary to complete the job.

$$\text{ESPCF.K} = \frac{(\text{TEEF.K}) (\text{ETEF.K})}{\text{BNKPF.K}} \quad 3-9, \text{ A}$$

ESPCF--Estimated Scheduled Percent Completion of the project at the Firm (percentage completion)  
 TEEF--Total Engineering Effort at the Firm (man-months of effort)



BNKPF--Believed Needed Know-how for development  
of the Product by the Firm (effective  
man-months of effort)

The equation simply states, for example, that if the firm had expanded 100 man-months of engineering effort, which it had previously estimated to be 50 percent effective, into a job which had been estimated to require 500 effective man-months of engineering effort, then:

$$ESPCF = \frac{(100)(0.50)}{500} = \frac{50}{500} = 0.10$$

In other words the firm would have estimated that 10 percent of the job would have been done. If in fact a different percentage of the task were actually completed, then over a period of time one might expect the firm to recognize that its estimates were mistaken and to gradually revise them. This is the process described by Equation 3-8 and later by Equation 3-24.

During the early stages of project life the firm is unable to sense the difference between its scheduled progress and its real progress since in general it gets very few real indications of how the project is going. However, as the project nears physical completion, test results and the physical manifestation of progress begin to indicate to the firm technical measures of the state of completion of the job. For instance, once the job is in fact one hundred percent complete and is actually working, it will not take very long before the firm recognizes this fact. On the other hand, the firm's estimating procedure for determining the percent of completion of the job may well begin to produce estimates that appear to be nearing completion long before the job itself does. Under such a circumstance, the firm gradually begins to recognize that while its estimates say that the job is well on its way,

the careful review of progress that becomes necessitated as the job supposedly nears completion begins to reveal flaws in the firm's estimating process. Thus we have a situation which appears to have three aspects to it. First, if both estimated and real percent progress are small, the firm is unable to recognize an existing error in its estimate because it has almost no available measures of the progress. Secondly, as the job really nears completion with the estimate lagging, the tangible facts of product test performance will indicate to the firm the need to revise its completion estimate. Thirdly, as the estimated progress nears completion with the real accomplishment lagging the same facts of product test performance will not yet show the project completeness previously estimated. Thus again the firm will recognize the need to revise its estimate.

In general these factors are incorporated into the curve for the Fraction Of Gap Recognized by the Firm. The vertical axis shows the percentage estimation error recognized each month while the horizontal axis is the dominant indicator of progress status.

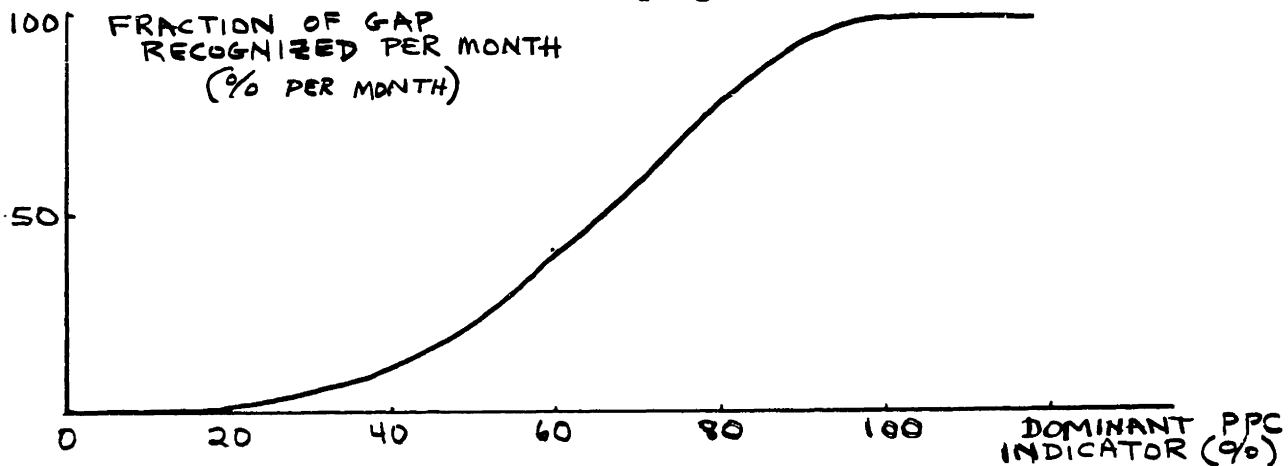


Figure 3-9 Influence of Phase of Project on Gap-Recognition

IPPGR\* 0/0/0/ .05/.12/.20/.35/.60/.80/.99/1.0/1/1/1/1/1

As explained above the indicator which dominates the recognition of estimation error is the larger of the estimated or the real percentage completion of the project. The fractional part recognized is found by the DYNAMO table look-up function in Equation 3-10 and the dominant progress indicator is determined by Equation 3-11.

$$\text{FOGRF.K} = \text{TABLE} (\text{IPPGR}, \text{DPPCF.K}, 0, 1.5, 0.1) \quad 3-10, A$$

$$\text{DPPCF.K} = \text{MAX} (\text{PPC.K}, \text{BPPCF.K}) \quad 3-11, A$$

FOGRF--Fraction Of Gap Recognized by the Firm  
(percentage of gap recognized/month)  
IPPGR--Influence of Phase of Project on Gap  
Recognition, a table of those numbers  
which indicate the value of FOGRF as a  
function of DPPCF  
DPPCF--Dominant Percent of Project Completion at  
the Firm (percentage completion)  
PPC--Percent of Project Completion (percentage  
completion)  
BPPCF--Believed Percent of Project Completion by  
the Firm (percentage completion)

This completes the description of the factors which produce the firm's changing estimate of the size of the job. We can now examine the firm's estimation of the technical effectiveness of its engineers. As shown in the next diagram, Figure 3-10, exogenous technological developments create changes in the state of the technical art which integrate to produce the current real state of the art's technical effectiveness. Because of the time delays in communicating technological information from the source of the breakthrough to the area of the application, there is a distinction between this real state of the art effectiveness and the state of the art which is available to any given project organization under consideration. The rate of change in the available state of the art in any organization is a function of the gap between the state of the art previously available to the firm and

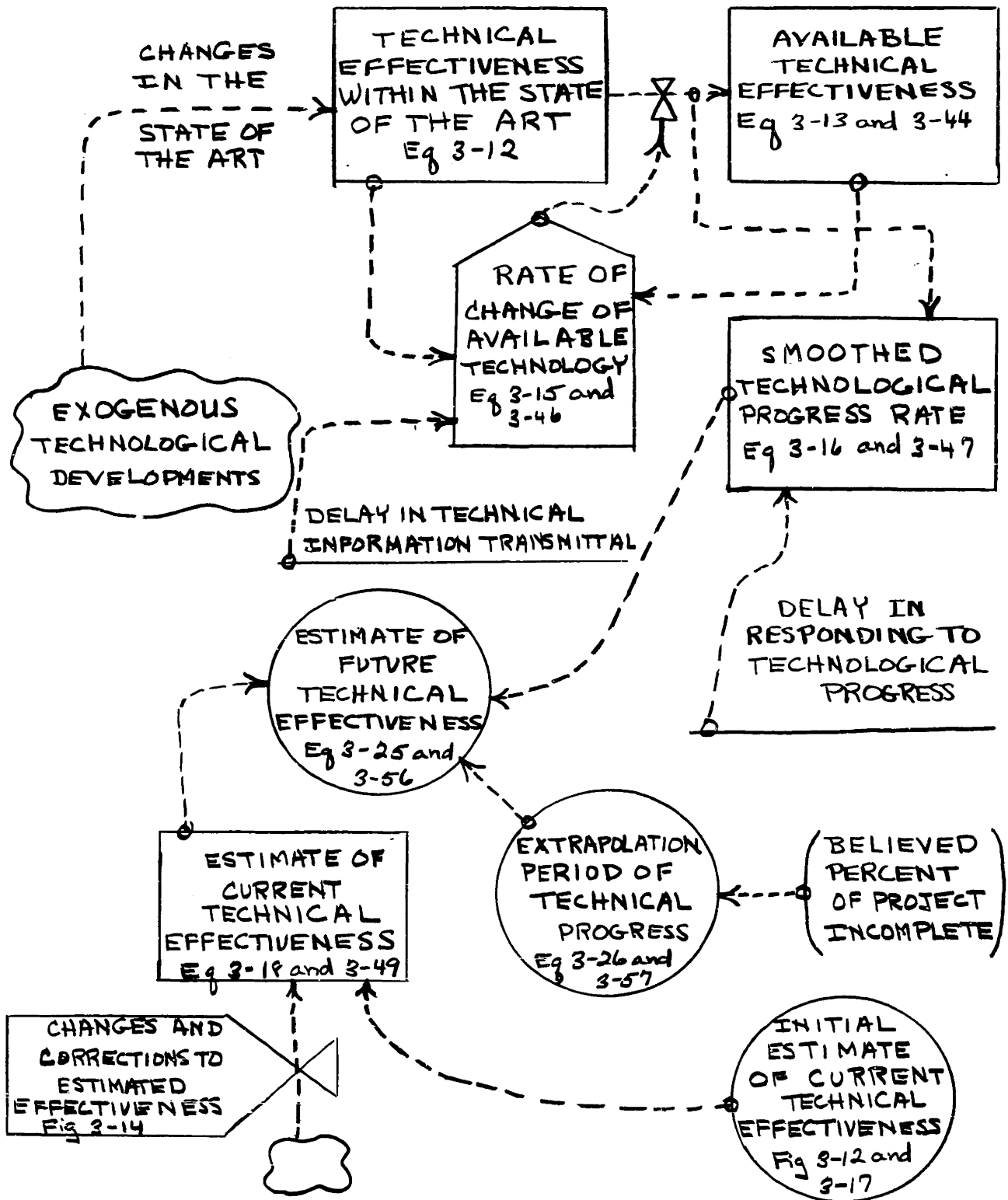


Figure 3-10 Estimate of Technical Effectiveness

that which existed in technology in general, as well as the length of the delay in transmitting and absorbing this new knowledge. As the organization receives new information about the state of the art, it takes this into account over a period of time through a process which recognizes some average believed rate of technological growth. Thinking about how much of the job is completed, and hence how much of the job is left to be completed, the organization projects this rate of technological growth into the future, estimating the technical effectiveness that will be available for use on the remainder of the job. This extrapolated technological growth is added to the basic estimate of current technical effectiveness. The estimate of current technical effectiveness is, in turn, the resultant of the initial estimate of current technical effectiveness combined with the changes in the estimated effectiveness which take place as technology evolves and also with the corrections which are made to previous effectiveness estimates.

The actual technical effectiveness that is possible within the existing state of the art changes over time and is supplied as a basic input to the model. It, of course, as the other previously specified basic inputs, will be changed from one computer run to another to see the effects of such changes.

TE.K = TABLE (TETAB, TIME. K, 0, 180, 6) 3-12, A

TE--Technical Effectiveness within the state of the art (percent effectiveness of engineers)

TETAB--Technical Effectiveness TABLE, a table of stored numbers which will give the appropriate value for TE as a function of the project life cycle

As can be seen from the equation, values for TE are stored in the table

at six-month intervals from TIME = 0 to TIME = 180 months. For the initial model simulation the state of the art will be assumed to change over time in a manner shown in Figure 3-11. The table below the curve specifies the values of the Technical Effectiveness that is within the state of the art as time and technology evolves.

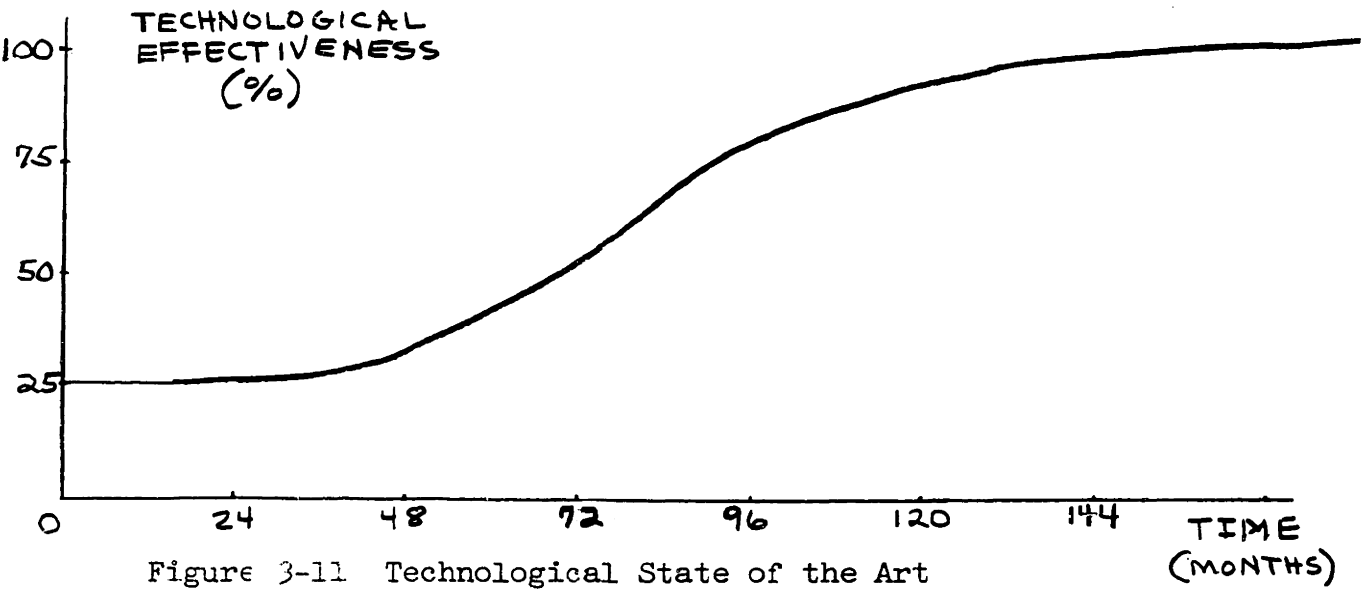


Figure 3-11 Technological State of the Art

TETAB\* = .25/.25/.25/.25/.26/.27/.28/.30/.32/.35/.38/.42/.46/.51/.57/.63/.70/.77/.82/.86/.89/.91/.93/.94/.95/.96/.97/.98/.99/.995/1.0

Proceeding as before, we shall now describe the equations which determine the estimate of technical effectiveness for the firm. The first equation will describe the level of the state of the art which is available to the firm as distinct from the state of the art available to technology in general. The available state of the art is represented as a first-order exponential smoothing of the input technical effectiveness. This means that over a period of time indicated by DTITF, the Delay in Technical Information Transmittal to the Firm, the firm acquires the information relating to the exogenous state of the art and has it available for its own project engineering use.

$$\text{ATEF.K} = \text{ATEF.J} + (\text{DT}) (\text{RCTAF.JK}) \quad 3-13, \text{ L}$$

$$\text{ATEF} = \text{ITE} \quad 3-14, \text{ N}$$

$$\text{RCTAF.KL} = \frac{\text{TE.K} - \text{ATEF.K}}{\text{DTITF}} \quad 3-15, \text{ R}$$

ATEF--Available Technical Effectiveness at the Firm (percent effectiveness of engineers)  
 RCTAF--Rate of Change of Technology Available at the Firm (percent effectiveness/month)  
 ITE--Initial Technical Effectiveness (percent effectiveness of engineers)  
 TE--Technical Effectiveness within the state of the art (percent effectiveness of engineers)  
 DTITF--Delay in Technical Information Transmitted to the Firm (months)

ITE represents the initial value of the table of technical effectiveness, which is assumed also to be available to the firm. From Figure 3-11 we see that TE initially shows a 25 percent effectiveness. Therefore,

$$\text{ITE} = 0.25 \text{ (decimal percent effectiveness)}$$

For the highly skilled firm being represented in this project simulation (QF has been initially set equal to one), the delay in finding out about new technological breakthroughs is relatively short. Here it will be set as eight months and changed in later studies.

$$\text{DTITF} = 8 \text{ months}$$

As changes take place in the state of the art available to the firm, the firm gradually recognizes this rate of technological growth.

$$\text{STPRF.K} = \text{STPRF.J} + (\text{DT}(1/\text{DRTPF}))(\text{RCTAF.JK} - \text{STPRF.J}) \quad 3-16, \text{ L}$$

$$\text{STPRF} = 0 \quad 3-17, \text{ N}$$

STPRF--Smoothed Technological Progress Rate at the Firm (percent effectiveness/month)  
 DRTPF--Delay in Responding to Technological Progress at the Firm (months)  
 RCTAF--Rate of Change of Technology Available at the Firm, (percent effectiveness/month)

As can readily be seen from examination of Figure 3-11, technical

effectiveness is initially in an unchanging state. Thus the initial condition for the average rate of recognized technological change, found in Equation 3-17 above, is zero. The delay in responding to this technical progress rate is visualized as being very short, meaning that the firm's opinion of technological growth changes rapidly as it becomes knowledgeable about new breakthroughs. For this purpose,

$$\text{DRTPF} = 2 \text{ months}$$

The estimate of the current technological effectiveness made by the firm really represents the summation of all of the changes and corrections in the estimate since the beginning of the project.

$$\text{ETEF.K} = \text{ETEF.J} + (\text{DT})(\text{RCEEF.JK} + \text{RCPEF.JK}) \quad 3-18, \text{ L}$$

- ETEF--Estimate of current Technical Effectiveness by the Firm (percent effectiveness of engineers)  
 RCEEF--Rate of Change of Estimated current Effectiveness by the Firm (percent effectiveness/month)  
 RCPEF--Rate of Correction of Previous effort Estimate by the Firm (percent effectiveness/month)

The initial estimate of the technical effectiveness of the firm represents a combination of the influences of the actual effectiveness of the firm's engineers and the relative optimism of the firm as expressed in its estimating procedures. The relative optimism of the firm is taken as being analogous or basically similar to the firm's willingness to accept risk that was used in an earlier formulation. This characteristic of the firm produces a bias factor which is modified by consideration of the actual qualifications of the firm's management, as was done in the formulation of BNKPF, Equation 3-2, on an earlier page in this chapter. The influences on the initial effectiveness estimate



are pictured in Figure 3-12 below.

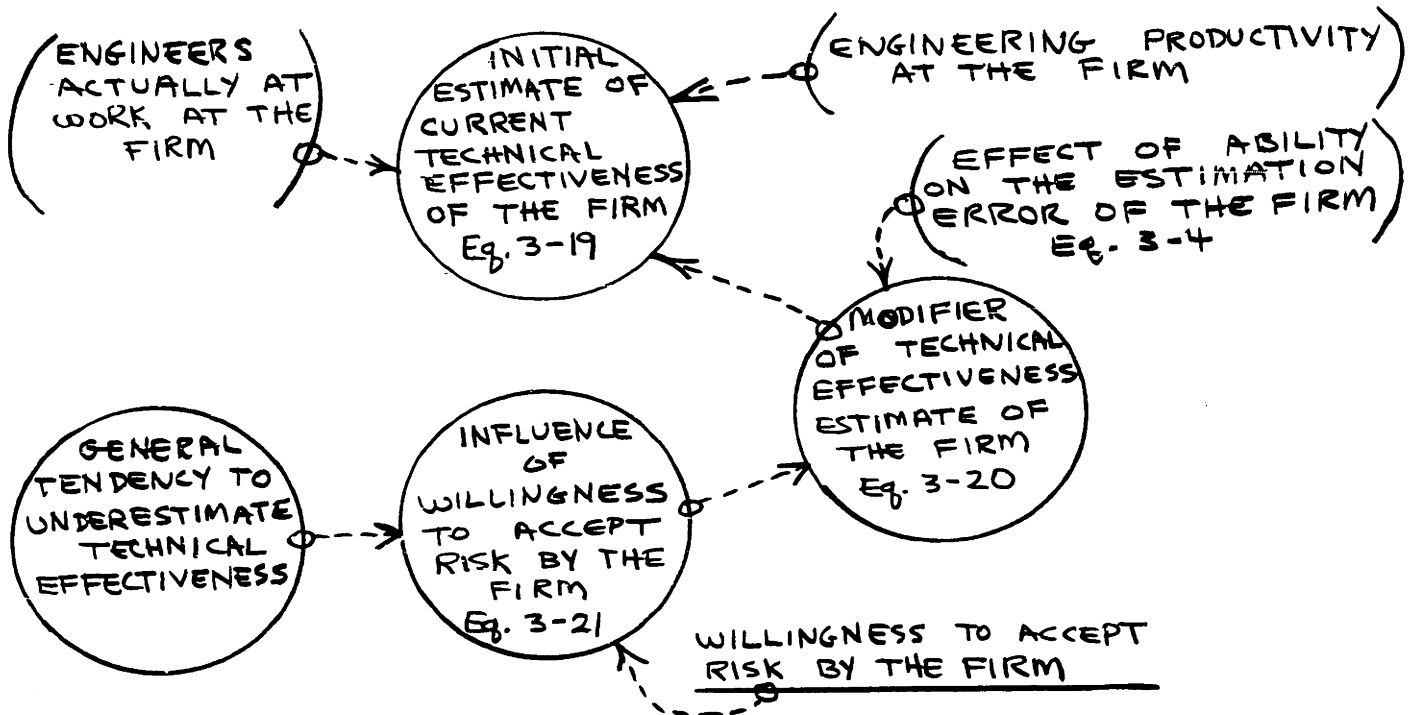


Figure 3-12 Initial Estimate of Current Technical Effectiveness of the Firm

The three equations which follow incorporate the influences shown in the flow chart. First, the initial estimate of technical effectiveness itself is the engineering productivity per engineer at work multiplied by a modifying factor. The modifier, Equation 3-20, incorporates the effect of the firm's ability on the estimation error. The ability effect was already discussed in reference to Equation 3-4. Finally the equation for IWARF below uses a DYNAMO table look-up to combine the specific risk-propensity effects with a general tendency for the firm to underestimate technical effectiveness.

$$ETEF = \left( \frac{ENPRF}{ENAWF} \right) (MTEF) \quad 3-19, N$$

$$MTEF = 1 + (IWARF)(EAEEF) \quad 3-20, N$$

$$IWARF = \text{TABLE} (IWTAB, WARF, 0, 1, 0.2) \quad 3-21, N$$

ETEF--Estimate of the current Technical Effectiveness by the Firm (percentage effectiveness of engineers)

ENPRF--Engineering Productivity at the Firm  
(effective man-months/month)  
 ENAWF--Engineers Actually at Work at the Firm  
(men)  
 MTEF--Modifier of Technical effectiveness Estimate by the Firm (percentage)  
 IWARF--Influence of Willingness to Accept Risk by the Firm (percentage)  
 EAEEF--Effect of Ability on the Estimation Error of the Firm (percentage)  
 IWTAB--Influence of Willingness TABLE, a table of stored numbers which gives a value for IWARF for each input value of WARF  
 WARF--Willingness to Accept Risk by the Firm (percentage)

The influence of the firm's willingness to accept risk on the estimates of technical effectiveness is pictured in the diagram below, Figure 3-13, which incorporates the values selected for the initial IWTAB. This table of numbers also accounts for the general tendency to underestimate technology before actually getting into the project.

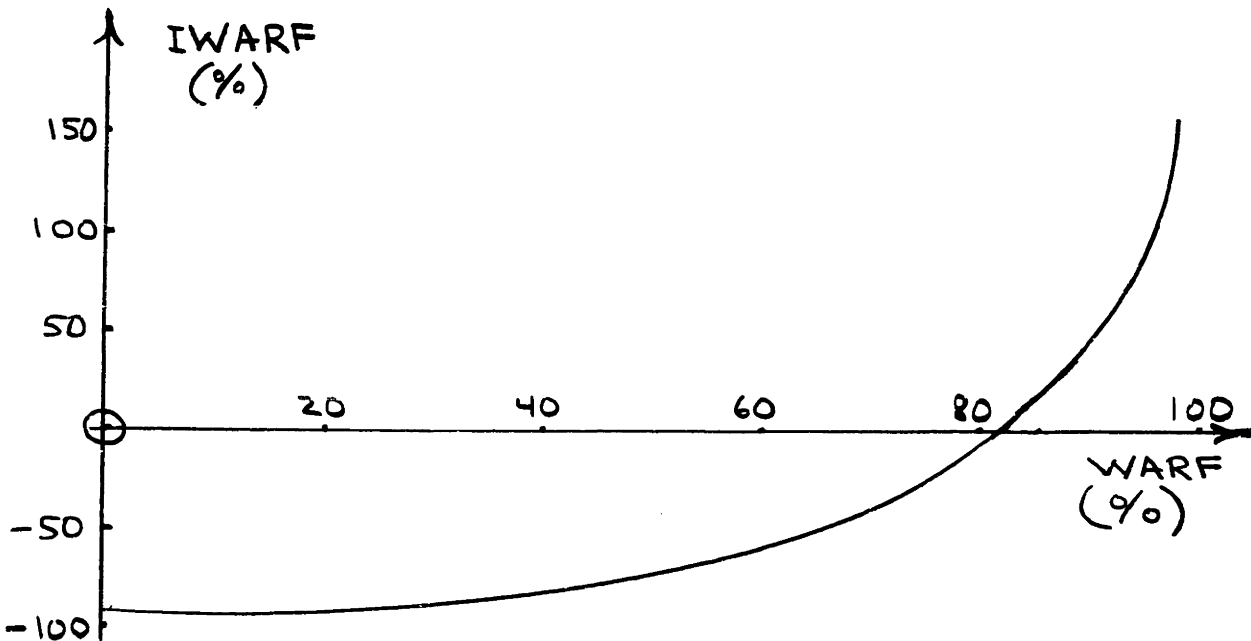


Figure 3-13 Influence of Risk-taking Propensity on Estimates of Technology

$$IWTAB^* = -.9 / -.75 / -.60 / -.40 / -.25 / 1.5$$

The firm's willingness to accept risk was specified in the Appendix of Chapter II as equal initially to 100 percent.

The actual changes in the firm's estimate of technical effectiveness are of two types: first, the updating of the estimate to recognize the firm's current progress rate; secondly, the correction of the estimate to take account of recognized earlier errors which have led to mistaken percentage completion estimates. Figure 3-14 shows these two change sources with their inputs, with equation numbers for the customer also indicated:

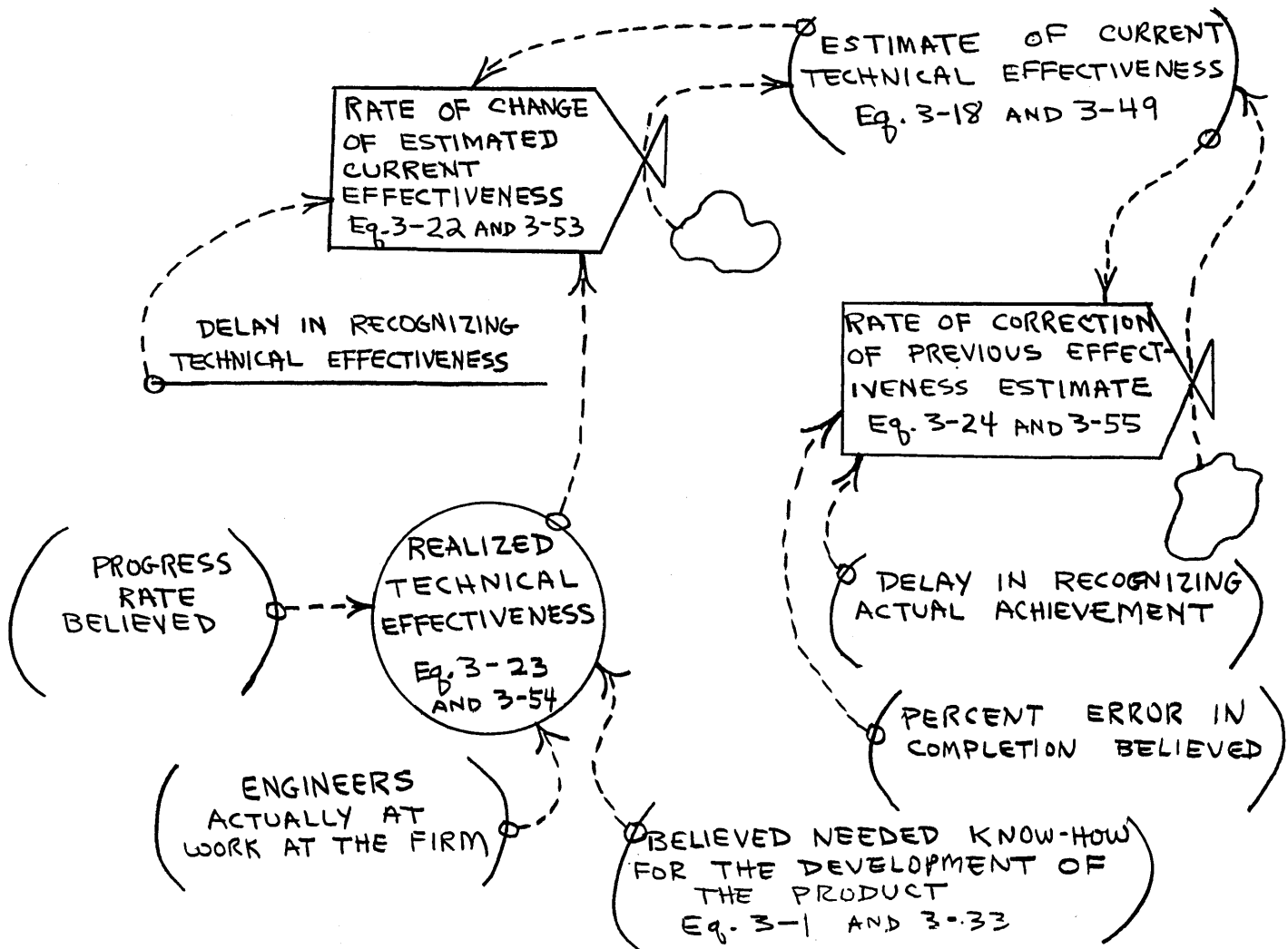


Figure 3-14 Changes in the Current Effectiveness Estimate

The actual rate of change of the firm's estimate of its current effectiveness shows a shift towards the effectiveness which the firm detects in its current engineering efforts. This shift by the firm takes place over a brief period of time of DRTEF months, where

$$\text{DRTEF} = 2 \text{ months}$$

$$\text{RCEEF.KL} = \frac{\text{RTEF.K} - \text{ETEF.K}}{\text{DRTEF}} \quad 3-22, \text{ R}$$

RCEEF--Rate of Change of Estimated current Effectiveness by the Firm (percent effectiveness/month)

RTEF--Realized Technical Effectiveness by the Firm (percent effectiveness of engineers)

ETEF--Estimate of current Technical Effectiveness by the Firm (percent effectiveness of engineers)

DRTEF--Delay in Recognizing Technical Effectiveness by the Firm (months)

The realized technical effectiveness of the firm is the firm's belief as to the current progress rate in terms of the effective man-months per month that is being accomplished divided by the number of engineers who are actually at work during the given period.

$$\text{RTEF.K} = \frac{(\text{PRBF.JK})(\text{BNKPF.K})}{\text{ENAWF.K}} \quad 3-23, \text{ A}$$

RTEF--Realized Technical Effectiveness of the Firm (percent effectiveness of engineers)

PRBF--Progress Rate Believed by the Firm (percent completion/month)

BNKPF--Believed Needed Know-how for development of the Product by the Firm (effective man-months of effort)

ENAWF--ENgineers Actually at Work at the Firm (men)

The rate of correction of the previous effectiveness estimate is a fraction per month of the error magnitude indicated by the product of ETEF and the percent error in project completion believed by the firm. The fraction of this amount recognized each month is specified by 1 divided by the delay in recognizing actual achievement at the firm.

$$RCPEF.KL = \frac{(PECBF.K)(ETEF.K)}{DRAAF.K} \quad 3-24, R$$

RCPEF--Rate of Correction of Previous effectiveness Estimate of the Firm (percent effectiveness/month)  
 PECBF--Percent Error in Completion Believed by the Firm (percentage error)  
 ETEF--Estimate of current Technical Effectiveness by the Firm (percent effectiveness engineers)  
 DRAAF--Delay in Recognizing Actual Achievement at the Firm (months)

The estimate of the future technical effectiveness is based on the current estimate and on an extrapolation of the rate of technological growth that the firm has perceived.

$$EFTEF.K = ETEF.K + (XPTPF.K)(STPRF.K) \quad 3-25, A$$

EFTEF--Estimate of Future Technical Effectiveness by the Firm (percent effectiveness of engineers)  
 ETEF--Estimate of current Technical Effectiveness by the Firm (percent effectiveness of engineers)  
 XPTPF--eXtrapolation Period for Technical Progress by the Firm (months)  
 STPRF--Smoothed Technical Progress Rate at the Firm (percent effectiveness/month)

This extrapolation period recognizes the fact that if technology continues to grow at its current rate, then, on the average, only half of the increase in technology from now until the end of the project will be available for utilization in the project work. Thus, the period depends upon consideration not only of the normal project duration, but also of the percent of the project left to be completed.

$$XPTPF.K = (BPPIF.K) \left( \frac{NPD}{2} \right) \quad 3-26, A$$

XPTPF--eXtrapolation Period of Technical Progress at the Firm (month)  
 BPPIF--Relieved Percent of Project Incomplete by the Firm (percentage)  
 NPD--Normal Project Duration (months)

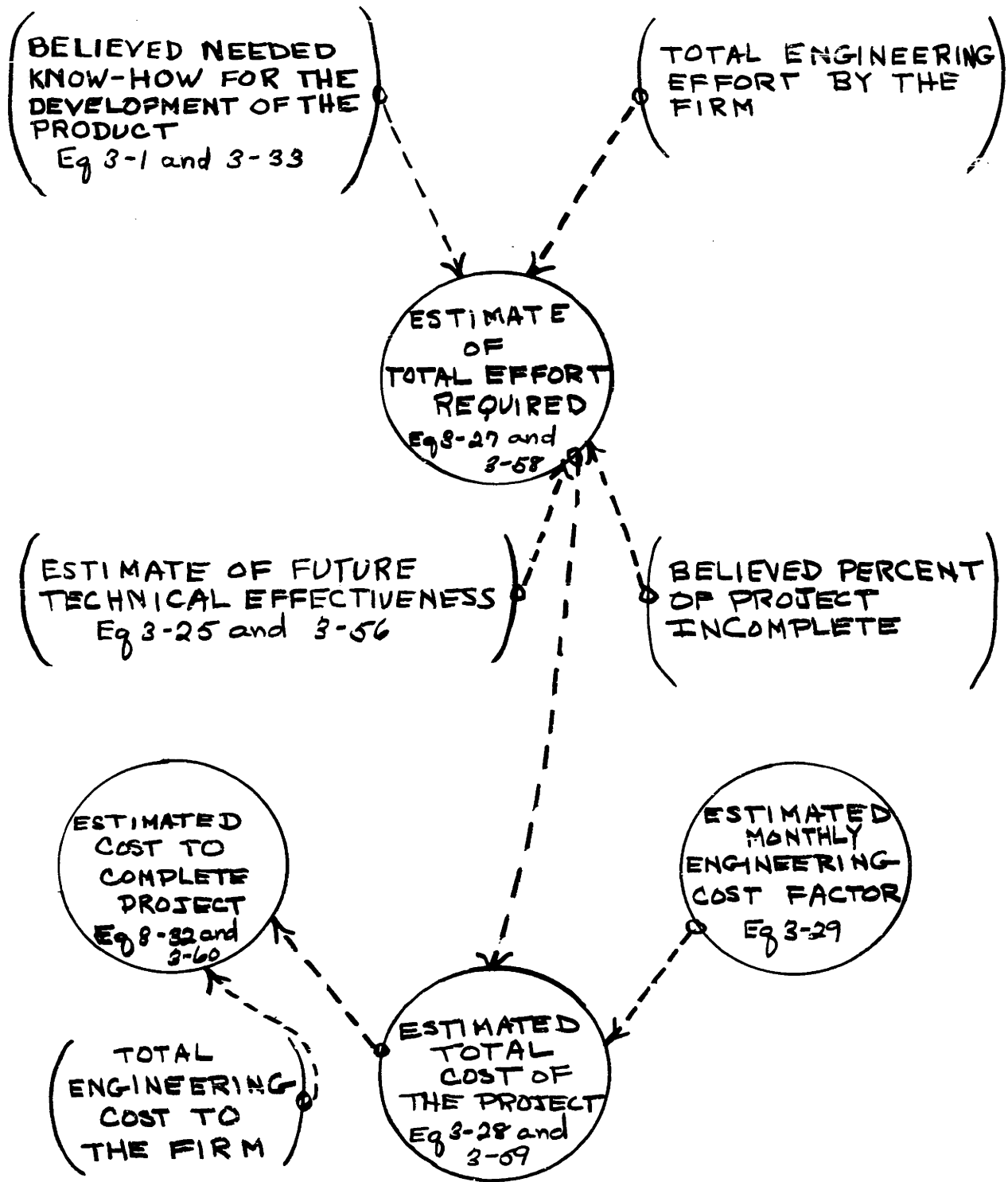


Figure 3-15 Estimate of Effort and Cost Requirements.

The normal duration of the project will initially be set at two years and changed in later runs. Thus,

$$\text{NPD} = 24 \text{ months}$$

To complete the initial description of the equations for Chapter III let us now turn to Figure 3-15 which pulls together the outcomes of the previous two sections into the factors relating to estimating the actual effort and cost requirements. In the diagram, it is clearly shown that the estimate of effort required is formed by taking into account the total amount of engineering effort that has been done to date and adding to this the amount of engineering that is expected to be required in the future. The future requirements are determined by the estimate of the job size, the estimate of the future technical effectiveness, and the believed percent of the job left to be done. Once the estimate of effort required is determined, one can readily find the estimate of total cost required by combining the effort estimate with the average monthly costs per engineer. Subtracting from this amount the total cost to date produces an estimate of the cost to complete the project.

Let us now write the equations for this final sector, starting with the equation for the estimate of effort required.

$$\text{EERF.K} = \text{TEEF.K} + (\text{BPPIF.K})(\text{BNKPF.K}/\text{EFTEF.K}) \quad 3-27, \text{ A}$$

EERF--Estimate of total Effort Required by the Firm (man-months of effort)

TEEF--Total Engineering Effort by the Firm (man-months of effort)

BPPIF--Believed Percent of Project Incomplete by the Firm (percentage)

BNKPF--Believed Needed Know-how for development of the Project by the Firm (effective man-months of effort)

EFTEF--Estimate of Future Technical Effectiveness by the Firm (percent effectiveness of engineers)

This equation adds to the effort already expended, TEEF, the estimate of additional effort needed. The latter is found by multiplying the believed job size by the percent of the project believed to be remaining to be done. This produces the estimated additional effective work needed, and when divided by the expected future effectiveness of the engineers gives as a result the estimated additional effort.

The estimated total costs reflect this effort requirement and the cost per engineer, taking into account in determining the average cost factor the absenteeism of the engineers.

$$ETCPF.K = (EMECF)(EERF.K) \quad 3-28, A$$

$$EMECF = (MESOH)(ABSCM) \quad 3-29, N$$

$$MESOH = ESOHR/12 \quad 3-30, N$$

$$ABSCM = \frac{1}{1- AVABS} \quad 3-31, N$$

ETCPF--Estimated Total Cost of the Project by the Firm (dollars)

EMECF--Estimated Monthly Engineering Cost Factor (dollars/man-month)

EERF--Estimate of total Effort Required by the Firm (man-months)

MESOH--Monthly Engineering Salary and OverHead (dollars/man-month)

ABSCM--ABSenteeism Cost Modifier (percentage)

ESOHR--Engineering Salary and OverHead Rate (dollars/man-year)

AVABS--AVerage ABSenteeism (percentage)

From the studies cited earlier in this chapter \$30,000 seemed to be an average figure for annual salary, overhead, and support costs of scientists and engineers in military-oriented research and development work. Thus,

$$ESOHR = 30,000 \text{ dollars/engineering man-year}$$



The average absenteeism of engineers, including actually the effects of holidays and vacations, as found in an earlier study of engineering costs, amounts to approximately 11 1/2 percent of the scheduled work days during the year.<sup>26</sup>

$$AVABS = 0.115 \text{ (decimal percentage)}$$

Finally, the estimated cost to complete the project is simply equal to the total cost estimate minus the cost that has been incurred thus far.

$$ECCPF.K = ETCPF.K - TECF.K \quad 3-32, A$$

ECCPF--Estimated Cost to Complete the Project  
at the Firm (dollars)  
ETCPF--Estimated Total Cost of the Project at  
the Firm (dollars)  
TECF--Total Engineering Cost to the Firm (dollars)

The above equations which describe the firm's process of estimating project effort and cost also certainly apply to the customer's similar efforts. Thus these equations will be repeated below for the customer with very little added explanation. The customer's estimate of the size of the job has the same form as the firm's estimate, Equation 3-1.

$$BNKPC.K = BNKPC.J + (DT)(RGEJC.JK) \quad 3-33, L$$

$$BNKPC = (MSEC)(NLKP) \quad 3-34, N$$

BNKPC--Believed Needed Know-how for develop-  
ment of the Product by the Customer  
(effective man-months of effort)  
RGEJC--Rate of recognition of Gap in Estimate  
of Job size by the Customer (effective  
man-months/month)  
MSEC--Modifier of the job Size Estimate of the  
Customer (percentage)

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<sup>26</sup>Edward B. Roberts, "The Digital Computer as an Element of a Financial Control System" (unpublished Master of Science thesis, M.I.T. Department of Electrical Engineering, June 1958), p. A1-27, 28.

NLKP--Needed Level of Know-how for development of the Product (effective man-months of effort)

NLKP was earlier set equal to 6000 effective man-months of effort.

The factors which cause customer errors in its estimates of NLKP are shown in Figure 3-16, which is a replica for the customer of the earlier diagram, Figure 3-6, for the firm.

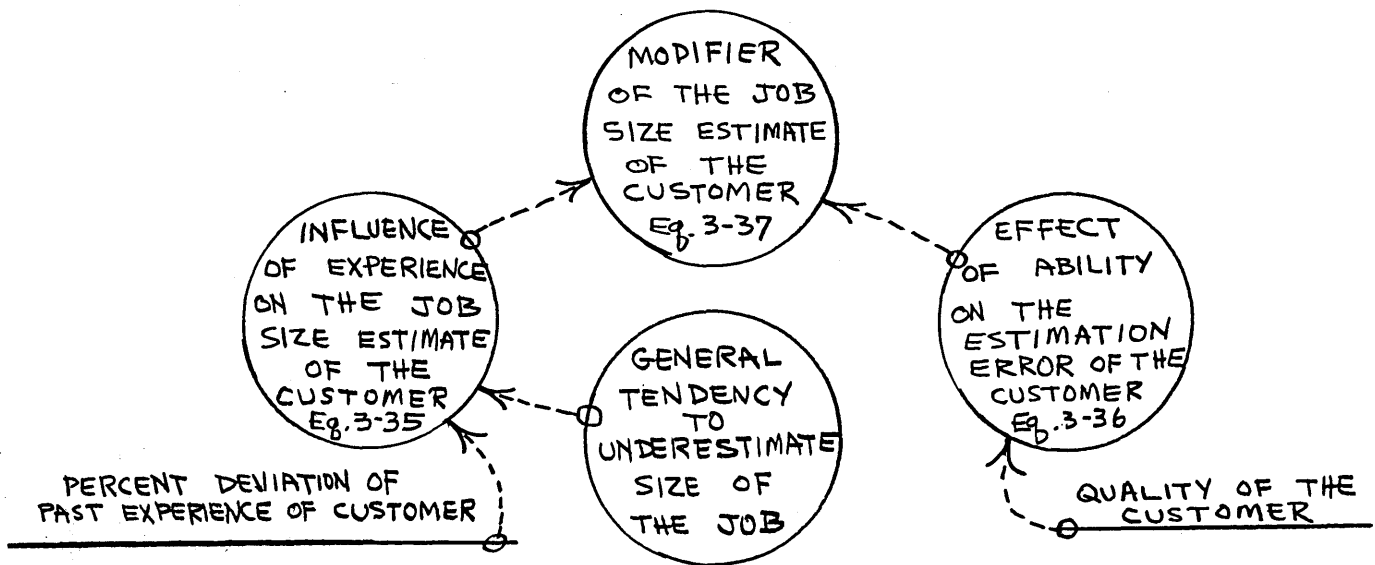


Figure 3-16 Other Influences on the Job Size Estimate of the Customer

Equations 3-35, 36, and 37 parallel Equations 3-3, 4, and 5 which were used for the firm.

$$\text{IESEC} = \text{TABLE} (\text{IETAB}, \text{PDPEC}, -1, +1, 0.2) \quad 3-35, N$$

$$\text{EAEEC} = \text{TABLE} (\text{EAETB}, \text{QC}, 0, 1, 0.1) \quad 3-36, N$$

$$\text{MSEC} = 1 + (\text{EAEEC})(\text{IESEC}) \quad 3-37, N$$

IESEC--Influence of Experience on Size Estimate of the Customer (percentage error of the job)

IETAB--Influence of Experience TABLE, a table of numbers which gives an appropriate value for IESEC for every value of PDPEC

PDPEC--Percent Deviation of Previous Experience of the Customer (percentage)

EAEEC--Effect of Ability on the Estimation Error of the Customer (percentage)

EAETB--Effect of Ability on estimation Error,  
Table, a table of stored constants,  
shown under Figure 3-8, which produce the  
appropriate value of EAEEC for a given  
value of QC

MSEC--Modifier of the job Size Estimate of the  
Customer (percentage)

QC--Quality of the Customer (percentage)

IETAB is shown beneath Figure 3-7. As an initial input describing the customer we shall assume that the average size of his previous projects is 17.5 percent smaller than the job being considered currently. Thus,

$$PDPEC = -0.175 \text{ (decimal percentage)}$$

This constant will be changed in later simulation runs. The customer will initially be assumed to be of slightly above average capability, and will be assigned a 60 percent quality measure. Thus,

$$QC = 0.60 \text{ (decimal percentage)}$$

The next group of equations are just repeats for the customer of the firm's Equations 3-6 through 3-11. The equations will just be stated here for completeness, without further comment.

$$GEAC.K = \frac{ESPCC.K - BPPCC.K}{BPPCC.K} \quad 3-38, A$$

$$GENKC.K = (GEAC.K)(BNKPC.K) \quad 3-39, A$$

$$RGEJC.KL = (GENKC.K)(FOGRC.K) \quad 3-40, R$$

$$ESPCC.K = \frac{(TEEF.K)(ETEC.K)}{BNKPC.K} \quad 3-41, A$$

$$FOGRC.K = \text{TABLE} (\text{IPPGR}, \text{DPPCC.K}, 0, 1.5, 0.1) \quad 3-42, A$$

$$DPPCC.K = \text{MAX} (\text{PPC.K}, \text{BPPCC.K}) \quad 3-43, A$$

GEAC--Gap in Engineering Accomplishment at the  
Customer (percentage error)

ESPCC--Estimated Scheduled Percent Completion of  
the project at the Customer (percentage  
completion)

BPPCC--Believed Percent of Project Completion by  
the Customer (percentage completion)

GENKC--Gap in the Estimate of Needed Know-how at  
the Customer (effective man-months of effort)

BNKPC--Believed Needed Know-how for development  
 of the Product at the Customer (effective  
 man-months of effort)  
 RGEJC--Rate of recognition of Gap in Estimate of  
 Job size at the Customer (effective man-  
 months/month)  
 FOGRC--Fraction Of Gap Recognized by the Customer  
 (percentage of gap recognized/month)  
 TEEF--Total Engineering Effort at the Firm  
 (man-months of effort)  
 ETEC--Estimate of current Technical Effectiveness  
 by the Customer (percentage effectiveness)  
 IPPGR--Influence of Phase of Project on Gap Recog-  
 nition, table of stored numbers which gives  
 the appropriate value for FOGRC for any  
 given value of DPPCC  
 DPPCC--Dominant Percent of Project Completion to  
 the Customer (percentage completion)  
 PPC--Percent of Project Completion (percentage  
 completion)

We can now represent the process of customer estimation of the  
 technical effectiveness of the firm's engineers. The following equations,  
 3-44 through 3-48, correspond to the earlier equations for the firm num-  
 bered 3-13 through 3-17.

$$\text{ATEC.K} = \text{ATEC.J} + (\text{DT})(\text{RCTAC.JK}) \quad 3-44, \text{ L}$$

$$\text{ATEC} = \text{ITE} \quad 3-45, \text{ N}$$

$$\text{RCTAC.KL} = \frac{\text{TE.K} - \text{ATEC.K}}{\text{DTITC}} \quad 3-46, \text{ R}$$

$$\text{STPRC.K} = \text{STPRC.J} + (\text{DT})(1/\text{DRTPC})(\text{RCTAC.JK} - \text{STPRC.J}) \quad 3-47, \text{ L}$$

$$\text{STPRC} = 0 \quad 3-48, \text{ N}$$

ATEC--Available Technical Effectiveness at the  
 Customer (percent effectiveness of engineers)  
 RCTAC--Rate of Change of Technology Available at  
 the Customer (percent effectiveness/month)  
 ITE--Initial Technical Effectiveness (percent  
 effectiveness of engineers)  
 TE--Technical Effectiveness within the state of  
 the art (percent effectiveness of engineers)  
 DTITC--Delay in Technical Information Transmitted  
 to the Customer (months)  
 STPRC--Smoothed Technological Progress Rate at  
 the Customer (percent effectiveness/month)

DRTPC--Delay in Responding to Technological  
Progress at the Customer (months)

The customer is able to determine information as to the nature of technological breakthroughs from a great number of firms. Thus, despite the lessened over-all competence of the customer relative to the firm in the initial simulation parameters, we assume that the customer's delay in receiving new technical information is shorter than the firm's. For this reason,

$$DTITC = 6 \text{ months}$$

The customer is regarded as responding quickly to base his opinion about the changing state of the art on the most recent events which he has recognized. Thus,

$$DRTPC = 2 \text{ months}$$

The estimate of current technological effectiveness made by the customer is similar to Equation 3-18.

$$ETEC.K = ETEC.J + (DT)(RCEEC.JK + RCPEC.JK) \quad 3-49, L$$

ETEC--Estimate of current Technical Effectiveness by the Customer (percent effectiveness of engineers)

RCEEC--Rate of Change of Estimated current Effectiveness by the Customer (percent effectiveness/month)

RCPEC--Rate of Correction of Previous effort Estimate by the Customer (percent effectiveness/month)

The influences on the initial value of ETEC are pictured in Figure 3-17, which is similar to Figure 3-12 for the firm. The customer, through his relationships with the firms working in the technical area, has information about the available state of the art. However, the customer's confidence in the firm biases his judgment as to the firm's capabilities. In addition, the customer also responds to his own optimism

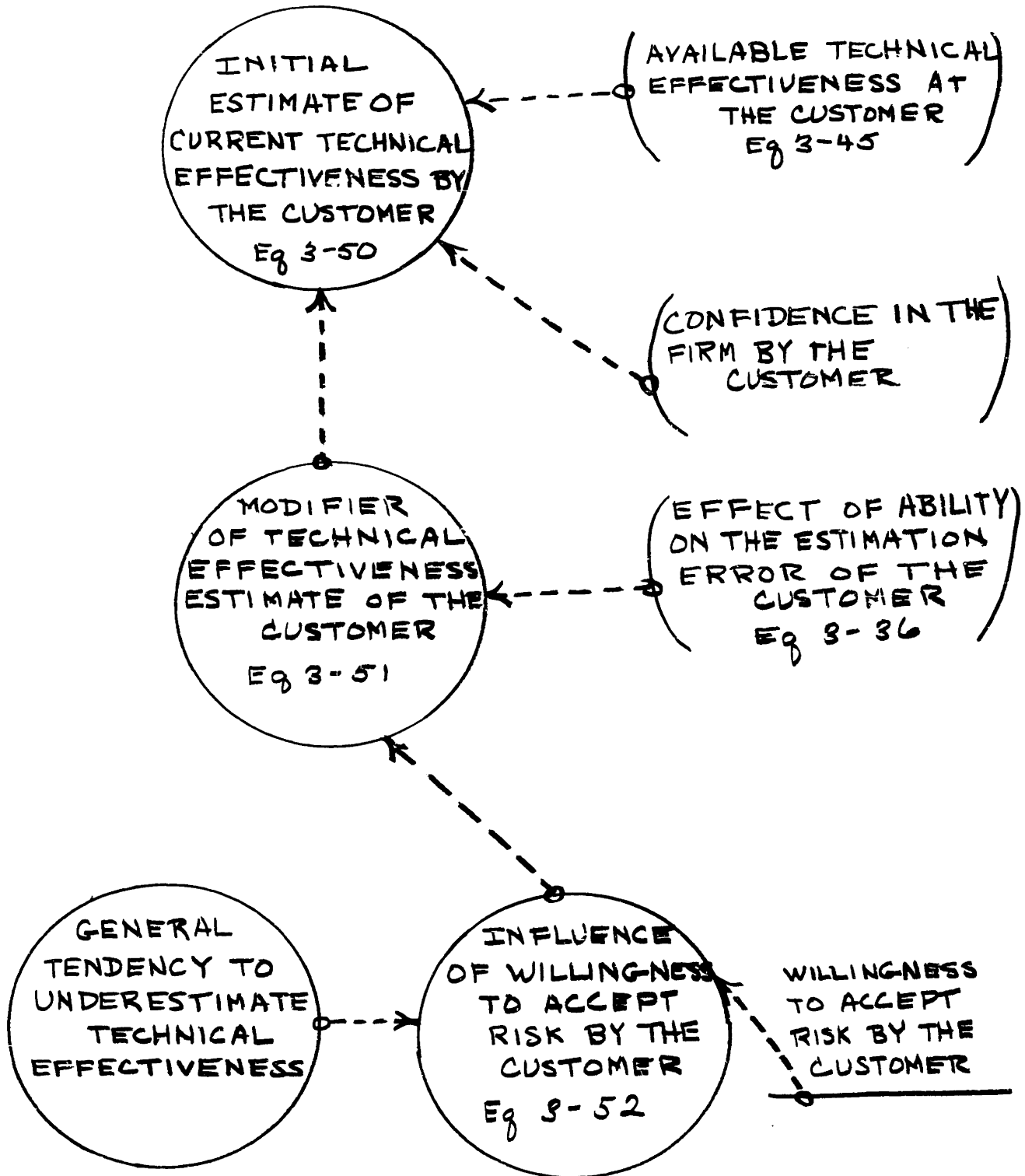


Figure 3-17 Initial Estimate of Current Technical Effectiveness by the Customer

(or willingness to accept risk) in generating an initial estimate of effectiveness. The error due to this latter cause is modified by the over-all ability of the customer.

The factors shown in the diagram are represented in the next three equations. The first equation, number 3-50, indicates that the initial effectiveness estimate is the product of the customer's knowledge as to the available technology, his confidence in the firm, and other modifying influences. Equations 3-51 and 3-52 correspond to Equations 3-20 and 3-21 which were used in representing the firm's estimate.

$$\text{ETEC} = (\text{MTEC})(\text{ATEC})(\text{CNFC}) \quad 3-50, \text{ N}$$

$$\text{MTEC} = 1 + (\text{IWARC})(\text{EAEEC}) \quad 3-51, \text{ N}$$

$$\text{IWARC} = \text{TABLE} (\text{IWTAB}, \text{WARC}, 0, 1, 0.2) \quad 3-52, \text{ N}$$

ETEC--Estimate of current Technical Effectiveness by the Customer (percent effectiveness of engineers)

MTEC--Modifier of Technical effectiveness Estimate by the Customer (percentage)

ATEC--Available Technical Effectiveness at the Customer (percent effectiveness of engineers)

CNFC--Confidence in Firm by the Customer (percentage)

IWARC--Influence of Willingness to Accept Risk by the Customer (percentage)

EAEEC--Effect of Ability on the Estimation Error of the Customer (percentage)

IWTAB--Influence of Willingness TABLE

WARC--Willingness to Accept Risk by the Customer (percentage)

Initially we shall assume that the customer has had slightly better than average relationships with the firm and has 60 percent confidence in the firm's ability.

$$\text{CNFC} = 0.60 \text{ (decimal percentage)}$$

The customer's willingness to accept risk was specified in the Appendix of Chapter II as also equal initially to 60 percent.

The actual changes in the customer's estimate of technical effectiveness are similar to the firm's revisions. The relationships are shown in Figure 3-14. Equations 3-52 to 3-55 below correspond to the firm's Equation's 3-22 to 3-24.

$$RCEEC.KL = \frac{RTEC.K - ETECK}{DRTEC} \quad 3-53, R$$

$$RTEC.K = \frac{(PRBC.JK)(BNKPC.K)}{ENAWF.K} \quad 3-54, A$$

$$RCPEC.KL = \frac{(PECBC.K)(ETEC.K)}{DRAAC.K} \quad 3-55, R$$

- RCEEC--Rate of Change of Estimated current Effectiveness by the Customer (percent effectiveness/month)
- RTEC--Realized Technical Effectiveness by the Customer (percent effectiveness of engineers)
- ETEC--Estimate of current Technical Effectiveness by the Customer (percent effectiveness of engineers)
- DRTEC--Delay in Recognizing Technical Effectiveness by the Customer (months)
- PRBC--Progress Rate Believed by the Customer (percent completion/month)
- BNKPC--Believed Needed Know-how for development of the Product by the Customer (effective man-months of effort)
- ENAWF--ENgineers Actually at Work at the Firm (men)
- RCPEC--Rate of Correction of Previous effectiveness Estimate of the Customer (percent effectiveness/month)
- PECBC--Percent Error in Completion Believed by the Customer (percentage error)
- DRAAC--Delay in Recognizing Actual Achievement at the Customer (months)

The shift by the customer to adopt its current realization of the firm's engineering effectiveness take place quickly. DRTEC has thus been chosen to equal eight months.

$$DRTEC = 8 \text{ months}$$

The customer also forms an estimate of the future technical effectiveness taking into account the extrapolation period which depends upon



his beliefs as to the percent of project left to be completed.

$$EFTEC.K = ETEC.K + (XPTPC.K)(STPRC.K) \quad 3-56, A$$

$$XPTPC.K = (BPPIC.K) \left( \frac{NPD}{2} \right) \quad 3-57, A$$

EFTEC--Estimate of Future Technical Effectiveness by the Customer (percent effectiveness of engineers)

ETEC--Estimate of current Technical Effectiveness by the Customer (percent effectiveness of engineers)

XPTPC--eXtrapolation Period for Technical Progress by the Customer (months)

STPRC--Smoothed Technical Progress Rate by the Customer (percent effectiveness/month)

BPPIC--Believed Percent of Project Incomplete by the Customer (percentage)

NPD--Normal Project Duration (months)

These two equations are similar to Equations 3-25 and 3-26.

Combining these factors, as was done before, the customer comes up with his projection as to the estimated effort requirements of the project as well as the total cost and additional cost to complete the job. They are incorporated in the final three equations of this appendix.

$$EERC.K = TEEF.K + (BPPIC.K)(BNKPC.K/EFTEC.K) \quad 3-58, A$$

$$ETCPC.K = (EMECF)(EERC.K) \quad 3-59, A$$

$$ECCPC.K = ETCPC.K - TECF.K \quad 3-60, A$$

EERC--Estimate of total Effort Required by the Customer (man-months of effort)

TEEF--Total Engineering Effort by the Firm (man-months of effort)

BPPIC--Believed Percent of Project Incomplete by the Customer (percentage)

BNKPC--Believed Needed Know-how for development of the Product by the Customer (effective man-months of effort)

EFTED--Estimate of Future Technical Effectiveness by the Customer (percent effectiveness of engineers)

ETCPC--Estimated Total Cost of the Project by the Customer (dollars)

EMECF--Estimated Monthly Engineering Cost Factor (dollars/man-month)

ECCPC--Estimated Cost to Complete the Project  
for the Customer (dollars)  
TECF--Total Engineering Cost to the Firm  
(dollars)

This completes the modeling for the estimation of project effort  
and cost.



## CHAPTER IV

### FUNDING THE RESEARCH AND DEVELOPMENT PROJECT

Chapters 2 and 3 discussed the ways in which both the customer and the firm determine their estimates of the worth and the cost of the project. These elements are essential to the activities required for providing funds for the project undertaking. The activities include three possible phases: (1) the firm's request for support of engineering effort; (2) the customer's evaluation of this request for funds and his response in the granting of such funds; and (3) the firm's decision to invest its own money in the project activity. The text of this chapter, therefore, will be divided into three corresponding sectors. Of course, all three of the activities to be discussed are continuously taking place during the project life cycle, as are the activities of value perception and effort and cost estimation discussed earlier.

#### The Firm's Bid for Support

Research and development companies, as a matter of necessity, employ at least a small number of people who are constantly looking into new product possibilities. "With such large investments in equipment, factories and personnel...large firms cannot afford to sit idly by, waiting for the military to decide that a certain piece of equipment is needed. They must go ahead on their own, anticipating military needs, and carrying out the preliminary planning at their own cost and at their own risk."<sup>1</sup> The people who do this studying may be

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<sup>1</sup>Creighton M. Marcott, "The Challenge of Space", Electronic Industries, April 1960, p. 110.

part of what is called a research laboratory, an advanced projects group, a preliminary design area, or they may just be regular members of the engineering team who are looking into the extensions of some product ideas beyond the current contracted research and development projects. As the firm engages in such activities, it develops some of the insights which aid the perception of the need for and value of a product, as was discussed in Chapter 2. Similarly, the firm begins to estimate the amount of effort and cost required to complete such projects. For what may amount to a long period of time, the firm's assessment of the value of the product versus the cost of the product may lead the firm to think that the customer will not yet deem the project economically feasible. Based on its own attitudes towards company-sponsored effort (which attitudes will be discussed in greater detail in the final section of this chapter), the company will, to at least some extent, continue these study activities. However, as the firm begins to feel that the resulting project idea might be valuable enough for both it and the customer to further consider, it will probably attempt to get the customer to support at least a portion of the costs of this initial study phase. When this condition is reached, the firm will request that the customer support the so-called "research" activities by means of a "study contract". The firm will probably continue to request funds for such study contracts until it feels in a position to make a sound proposal of a project which it expects will be viewed as economically feasible by the customer. This, then, involves the firm in a comparison not solely of its own estimates of project cost and value, but in addition in a comparison of the estimates of cost and value which it

believes that its potential customer will hold.

As time evolves, as the study activities continue, and as the estimates of project value and expected cost change, the firm's assessment of these factors will also change. In time, the R and D firm may begin to feel that the customer deems the project a worthwhile undertaking, as well as one in which the firm itself is willing to participate. The firm may apply many different criteria in determining its own willingness to participate in a development project. For example, the firm may not be interested in taking part in any development project of size or expected profitability smaller than some minimal amount. The firm may be concerned with the long-run effects on the company's technological growth of participating in such a project undertaking. It may also consider the amount of concentration within some technical area to which the research and development project would lead. Thus there are several prerequisites which the firm may feel are necessary before it is willing to even try to obtain a larger-scale development project.

Once the firm is willing to go ahead, it must consider the reasonability that the customer will support such a research and development project. Under different sets of relationships between the potential customer and the R and D firm, different specific factors might affect the firm's evaluation of the probability of achieving customer support. There is, of course, a great deal of discussion between the marketing and engineering activities of the firm and the contracting agencies of the customer, with the intent of exchanging views on the new ideas of the firm and the newly-found needs of the customer. These continuing

relationships give the firm a fairly good idea as to the customer's position on any given potential project. As a result, in most large-scale undertakings the firm which obtains the R and D contract has from an early stage participated in discussions with the customer about his product needs in that area. The author is aware of several as yet unpublished company studies which have found from analyses of their own proposal and contract activities that the vast proportion of their business has resulted from these early negotiations. Through such discussions and negotiations, the firm forms its own belief as to the likelihood that the customer is willing to go ahead on a project. When this confidence-point is reached, the firm intensifies its negotiation, marketing, and solicitation activities and/or submits an unsolicited proposal to the customer agency.

This whole process is succinctly stated by the Managing Editor of Electronic Industries in the article cited earlier.

To compete for Government defense projects, a firm must be willing to spend a good deal of its own money on research. For instance, the usual form of the military defense project will work something like this: The defense firm...will foresee the need for a certain type of weapon for countermeasure gear or detection equipment, etc. Using their own funds they will investigate the problem to determine whether it is feasible, whether there is a possibility of interesting the military in providing funds for such a development. The money that goes into the initial study, which can be quite considerable, will be completely lost if the Government cannot be convinced that there is a future in this kind of equipment. If the Government is interested, the second stage of the project begins, probably partially supported by Government funds. If the second stage indicates that this piece of hardware can be successfully developed and serve a useful military purpose, stage three begins. This stage will be completely financed by the Government.<sup>2</sup>

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Ibid.

Before discussing the specific nature of contents of project proposals by the firm, it is worthwhile to pause and reflect upon what is here being said about the nature of research and development. In effect, the basic difference between that "research" and that "development" which constitute the typical R and D project is one of attitude and scope, not of basic work content. During the phase of time when the firm believes that the estimate of cost versus value is such that there is little likelihood that the customer will support a program, the firm may still continue activities toward developing new know-how, new techniques, and new ideas relative to the potential project. The funds that it requests for support during this phase of activity may well be labeled "research funds" or study contracts. However, as the attitude of the firm changes toward the relationship of cost and value, the firm also changes what it is willing to request and what it expects the customer is willing to provide for the R and D undertaking. When the firm finally believes the project has reached or will soon reach what might be deemed by the customer to be a condition of economic feasibility, the firm will request the funds necessary to support a larger-scale or wider-scope R and D undertaking. Moneys granted under this request are commonly known as a "development contract" or a development project. The prime distinction between the actions of the firm during the earlier phase discussed above and the phase in which it begins to undertake the development cycle is one largely due to its attitude towards potential support, which attitude comes from its assessment of the cost-value relationship in the project.

This same attitude question distinguishes the customer's feelings



during these two so-called phases of the typical research and development project. For example, during 1960 the Director of Research of the National Aeronautics and Space Administration made the following statement: "Our research on supersonic transports has reached a stage where we believe a design and development program is feasible."<sup>3</sup> However, it has been well known long before 1960 that it was physically possible to build such a supersonic transport plane. Thus the statement seems really to mean that the study program has advanced enough so that the expected costs to produce such a supersonic transport are now within an economically feasible range of the expected value of the aircraft. This in part explains the confused attempts of so many people to distinguish research from development. The source of confusion is the fact that, except in the case of extremely pure basic research (which is so very hard to find in existence), the remainder of the gamut from what is called "applied research" through "development" through "production engineering" is in reality a multiple labeling of engineering efforts aimed at reducing the costs of being able to physically achieve the existence of some desired end product. These different labels are created only by the fuzzy distinctions in mental attitudes as to economic feasibility. When the firm feels that the customer might be willing to support a larger-scope undertaking, what factors determine the characteristics of the financial proposal that the firm then submits to the customer? Primarily, of course, the figures submitted are influenced by the firm's current estimate of the

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<sup>3</sup>Ira H. Abbott, "Research Plans and Programs", NASA--Industry Conference Report, July 28-29, 1960, p. 14.

amount of effort and cost required to complete the job, as well as the firm's estimate of the worth of the end product to the potential customer. But it is very unlikely that these initially-held internal estimates are identical to the figures which appear in the firm's proposal to the customer. Another basic influence enters in the preparation and submission of a proposal to the customer. This is the firm's integrity. Many people have masked the fundamental nature of this integrity influence by referring to the problem of "assessing the competitive situation". By this, they mean that a company recognizes that the low bidder has greater likelihood of receiving the contract. Therefore, many firms attempt to assess what its competitors are likely to bid and, if at all possible, "justify" a bid below that of their competitors. Regardless of how one attempts to rationalize such practices, the fact is that questionable integrity on the part of the bidding firms influences the size of the request for funds in the proposals submitted to the customer. That "everybody's doing it" does not minimize the influence of this integrity factor. Some companies are more susceptible to practices of this sort than others. These companies one could describe as having a lower integrity characteristic than the less susceptible type of company. The lower the integrity of the company, the more it will be willing to "adjust " or "reassess" the cost and effort estimates which are internally held before submitting such estimates to the customer organization.

Some people treat this integrity influence under different labels, for instance the "Wishful Thinking" used by the writer next quoted. But even his terminology points up the integrity aspect.

When the company is anxiously seeking new business... the judgement of the company management is frequently... distorted by wishful thinking. In these cases, over-optimistic estimates are not only accepted at their face value, but are even encouraged by the sales department and the company management. As a result, it is not uncommon to find both schedule and budget estimates processed through all levels of the company with such a strong element of hope that the degree of self-deception in an otherwise reasonably intelligent organization is truly remarkable.<sup>4</sup>

This discussion on integrity is not an attempt to find moral fault in the company procedures for handling research and development. Rather, it is an attempt to identify those factors which influence the behavior that is manifested in research and development projects. The presence or absence of integrity in the practices of the development firms will have a bearing on the proposal requests that are submitted to the customer and consequently on the contracts that are granted by the customer. Thus it is important to recognize the influence of the integrity factor in these bidding activities.

What have been described thus far are the factors which determine when and how the potential developing firm requests funds from the customer organization, first for support of so-called study activities, and later for support of so-called larger-scale development projects. The question might well be asked, "Under what conditions does the firm change its request for funds, i.e., revise its submitted estimates of the dollar amount which will be necessary to complete the job?" During the early phase of "study-contract" activities, whenever the firm feels

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<sup>4</sup>A. L. Stanly, "Logic and Illogic in Engineering and Management", IRE Transactions on Engineering Management, Vol. EM-5, No. 1 (December 1958), p. 145.

that the study project is worthy of more investment, it will then request additional study funds and try to convince the customer of the reasonability of granting such additional support. Similarly, during the larger-scale project undertaking, the firm will revise the cost estimates it has provided the customer, whenever it expects that the over-running costs or possibly the excess of funds is large enough so that it should take action. The firm will then request additional money or reduce its request for funds. Under either of these conditions, the influence of integrity still exists and in part determines the extent of the requests for revision in the customer's support of the project.

#### The Customer's Evaluation of the Funds Request

When the customer receives an unsolicited request for support either of study activities or of a large-scale development program, it must make the decision as to whether or not and to what extent it should financially support these undertakings. In addition, of course, actively considering its own needs, the customer will often initiate requests for such proposals, which in turn will result in the requirement of providing financial resources to some contracting organizations. It would be desirable, at least theoretically, to be able to describe the formal procedure used by the military contracting organizations to evaluate all such requests. However, this is impossible because no such formal criteria exist. Among other reasons for this lack of formal rationale is the fact that, "the contracting activities of large government agencies have become instruments for achieving indirect objectives. These include (1) assisting small business, (2) channeling public funds

into depressed and labor-surplus areas, (3) maintaining a broad national industrial base for mobilization, and (4) supporting academic and institutional programs."<sup>5</sup>

These many factors tend to make the government's project evaluation decisions quite complex in structure, with their basis far less than obvious from evidence only out of the public knowledge on research and development. To define the understanding of the project evaluation area more clearly, the author has undertaken a research study under NASA sponsorship which seeks a sharper picture of actual government evaluation practices.

All of these complicating factors, however, can temporarily be regarded as merely some random elements superimposed upon the underlying stream of evaluation activity. One can also recognize that the customer's evaluation of the reasonability of supporting a project is dependent upon the way he perceives the need for or value of the product versus the way he estimates the amount of effort or cost required to achieve the product. The specific ways and means by which he compares these two factors, the cost and the value, comprise the relationship which is difficult to pin down. From an economic-theory point of view, the customer should discount back to the present the stream of future costs and value which will result from the project undertaking, using some appropriate interest rate as a discount factor.<sup>6</sup> In regard

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<sup>5</sup> McKinsey and Company, Inc., An Evaluation of NASA's Contract Policies, Organization and Performance (Washington: National Aeronautics and Space Administration, 1960), p. 1-4.

<sup>6</sup> In a very interesting and different approach, Stephen Marglin of Harvard University has attacked the traditional view that

to this, however, one article maintained, "Most sophisticated industrial solutions depend on the use of a discount factor to permit the summation of cost and income, or of profit, over time, i.e., the calculation of the present value of a future stream of incomes and costs. In the military case, there are considerable difficulties in the way of establishment of an appropriate discount rate for future expenditures, and even greater obstacles to integrating effectiveness over future years."<sup>7</sup> Even were these difficulties nonexistent, it is unlikely that the military customer would utilize the theoretically advisable approach to the evaluation decision-making. In nearly all investigations of investment decision-making practices, evidences of the use of the approach advocated by economic theory have been almost nonexistent.<sup>8</sup>

The literature which describes research and development project selection by private companies may shed some light on how the military customer actually evaluates and selects new product development projects.

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has said the choice for investment is the alternative which has the current highest discounted cash flow. He calls this the "Myopia Rule" since it nearsightedly ignores the possibility of a time sequence of investments which create highest total discounted flow, but in which the current investment may not be highest in this regard. Mr. Marglin's full discussion of this approach is in preparation for publication.

<sup>7</sup>Richard B. Foster and Francis P. Hoerber, "Cost-Effectiveness Analysis for Strategic Decisions". Journal of the Operations Research Society of America, Vol. 3, No. 4 (November 1955), p. 485.

<sup>8</sup>See, for example: W. W. Heller, "The Anatomy of Investment Decisions", Harvard Business Review, March, 1951, pp. 95-103; J. F. Ebersole, "The Influence of Interest Rates", Harvard Business Review, 1938, pp. 35-39; H. D. Henderson, "The Significance of the Rate of Interest", Oxford Economic Papers, October, 1938, pp. 1-13; and John R. Meyer and Edwin Kuh, The Investment Decision, Harvard University Press (Cambridge, 1957).

Nelson's survey of the literature points to several different analyses of project selection procedures.

A large number of companies state that they have no specific formal plan for selecting projects. In these companies the personal influence of the director is of great importance..... Of the two hundred companies interviewed by the National Science Foundation, forty-six have formal methods for computing returns on research and development projects. Many of these companies, however, calculate returns ex-post as an indicator of how well the laboratory has done in the past, and do not use the method for the purpose of predicting returns from alternative new projects..... Where the R and D computing methods were used to compute relative worth of alternative projects that the company might undertake, the methods usually seemed arbitrary to the point of being worse than useless. A major petroleum company assigns "points" to a project proposal on the basis of chances of success, pay-off, capital required in order to produce the product developed in the laboratory, etc. Project proposals must have a certain number of points before they are accepted. The "point table", however, seems to be built on no rational base.. This does not seem to be atypical.<sup>9</sup>

These evidences are supported by a MIT-sponsored survey of some thirty-seven laboratories operated by twenty-nine large industrial companies, most of whom maintain substantial research and development programs. The report says in part,

Although research executives and company managers have had little success in applying mathematical formulas to the evaluation of research and development, many continue to try to develop valid quantitative yardsticks such as a "profit and loss" function or an "index of return" formula. They use such formulas to decide, in advance, whether a particular project is worth undertaking, as well as to appraise the general value of research projects after completion. Here are several illustrative methods described by respondents:

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<sup>9</sup>Richard R. Nelson, "Invention, Research, and Development: A Survey of the Literature", U. S. Air Force Project Rand Research Memorandum, RM-2146 (April 15, 1958), pp. 55, 56, 57.

"Results are evaluated beforehand by comparing the five-year estimated revenue with the total estimated development expense. They are evaluated afterwards by comparing the estimated two-year savings with the actual savings for machine improvement development."

"Results are evaluated by these formulas:

$$\text{Return on investment} = \frac{\text{New earnings (after taxes)}}{\text{Total investment involved}}$$

$$\text{Payout period} = \frac{\text{Capital outlay on projects}}{\text{New average annual revenue (after taxes)}}$$

"Direct returns expressed on an annual basis are compared with expenses. R and D is credited with the returns for the first three years of commercial application of the work."

"Only a few such formulations have been described in the literature. The best-known formula is the "index of return" developed by a division of the Olin Mathieson Chemical Corporation (before it became part of O-M) several years ago. This formula credits research with the sum of process savings for one year and a fixed percent of sales of new products and improved products for given time periods. The actual percentages and time periods have been subject to change during the years the formula has been in use. The validity of most formulas has been challenged. Also their originators have generally been careful to point out the arbitrary nature of some of the numbers used and the necessity for company-wide agreement on the manner in which R and D "takes credit" for economic results.<sup>10</sup>

Finally, the Director of Research and Development of the United States Air Force offered his analysis of the project selection base. "Since we normally have twice as much work as money, some system of priority must be developed. In applied research the priority is based upon the future operational need, the military advantage to be gained, the technical deficiency, the cost and the risk involved. It is at this point that the program formulation relies heavily on the judgment,

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<sup>10</sup> Albert H. Rubenstein, "Setting Criteria for R and D", Harvard Business Review, January-February, 1957, p. 98.



and knowledge of the research and development personnel.<sup>11</sup>

The only generalization that can be drawn from the above evidence is that companies practically uniformly consider in some fashion both the potential value and the expected cost aspects of an R and D project. The specific way in which they relate these differs from company to company and from lab to lab. It is no doubt true that the military customer also considers both the value and cost aspects of a proposed development. Similarly, however, there is probably no set sufficiency criterion that the relationship of cost and value must pass. The greater the value that the military customer does consider as the expected value of the project, and the lower the expected cost to develop the end results, the more favorable the relationship between these two aspects. The higher the value relative to the cost, the greater the likelihood that the customer will undertake sponsorship of a development effort in this area. The customer's willingness to support a project thus depends upon this value-cost ratio. The amount of money the customer is willing to spend is therefore related to his expectations that the end results of the project will be favorable, according to his own criterion of favorability. During the early phases of a project life cycle, when the firm is merely requesting support for study activities being carried out with relatively small amounts of funds, the customer will support such activities to the extent that he senses this area as having potential value, despite

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<sup>11</sup> Major General M. C. Demler, Speech to the National Aeronautical Electronics Conference, Dayton, Ohio, May 4-6, 1959.

its current lack of "objective" merits. Support of such undertakings is justified by the customer under the label of "supporting research", seeking general knowledge rather than seeking a final product. Here the willingness of the customer to undertake risky ventures will certainly influence the kinds of activities he will be willing to support.

The process of discussion and negotiation between the customer and the firm, which was discussed earlier in this chapter, provides the customer with the firm's public estimate of the cost and value of the proposed project. The customer is influenced by these estimates submitted by the firm to the extent to which he has confidence in the firm's knowledge and ability. This means that following the receipt of a proposal from the firm, the customer may well adjust his estimate of both the value and the cost of the project, moving to at least some extent closer to the estimates expressed by the firm. On the basis of these estimates of value and cost accepted by the customer, the customer will determine the extent to which he is willing to support the financial requirements of the project. In this way the customer determines the total allocations which he desires to make for the particular project under consideration. The actual allocation rate, however, is dependent not only upon these desired allocations, but also upon the availability of sufficient funding authority for the desired allocation level. The customer is not able to exceed any authorization limitations that may have been placed upon him, and even within these bounds will certainly not allocate the full desired amount immediately. There is a delay involved in carefully considering the request for fund funds and the requirements for the project, and in fact, in deciding

to allocate the necessary funds.

The time required to establish and coordinate a general operational requirement for a large system often runs into years even after the fundamental need for a system is fairly well understood. In part, the time is spent in convincing many more or less independent officials of the need. In part, it is spent in elaborating and refining the requirements..... A delay which might be called decision time usually follows. The larger the system, the more deliberation is required by all of the officials who must make decisions and the more officials get into the act. Like requirement time, decision time increases more rapidly than the size and complexity of the system.<sup>12</sup>

Thus a delay in actually allocating the funds to support the firm's activities may in fact, as the cited author mentioned, be related to the size and complexity of the project undertaking, and it certainly may be related to other factors. There is no doubt a minimum budgeting delay necessary for handling the formal paper work and obtaining the minimal number of approvals. Beyond this, there are additional delays that in part depend upon the amount of money that is involved, and in part upon the obviousness of the project justification. If the project is a questionable one in the customer's opinion, it will no doubt take longer to acquire an allocation of funds than if the situation is one in which the need is overwhelming and the cost is tiny, just to cite an extreme. These same basic factors will affect the customer's allocation of funds at any stage of the project life cycle, whether it is before the major work effort has begun or later in the project life. The customer may, as the project evolves, change his earlier estimates

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<sup>12</sup>Dr. Richard C. Raymond, "Avoiding Obsolescence in System Planning" (General Electric Technical Military Planning Operation, May 1959), p. 4.

of cost or value. Such estimate changes may of course result from the request for additional funds by the firm or, on the other hand, from the customer's own internal investigations or intuition. Under such circumstances, the decision to allocate funds may amount to a decision to cancel a certain portion of the allocation in just the same sense that it can be a decision to add additional funds to the previously allocated amounts.

Although the customer may already have allocated funds for a given project, this does not necessarily mean that the customer has released these funds to the firm to spend. For instance, during the phase of project life that has been referred to as the study contract phase, the customer in general does not fully support the costs of the firm. The customer here expects that the firm will invest some of its own money in such a study contract in anticipation that a successful effort will lead to a much greater project later on, bringing additional profits to the firm. Recent changes in practices by military organizations have in fact strengthened this policy of providing only partial funding, and today the customer usually pays about half of the so-called research costs during these study phases. In addition, of course, the customer may feel that he should not bother to support any research activity by the firm, unless this activity is becoming to some extent substantial. The customer may well have a minimal threshold level of research activity below which he will expect the firm to fully support the engineering effort out of the firm's own funds. Thus until this effort rises above such a threshold, the customer will not release any support funds to the firm.

During the portion of the R and D life cycle which is usually labeled the "design and development phase", the customer will make available to the firm funds which do not exceed the actual costs incurred by the firm. The amount of the allocation which is made available at any given time depends upon the schedule which the customer and firm negotiate. As the project evolves, however, the customer may adjust the project schedule. This usually occurs as the customer's evaluation of the merits of the project begins to change. For example, his estimate of product value may decrease, or his estimate of costs increase. In such a case, the customer may well begin to stretch out the project, extending the project duration with the same total of funds. Thus the customer can slow down the expenditure rate of the firm, giving himself more time to see what's what while not spending too much additional money. In this manner, the customer has more or less direct control over the expenditure of his own funds and thereby exercises indirect control over the amount of effort that is put forth by the firm. This general process that we have described thus far--the customer's evaluation of the funds request, his granting or allocation, and his release of the funds--incorporates not only the initiation of large-scale activity, but also the possibility of cancellation of the project. Such cancellation can take place directly by reducing the allocation that has been made to the project, and less directly by gradually stretching out, even to an infinite duration, the project life and gradually withdrawing the funds from the project.

### The Firm's Investment Decision

The firm which does research and development work for the military product market engages in the same kind of evaluation, allocation, and fund release sequence as has just been described for the customer. The earlier discussion pointed out the difficulty of properly selecting and/or evaluating research and development projects. The research or engineering supervisor plays a great role in determining which projects shall be undertaken. In his study of an R and D laboratory, Marcson found that, "The supervisor is not certain whether the research suggestion will prove impractical. Under these circumstances he hedges against the possibility of error. He takes a chance on a suggestion, but only a small chance. He permits the staff man to spend part of his time on a suggested idea--usually a very small part of his time."<sup>13</sup>

By this backhanded method, the projects which after-the-fact are usually labeled "research" are often started. In an earlier discussion we pointed out that the attitude in undertaking these projects is that one does not immediately recognize the economic feasibility of such a proposed undertaking. The study efforts of the firm are thus determined in this relatively informal manner. Quoting from Marcson's report again,

The choice of ideas for research is one of the crucial problems of the laboratory. This is guided by a concern for the development of goods and services. This is not always discernible, and it

raises the continuous question as to which ideas, which projects, lend themselves to such a course. There is, then, always the problem of choice and decision. The guide lines for such decisions are inadequate, but I [the director of research] have to make a decision.<sup>14</sup>

An amusing comment as to who does the project selection is quoted by

Nelson:

The best person to decide what research work shall be done is the man who is doing the research. The next best is the head of the department. After that, you leave the field of best persons and meet increasingly worse groups. The first of these is the research director who is probably wrong more than half the time. Then comes a committee, which is wrong most of the time. Finally, there is a committee of company vice presidents which is wrong all of the time.<sup>15</sup>

But, of course, regardless who makes the project selection decision, he will try to make it intelligently.

A rationally planned inventive effort will only be undertaken if the expected revenue of the invention exceeds the expected cost. In many instances the economic utility of a particular invention is so great that an inventive effort is economically rational, even though the underlying scientific knowledge is scanty, hence the expected cost of making the invention is great. Edison's attempt to develop an incandescent lamp, Goodyear's attempt to improve the characteristics of rubber, are cases in point. In these cases, since there was little useful underlying scientific knowledge, the invention procedure was trial and error, the next trial being roughly--but only roughly--indicated by a very loose theory formulated as the research proceeded. But though the inventors knew that it would probably prove costly to achieve their objective, they believed that the gains, if they were successful, were sufficiently

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<sup>14</sup>Ibid., p. 42.

<sup>15</sup>Richard R. Nelson, "Invention, Research and Development: A Survey of the Literature", op. cit., p. 58.

great to make the effort profitable.<sup>16</sup>

The same fundamental considerations apply to the firm doing research and development for the military market. The amount of money which it is willing to invest in the project depends upon its expectations as to the ultimate profitability of the resulting project, and upon its own willingness to gamble (i.e., invest with no contract assured) its expected profits. Thus the maximum amount of funds that the firm is willing to invest in a particular project depends upon its estimate of the likelihood that the customer will later support that project, its estimate of the profits which would accrue from such support, and its willingness to accept the risk of investing some fraction of those anticipated profits. As time evolves, and its estimates of product value and development cost change, the firm also changes its estimate as to the probability that the customer will undertake large-scale development. Any actions taken by the customer which show an increased (or decreased) willingness to support the project affect the firm's assessment of the situation.

Thus the firm continuously decides upon a total amount which it is willing to invest. It also decides upon a rate of expenditure of these funds, taking into account both the likely duration of its own required support and the availability of company funds for such a purpose. The firm will continue to support the project effort at the rate its investment evaluation process deems appropriate, even after the customer begins partial support through a study-type contract.

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<sup>16</sup>Richard R. Nelson, "The Simple Economics of Basic Scientific Research--A Theoretical Analysis", p. 7.



On the other hand, once the customer has approved a larger-scale project effort, the firm usually withdraws additional support funds, and allows the customer to determine the project funding and, hence, scheduling. However, when the customer encounters funding delays, or cuts back on project support, the firm may again provide additional money to the project if such support is in line with the firm's usual investment evaluation practices.

Thus the dual funding paths initially described in Chapter 1 have been more thoroughly treated here. In the first path the firm requests financial support from the customer organization, the customer evaluates this request based on his own evaluation policies, and may allocate and release funds to the firm for research and development activities. In the second path the firm assesses the likelihood of later obtaining customer support and risks some portion of its expected profits in the project effort investment. Both paths may be in active use simultaneously. Both involve continuous assessment and reaction to the cost-value situation, as determined by the latest available product and project information. Both paths lead to the provision of funds prerequisite to the acquisition of resources and their productive employment, which activities will be described in the next chapter.

## APPENDIX TO CHAPTER IV

The first section of this appendix shall be concerned with those factors which affect the firm's request for funds from the customer. Figure 4-1 portrays these factors. The diagram shows that the firm takes into account its current monthly research costs, projecting them on an annual basis, and requests from the customer support of these research activities. During this period of time the firm is also considering the expected suitability of the project to the customer. In doing this, the firm tries to take into account the investment criteria of the customer, the expected cost of the project to the customer, and the customer's estimate of the product value, to whatever extent the firm is knowledgeable about these customer opinions. As the firm begins to feel that the project would be regarded as suitable by the customer, he changes from requesting funds for support of research to requesting funds for a development project. This change might take place in response to the customer's request for a proposal, or it may be self-initiated by the firm. In determining its request for project funding, the firm takes account of its estimate of the total project costs. However, this total estimate is modified by the integrity of the firm. After initial project funds have been granted, the firm compares the amount of funds that it has previously requested to its changing estimate of total project costs. The expected overruns or underruns in project funding enter into the request for changes in the project funding. The equations describing this part of the firm's activities now follow.

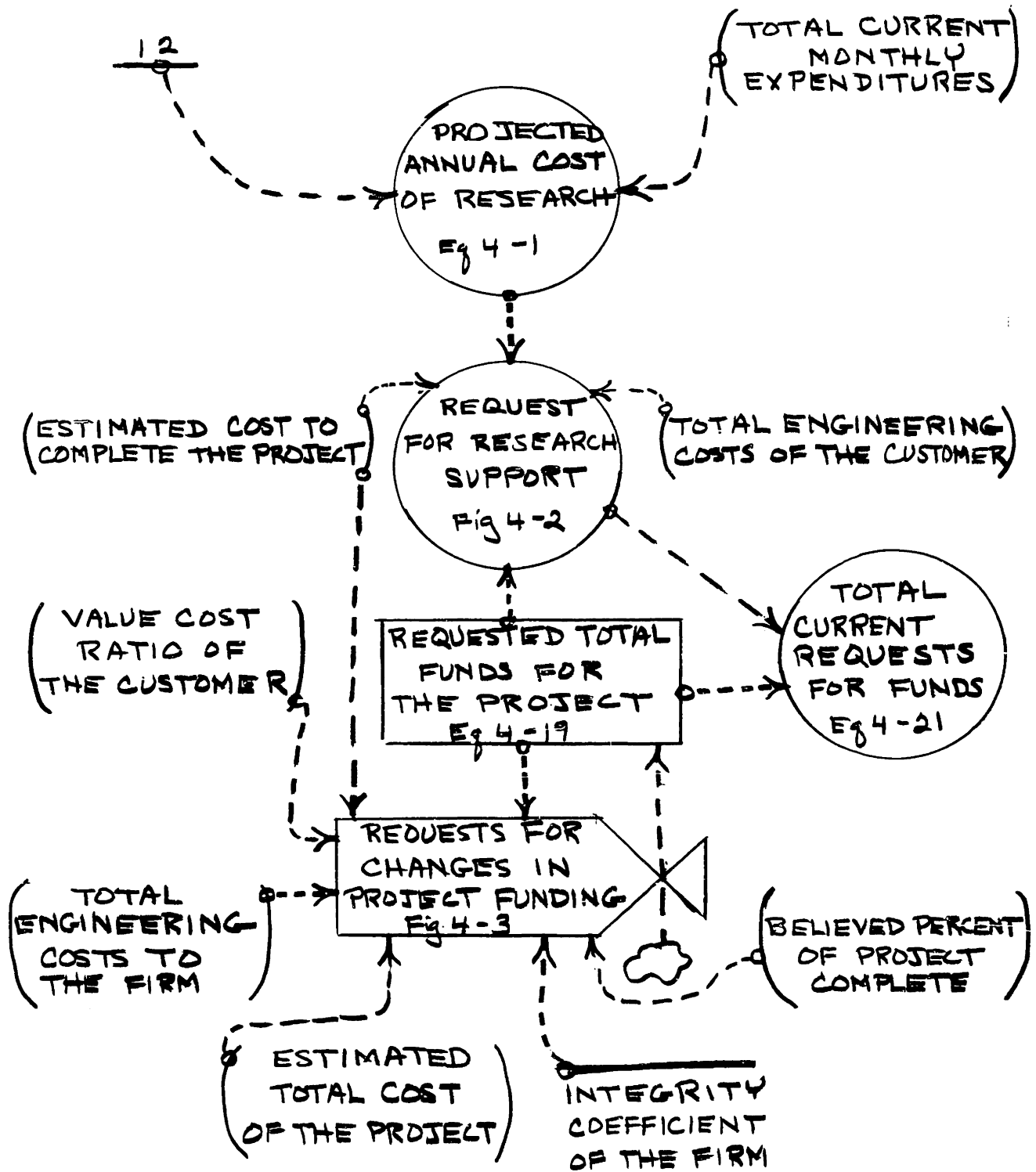


Figure 4-1 The Firm's Bid for Support

The projected annual costs of research at the firm merely extend the current monthly rate by the twelve-month factor to get the yearly rate.

$$PACRF.K = (12)(TCEF.K)$$

4-1, A

PACRF--Projected Annual Cost of Research of the Firm (dollars)

TCEF--Total Current monthly Expenditures at the Firm (dollars/month)

The firm's requests for research support are pictured below.

Here we see that the maximum research support cannot exceed the

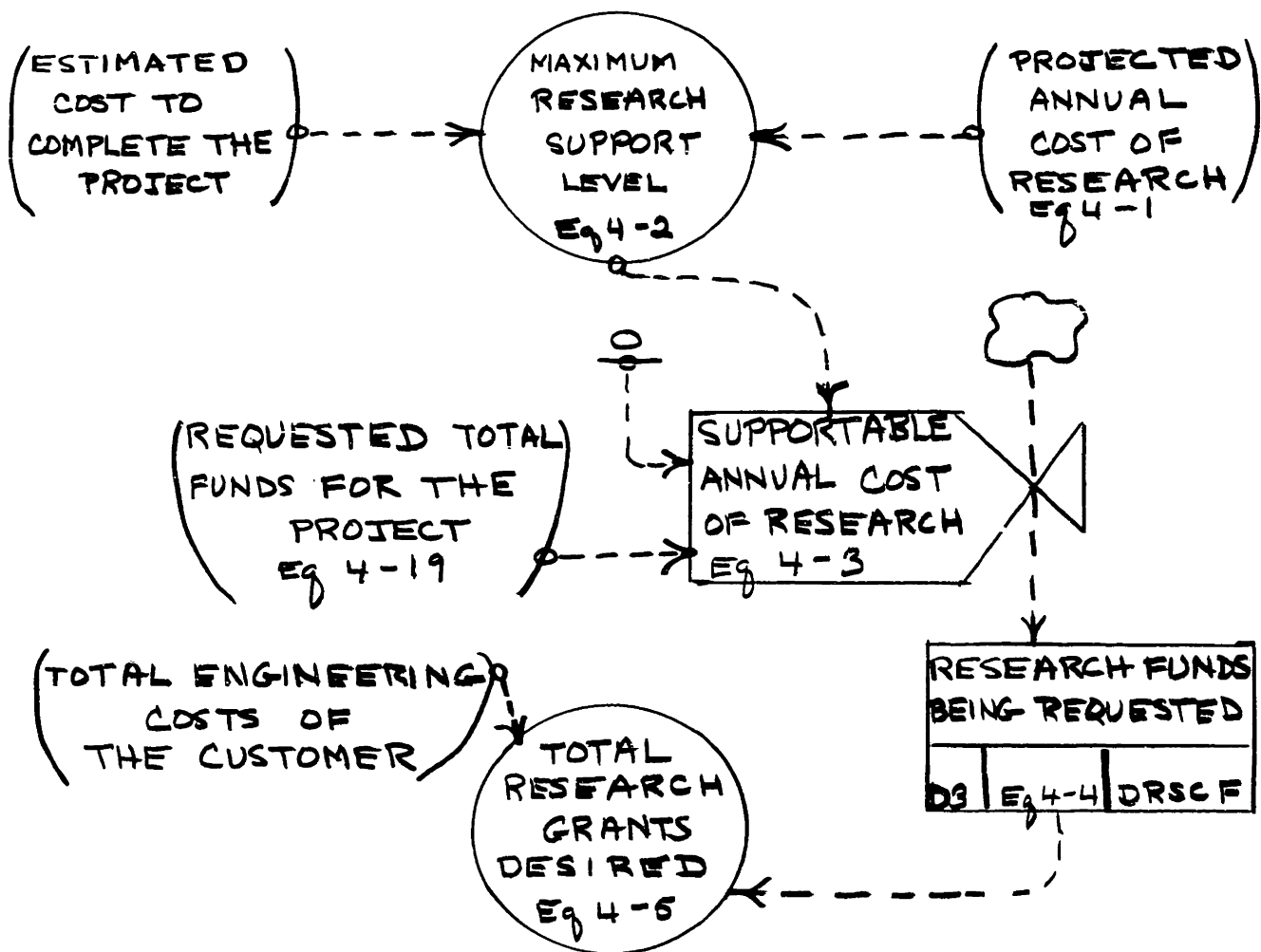


Figure 4-2 Request for Research Support

estimated cost to complete the job. Until the firm gets into the large-scale project it will request this amount of research support. A few months are needed to prepare the request and send it to the customer. These are incorporated in the four equations below.

The maximum research support level takes into account the fact that the research support requests would not exceed the estimated cost to complete the project if these requests were coming at a late stage of project life.

$$\text{MRSLF.K} = \text{MIN} (\text{PACRF.K}, \text{ECCPF.K}) \quad 4-2, \text{ A}$$

MRSLF--Maximum Research Support Level at the Firm (dollars)

MIN--a DYNAMO notation indicating that the smaller of the two values in the parentheses is taken to determine the value of the variable MRSLF

PACRF--Projected Annual Cost of Research at the Firm (dollars)

ECCPF--Estimated Cost to Complete the Project at the Firm (dollars)

The firm will request this maximum support level as long as it is still in a phase of activity that it regards as research. Once the actual development project has begun, the firm will no longer request additional funds to support these research activities. There is a delay between the determination of this support level and the actual request for support of these annual costs. The total research grants desired by the firm, taking into account the amount that the customer has previously supported, is merely a summation of the current request level and the previous support provided by the customer. These facts are incorporated in the following equations:

$$\text{SACRF.KL SWITCH} (\text{MRSLF.K}, 0, \text{RFPF.K}) \quad 4-3, \text{ R}$$

$$\text{RACRF.KL} = \text{DELAY3} (\text{SACRF.JK}, \text{DRSCF}) \quad 4-4, \text{ R}$$

$$\text{TRGDF.K} = \text{TECC.K} + \text{RACRF.JK}$$

4-5, A

SACRF--Supportable Annual Cost of Research at the Firm (dollars)  
 SWITCH--a DYNAMO notation indicating that if RFPF is not equal to zero, then SACRF will be set equal to 0; and if RFPF equals zero, SACRF will equal MLSRF  
 MRSLF--Maximum Research Support Level at the Firm (dollars)  
 RFPF--Requested total Funds for the Project by the Firm (dollars)  
 RACRF--Requested Annual Costs of Research by the Firm (dollars)  
 DELAY3---a DYNAMO notation indicating that RACRF is a third order exponential delay form of SACRF  
 DRSCF--Delay in Requesting Support of Costs by the Firm (months)  
 TRGDF--Total Research Grants Desired by the Firm' (dollars)  
 TECC--Total Engineering Costs to the Customer (dollars)

The firm does not need very much time to prepare its requests for research support. Let us therefore set this processing delay equal to two months.

$$\text{DRSCF} = 2 \text{ months}$$

The equations describing the requests for changes in project funding, as distinct from changes in research support, are diagrammed in Figure 4-3. These requests encompass both the initial request for project funds and the later increases or decreases in that requested amount. The firm's integrity will determine the fraction of the expected total costs it feels are biddable. This fraction changes as the project progresses, since the firm recognizes it must eventually face up to the full expected costs in order for it to receive adequate project funding. When the biddable amount is significantly more than the current funds request, the firm will ask for more money. Similarly,

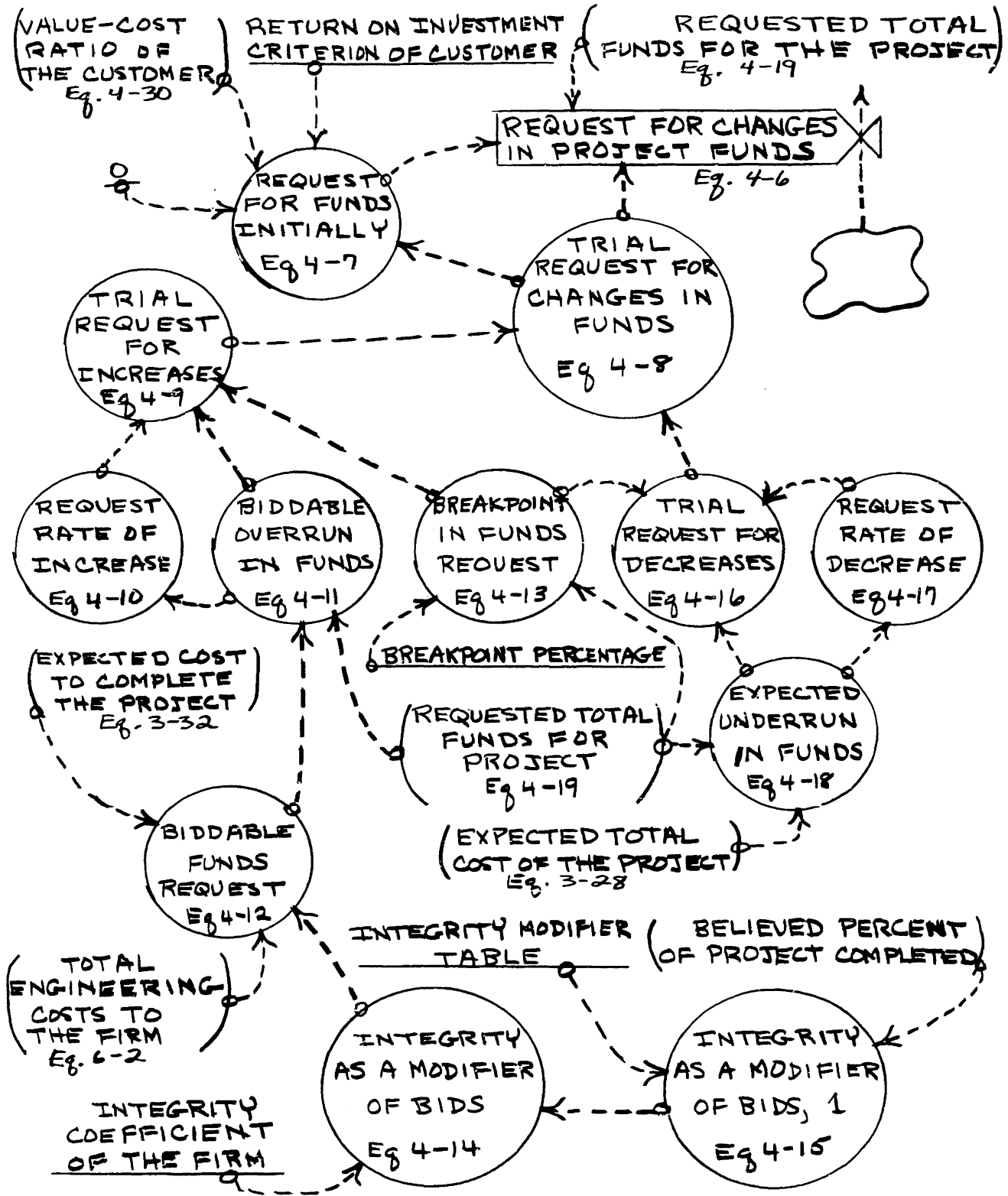


Figure 4-3 Requests for Changes in Project Funding

if the firm expects actual costs to be significantly below the current funds request it will notify the customer of the decrease in the funding requirement.

The first equation below says that if the firm has not yet requested funds ( $RFPF = 0$ ), then the rate of requested changes is determined by the initial request equation; if instead the firm is changing an earlier request, the rate of requested changes is determined by the TRQCF equation.

$RQCPF.KL = SWITCH (RQFIF.K, TRQCF.K, RFPF.K)$  4-6, R

RQCPF--ReQuest for Changes in Project funds  
by the Firm (dollars/month)

RQFIF--ReQuest for Funds Initially by the  
Firm (dollars/month)

TRQCF--Trial ReQuest for Changes in funds by  
the Firm (dollars/month)

RFPF--Requested total Funds for the Project by  
the Firm (dollars)

The firm will not take the initiative of requesting funds until it feels that the value-cost relationship from the customer's point of view exceeds the investment criterion that the customer utilizes. Here, it is assumed that the customer utilizes a return-on-investment criterion which seeks investments whose values are a particular multiple of the expected cost. This relationship is portrayed in the next equation.

$RQFIF.K = CLIP (TRQCF.K, 0, VCRC.K, ROICC)$  4-7, A

RQFIF--ReQuest for Funds Initially by the  
Firm (dollars/month)

CLIP--a DYNAMO notation indicating that if VCRC  
exceeds ROICC, then RQFIF will be set equal  
to TRQCF; if VCRC is less than ROICC, then  
RQFIF will equal 0

TRQCF--Trial ReQuest for Changes in funds by the  
the Firm (dollars/month)



VCRC--Value-Cost Ratio of the Customer (percentage)  
 ROICC--Return On Investment Criterion of the Customer (percentage)

The above equation says that until the value-cost relationship is satisfactory to the customer, the firm will not request funds for project support. It will continue requesting research funds as described in the equations for RACRF above. The customer is here viewed as being willing to undertake only those projects in which he expects the value to be received to be much greater than the cost of the project. Recognizing that other projects are competing for the customer's limited funds, and that the customer is further aware that final costs are likely to exceed current expectations, the customer seeks projects which initially seem to be able to yield a return that is some multiple of his cost. In this case the multiplier (Return on Investment Criterion of the Customer) is viewed as being equal to two, meaning that the expected value must at least equal twice the expected costs. Thus,

$$\text{ROICC} = 2.00 \text{ (decimal percentage)}$$

When the firm decides that it has become suitable to request project support, it will request the amount designated by the following equation for TRQCF. This equation, the trial request for changes in funds, is also the equation which describes the basic variables utilized during any later stage of the project when changes, either increases or decreases, in requested funds are being made by the firm.

$$\text{TRQCF.K} = \text{TRQIF.K} + \text{TRQDF.K} \quad 4-8, A$$

TRQCF--Trial Request for Changes in funds by the Firm (dollars/month)

TRQIF--Trial Request for Increases by the Firm (dollars/month)

TRQDF--Trial Request for Decreases by the Firm (dollars/month)

Thus the above equation has been written generally to include both the request for increases as well as decreases. It says that the request for changes is the sum of the request increases and the request decreases. Naturally, at any one time only one of those two terms would be non-zero.

Let us first look at the factors that lead the firm to request increases in the amount of funded support for the project that it has already begun. As the firm proceeds in a project, its changing estimates of total cost of the project are continuously compared to the amount of funds that have been allotted to it. When the expected overrun in costs increases to the point where the firm feels it must request additional funds from the customer, the firm will request such additional funds. These factors are included in the next several equations, which are thoroughly described below the equation listing.

$$\begin{aligned} \text{TRQIF.K} &= \text{CLIP} (\text{RQRIF.K}, 0, \text{BORFF.K}, \text{BPFRF.K}) && 4-9, A \\ \text{RQRIF.K} &= \text{BORFF.K}/\text{DT} && 4-10, A \\ \text{BORFF.K} &= \text{BFRF.K} - \text{RFPPF.K} && 4-11, A \\ \text{BFRF.K} &= \text{TECF.K} + (\text{IMBF.K})(\text{ECCPF.K}) && 4-12, A \\ \text{BPFRF.K} &= (\text{BP})(\text{RFPPF.K}) && 4-13, A \end{aligned}$$

TRQIF--Trial Requests for Increases by the Firm  
(dollars/month)  
RQRIF--Request Rate of Increase by the Firm  
(dollars/month)  
BORFF--Biddable OverRun in Funds by the Firm  
(dollars)  
BPFRF--BreakPoint in Funds Request by the Firm  
(dollars)  
BFRF--Biddable Fund Request by the Firm (dollars)  
RFPPF--Requested total Funds for the Project by  
the Firm (dollars)  
TECF--Total Engineering Costs to the Firm (dollars)  
IMBF--Integrity as a Modifier of Bids by the Firm  
(percentage)

ECCPF--Estimated Cost to Complete the Project by  
the Firm (dollars)  
BP--Breakpoint Percentage (percentage)

The first equation, TRQIF, says that when the amount of project overrun which the firm feels it can request from its customer exceeds some threshold level of request, the firm will in fact make the request for this additional amount of funds. Equation 4-13 says that the threshold fund request is some percentage of the current total requested funds for the project. This indicates that if the firm already has requested funds, unless it intends to make a substantial change in the request, at least greater than whatever BP percentage is, the firm will not bother to make such a request. The biddable overrun in funds is indicated by Equation 4-11 as being simply the total biddable funds minus the funds that have been requested by the project thus far. The equation of particular interest is 4-12, in which we define this concept of the biddable funds request by the firm. This equation takes into account the fact that the firm without complete integrity will not reveal to the customer the full extent of its expectations as to the total cost of the project, but rather will indicate only a fractional part of the additional cost to complete the job. The IMBF factor indicates the fraction of the expected additional costs that the firm will reveal to the customer. This fraction changes as the project progresses, as will be described in Equations 4-14 and 4-15. Thus Equation 4-12 says that the amount of total requests that are biddable in the firm's opinion is the sum of the total costs to the firm thus far plus some fraction of the expected additional costs, this fraction determined by the firm's integrity.

The percentage expected overrun which the firm can tolerate before requesting more money is an indicator of how rapidly it lets its customer know of expected (and biddable) changes in project costs. Here we have initially selected a five percent breakpoint. If  $BP = 0$ , the firm would continuously inform the customer of biddable cost changes.

$$BP = 0.05 \text{ (decimal percentage)}$$

The way in which integrity acts as a modifier of the bids submitted by the firm is incorporated in the next two equations. The basic integrity coefficient of the firm determines how it will initially modify its expected costs in presenting this estimate to its customer. However, as the project goes on, the firm recognizes that if it is to be able to recover its total costs, it must gradually admit to its full expectations. The equations for IMBF indicate this type of behavior by the firm.

$$IMBF.K = ICF + (1-ICF)(IMBF1.K) \quad 4-14, A$$

$$IMBF1.K = \text{TABLE} (IMTAB, BPPCF.K, 0, 1.5, 0.25) \quad 4-15, A$$

IMBF--Integrity as a Modifier of Bids of the Firm (percentage)

ICF--Integrity Coefficient of the Firm (percentage)

IMBF1--Integrity as a Modifier of Bids of the Firm, 1 (percentage)

IMTAB--Integrity Modifier TABLE, a table of percentile values for determining IMBF1

BPPCF--Believed Percent of Project Completion by the Firm (percentage completion)

The integrity coefficient of the firm will certainly differ from one company to another, and we will want to make several computer runs using different values of this integrity coefficient. Let us start off, however, with a coefficient that represents the firm that is almost completely straightforward in its processing of its request for

funds, and which understates its expected cost estimate by a mere caution factor of 10 percent. The integrity coefficient, therefore, is

$$\text{ICF} = 0.90 \text{ (decimal percent)}$$

The extent to which the firm will stick to this degree of underestimation of costs depends on how far along in the project the firm believes it is. If the project has just begun the firm will see little need to revise its degree of underestimation. However, pressure to admit to the full costs will increase as the project evolves and as the firm tends to get more concerned about receiving adequate project funding. The table of values, IMTAB, will be used to indicate the percentage of the gap between the normal integrity coefficient of the firm and the full recognition of costs that the firm will concede in its estimating procedures as the project evolves.

$$\text{IMTAB*} = 0/0/0/0.60/1/1/1$$

This table shows, with the help of the information of Equation 4-15, that the firm's basic integrity coefficient will determine the cost underestimation that is intentional until the project is felt to be fifty percent complete. Then the firm will gradually admit to the higher cost expectations, fully recognizing them by the time the job has been completed.

The preceding equation group, including Equations 4-9 to 4-15, described what happens when the firm thinks it has requested less funds than it needs for the research and development project. On the other hand, when the firm feels that it has requested more funds than it is going to require, it will also notify the customer and request revision downward in its previous request for funds. This factor works

on the same basic principle as before. The expected underrun (Equation 4-18) is the difference between the current request for project funds and the expected total cost for the project. When this underrun is greater than the threshold (or breakpoint) level at which the firm will make a change in its request for funds, the firm requests a downward revision in RFPF. These facts are incorporated in the following three equations.

$$TRQDF.K = CLIP (RQRDF.K, 0, EURFF.K, BPFRF.K) \quad 4-16, A$$

$$RQRDF.K = -EURFF.K/DT \quad 4-17, A$$

$$EURFF.K = RFPF.K - ETCPF.K \quad 4-18, A$$

TRQDF--Trial Request for Decreases by the Firm  
(dollars/month)

RQRDF--Request Rate Downward by the Firm (dollars/  
month)

EURFF--Estimated UnderRun of Funds by the Firm  
(dollars)

BPFRF--Breakpoint in Funds Request by the Firm  
(dollars)

RFPF--Requested total Funds for the Project by  
the Firm (dollars)

ETCPF--Estimated Total Cost of the Project by  
the Firm (dollars)

All of the above requests for changes in the project funding integrate to create the total level of requested funds for the project.

$$RFPF.K = RFPF.J + (DT)(RQCPF.JK) \quad 4-19, L$$

$$RFPF = 0 \quad 4-20, N$$

RFPF--Requested total Funds for the Project  
by the Firm (dollars)

RQCPF--Requested Changes in Project funds by  
the Firm (dollars/month)

The total current request for funds by the firm is the larger of the two previously described requests, the request for project funds and the request for research grants.

$$TCRFF.K = \text{MAX} (RFPF.K, TRGDF.K)$$

4-21, A

TCRFF--Total Current Requests for Funds by  
the Firm (dollars)

RFPF--Requested total Funds for the Project  
by the Firm (dollars)

TRGDF--Total Research Grants Desired by the  
Firm (dollars)

Figures 4-4 and 4-10 describe in general the customer's continuing evaluation of the suitability of the project, both before and during the period of the customer's actual support of the project, as well as the customer's funding response to this evaluation. Figure 4-4 examines those aspects pertaining to the evaluation and the actual allocation of funds by the customer. The diagram shows that the customer is concerned with determining the suitability of the project for investment. This determination consists of the customer taking into account an estimate of costs, project value, and his own investment criterion, and deciding to what extent he is then willing to support the costs of the firm. Both the cost estimate and value estimate which are actually used by the customer in this determination indicate that the customer pays some attention to the estimates presented to him by the research and development firm, modifying his own internally-held estimate of these factors to some extent based on the information given to him by the firm. The extent to which this modification takes place depends upon the customer's confidence in the firm.

As was mentioned earlier, the firm's request for project funds reflects not only the firm's own estimate of what the costs are going to be, but also takes into account the integrity (or lack thereof) of the firm. This same set of factors is also present in the firm's value estimate that is presented to the customer. Not only is the firm's

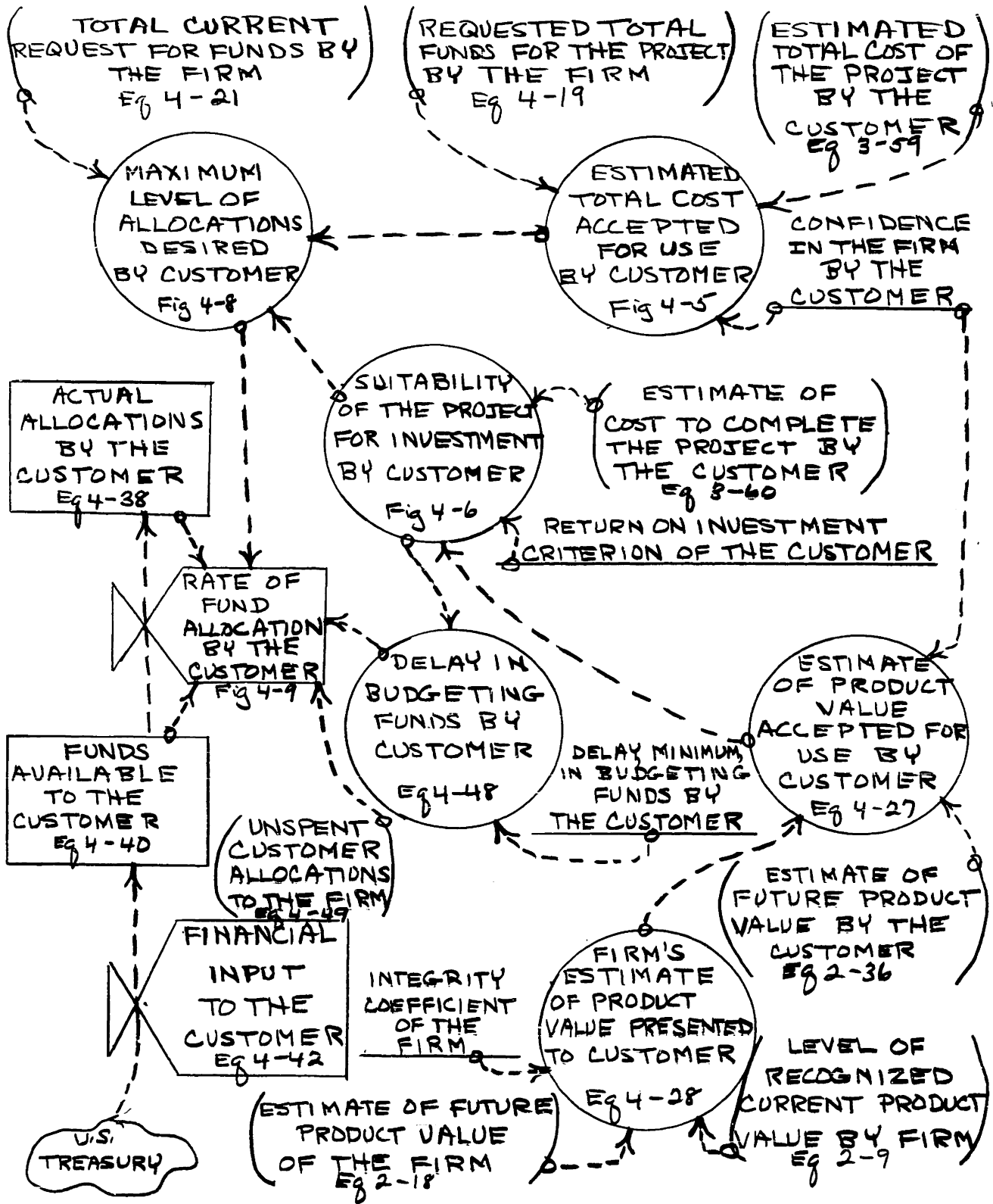


Figure 4-4 Customer Project Evaluation



internally-held estimate of future project value taken into account, but in addition, the firm's integrity may influence it to modify this estimate in trying to convince the firm that the project is, in fact, more worthwhile than the firm itself believes.

On the basis of the customer's determination of the suitability of the project for investment, the customer will determine his willingness to support the costs of the project. The project suitability, the cost estimate accepted for use by the customer, and the firm's own request for funds, determine the maximum amount of allocation that the customer will be willing to make. The suitability of the project in the customer's opinion will also determine to some extent how long it takes for the customer to actually make the approval of the project and begin to allocate funds. If the customer deems the project extremely worthwhile, then he will begin to allocate funds as soon as the minimum paper-processing has been completed. On the other hand, the more doubtful the customer is about the justifiability of the investment, the longer he will take before actually beginning to allocate funds for this purpose. These factors will finally enter into determining the customer's actual allocation rate, which will shift funds from those generally available to the customer (if there are, in fact, sufficient funds actually available) into the actual level of the funds allotted to the particular project under consideration.

Let us now turn to develop the equations which go along with the previous diagram, Figure 4-4. First, we shall take account of the fact that the estimate of the total cost which has been accepted for use by the customer combines not only the customer's internally-held cost

estimate, but also to some extent takes into account the firm's requests for funds. These considerations are shown in Figure 4-5. Here the accepted total cost estimate is indicated as the sum of the customer's internally-generated estimate plus some fraction of the difference recognized by the customer between its own estimate and the firm's requested funds for the project. The customer's confidence in the firm determines the extent to which he will substitute the firm's request for his own estimate. Two time-dependent factors also enter into the diagram. First, until the firm submits a bid to the customer (formal or informal) the customer does not have the firm's estimated cost available to it.

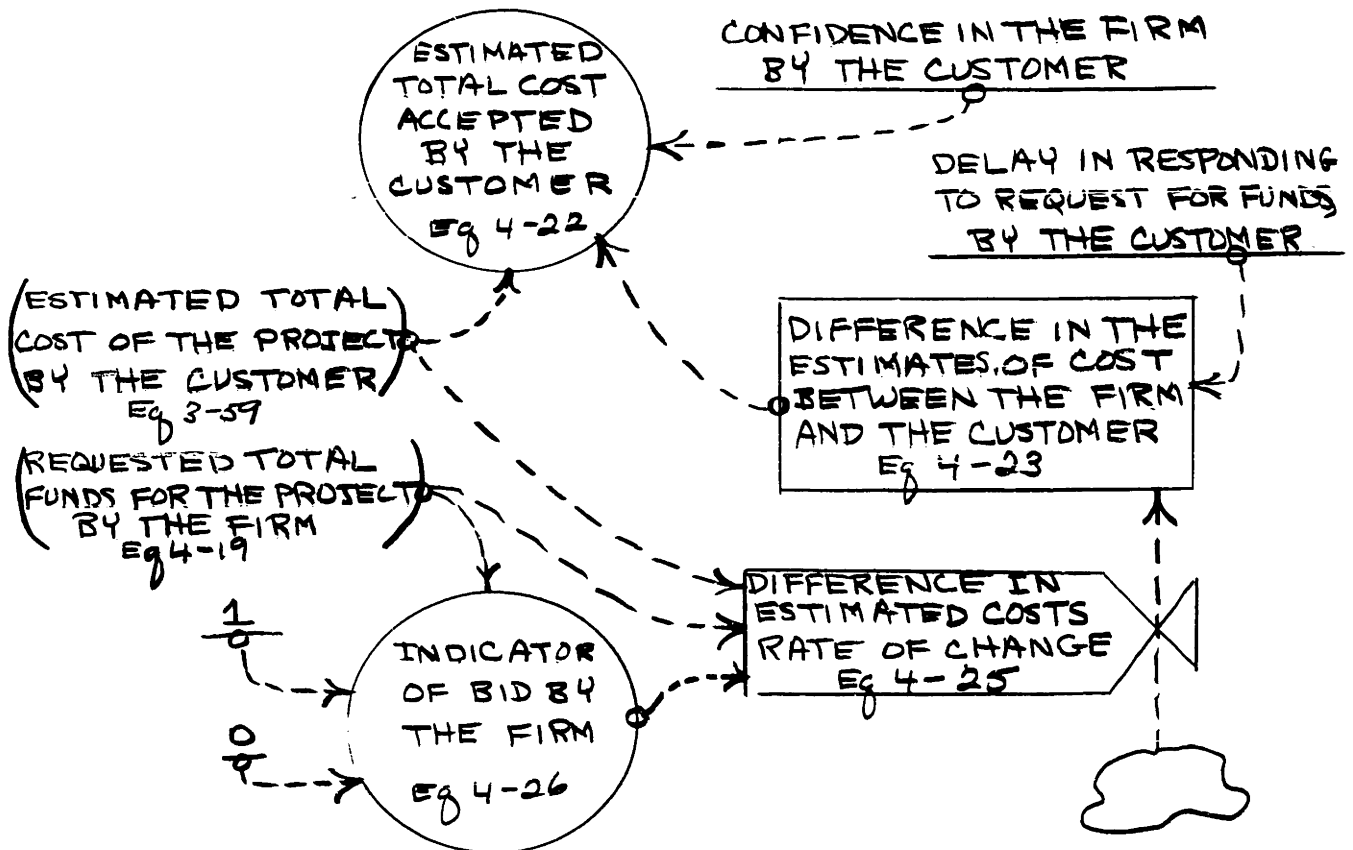


Figure 4-5 Estimated Total Cost Accepted for Use by the Customer

Secondly, even after receiving the firm's request, several months expire before the customer responds to the firm's estimate and begins to change his own estimate to take account of the firm's proposal project cost.

The equations which correspond to this diagram are listed below. The first equation, Equation 4-22, indicates that the cost estimates used by the customer in his decision as to the suitability of the project takes into account his own internal estimate,  $ETCPC$ , and some fraction of the difference between his own estimate and the estimate presented to him by the firm's request for funds. The extent to which the firm's request is actually taken into account depends upon the customer's confidence in the firm. For instance, if the customer has no confidence in the firm, the confidence indicator will be zero, and the equations indicate that the estimate of cost accepted by the customer will be wholly his own internally-generated estimate. On the other hand, if the customer has complete confidence in the firm, then the estimate will gradually move to be the amount represented by the customer's request for project funding. This change would take place over a period indicated by the delay,  $DRRFC$ , in the equation for  $DECFC$ . This is merely a smoothing of the actual difference between the firm's request and the customer's previously internally-held estimate, as indicated in Equation 4-25. This latter equation also takes into account the fact that the firm's cost estimate will not in general be known to the customer until he actually submits a bid for funds for the project. The fact of such submission is indicated by the equation for  $IBF$ , Equation 4-26.

$$\begin{aligned} \text{ETCAC.K} &= \text{ETCPC.K} + (\text{CNFC})(\text{DECFC.K}) && 4-22, \text{ A} \\ \text{DECFC.K} &= \text{DECFC.J} + (\text{DT})(1/\text{DRRFC})(\text{DECRC.JK} - \text{DECFC.J}) && 4-23, \text{ L} \\ \text{DECFC} &= 0 && 4-24, \text{ N} \\ \text{DECRC.KL} &= (\text{IBF.K})(\text{RFPF.K} - \text{ETCPC.K}) && 4-25, \text{ R} \\ \text{IBF.K} &= \text{SWITCH}(0, 1, \text{RFPF.K}) && 4-26, \text{ A} \end{aligned}$$

ETCAC--Estimated Total Cost Accepted by the Customer (dollars)  
 ETCPC--Estimated Total Cost of the Project by the Customer (dollars)  
 CNFC--Confidence in the Firm by the Customer (percentage)  
 DECFC--Difference in the Estimates of Cost between the Firm and the Customer (dollars)  
 DRRFC--Delay in Responding to Requests for Funds, by the Customer (months)  
 DECRC--Difference in Estimated Costs, Rate of Change (dollars/month)  
 IBF-- Indicator of Bid by the Firm (dimensionless)  
 RFPF--Requested total Funds for the Project by the Firm (dollars)

In Chapter 3 the customer's confidence in the firm was discussed in reference to the customer's estimate of the technological effectiveness of the firm. There CNFC was set equal to 60 percent for the initial runs. The second constant used in the above equations was DRRFC, the "Delay in Responding to Requests for Funds, by the Customer". This delay indicates how long it takes before the customer takes into account, in forming his own cost estimate, the funds request of the firm. It shall here be assumed to equal three months. Therefore,

$$\text{DRRFC} = 3 \text{ months}$$

The second aspect that enters into the customer's determination of suitability of the project is his estimate of value of the project. The same type of procedure as was used above in discussing the cost estimate will be used in discussing the value estimate accepted for

use by the customer. The customer modifies his own internally-generated estimate of the future product value by some fraction of the difference between this estimate and that which is presented to him by the firm. This extent again is dependent upon the customer's confidence in the firm. The firm's estimate that is presented to the customer represents what the firm believes to be its self-interest in trying to magnify the ultimate worth of the project by overstating the firm's internally-held beliefs as to the maximum value of the product. The degree of overstatement depends on the firm's integrity. The equations expressing these facts are:

$$\text{EVAUC.K} = \text{EFPVC.K} + (\text{CNFC})(\text{FEVPC.K} - \text{EFPVC.K}) \quad 4-27, \text{ A}$$

$$\text{FEVPC.K} = \text{EMXVF.K} + (1-\text{ICF})(\text{EMXVF.K}) \quad 4-28, \text{ A}$$

$$\text{EMXVF.K} = \text{MAX} (\text{EFPVF.K}, \text{LRPVF.K}) \quad 4-29, \text{ A}$$

EVAUC--Estimate of product Value Accepted for  
Use by the Customer (dollars)

EFPVC--Estimate of Future Product Value by the  
Customer (dollars)

CNFC--Confidence in the Firm by the Customer  
(percentage)

FEVPC--Firm's Estimate of product Value Presented  
to the Customer (dollars)

EMXVF--Estimate of MaXimum product Value by the  
Firm (dollars)

ICF--Integrity Coefficient of the Firm (percentage)

EFPVF--Estimate of Future Product Value by the  
Firm (dollars)

LRPVF--Level of Recognized current Product Value  
by the Firm (dollars)

The latter equation indicates the fact that the firm's estimate that is presented to the customer is based on the larger of the two estimates of the firm, the future value or the current value of the product outcome.

On the basis of the estimate of value and cost just prepared, the

customer now can determine how suitable the project is according to his own investment criterion. This process is illustrated in the next diagram. Taking into account his accepted product value estimate and his expectations as to the costs needed to complete the project, the customer determines the ratio of value to cost for the project. Comparing this to his investment criterion, a desired value-cost ratio, the customer decides how suitable the project appears for his investment purposes. This then determines the extent to which the customer will be willing to finance the costs of the project.

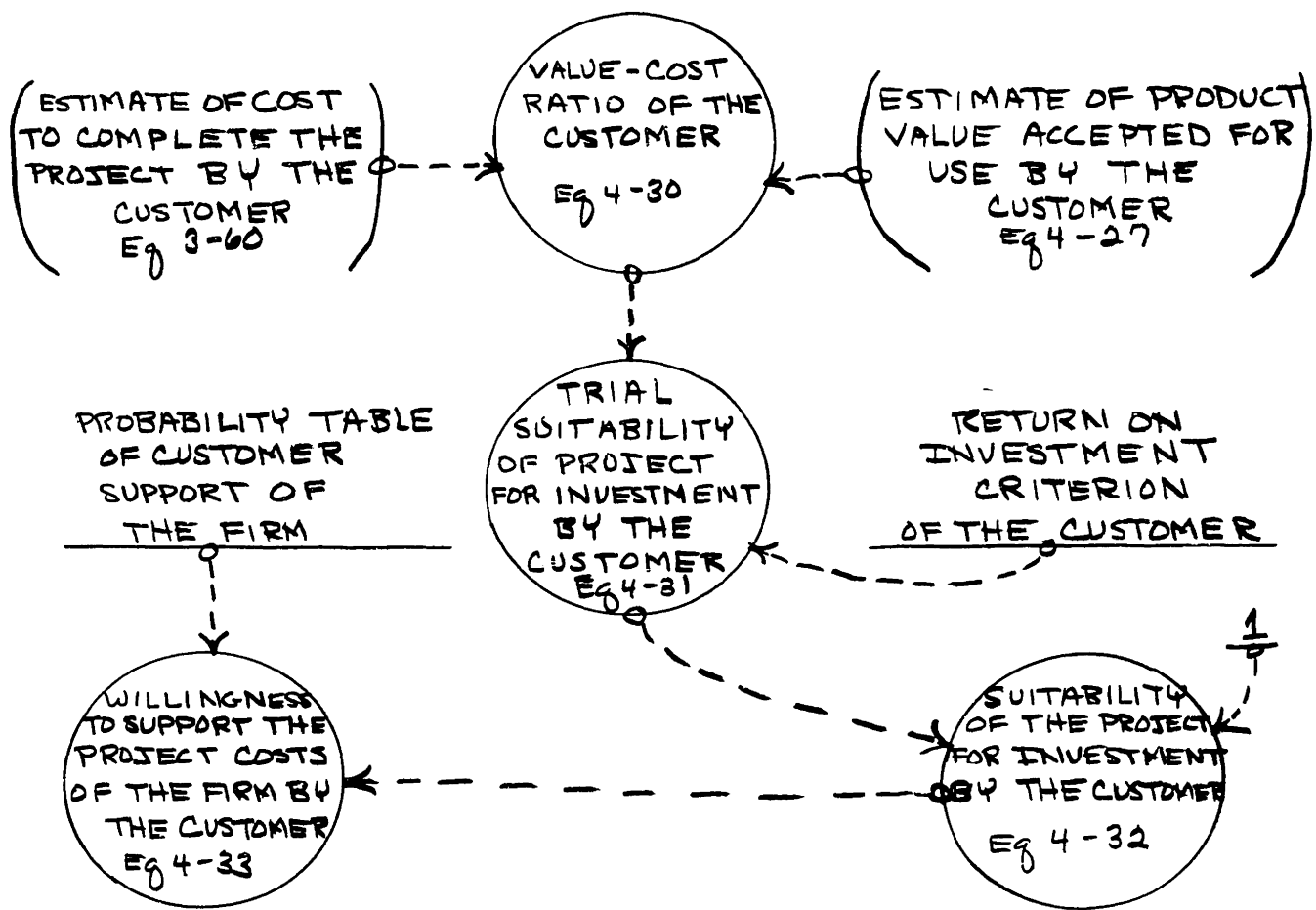


Figure 4-6 Suitability of the Project for Investment by the Customer

The first equation in the following group indicates that the value estimate is compared not with the total project cost estimate, rather with the estimate of the cost to complete the project. This indicates that the customer does not consider sunk costs in his investment decision making. Economic theory tells us that this is the way in which people are supposed to make investment decisions, that is, disregarding sunk costs. However, there are many who would question whether, in fact, this practice is followed. Here we are adopting for representation in the model the theoretically advisable practice and could if we wished, in later variations of the model equations, adopt any other type of value-cost comparison that is desired.

The second and third equations, Equations 4-31 and 4-32, take the ratio of this value-cost relationship to the return on investment criterion of the customer (which in turn expresses his desired value-cost relationship), and limits this ratio to numbers less than 1. The 1 limit indicates that the customer thinks the project is 100 percent suitable for his investment purposes. The final equation indicates that the probability of customer support is a tabular function of the relationship between the values, costs, and investment criterion of the customer. The equations now follow:

$$VCRC.K = \frac{EVAUC.K}{ECCPC.K} \quad 4-30, A$$

$$TSPIC.K = \frac{VCRC.K}{ROICC} \quad 4-31, A$$

$$SPINC.K = \text{MIN} (TSPIC.K, 1) \quad 4-32, A$$

$$WSCFC.K = \text{TABHL} (PCSF, SPINC.K, 0, 1, 0.1) \quad 4-33, A$$

VCRC--Value-Cost Ratio at the Customer  
(percentage)

EVAUC--Estimate of product Value Accepted for  
Use by the Customer (dollars)

ECCPC-- Estimate of Cost to Complete the Project  
 by the Customer (dollars)  
 TSPIC--Trial, Suitability of Project for Inves-  
 tment by the Customer (percentage)  
 ROICC--Return On Investment Criterion of the  
 Customer (percentage)  
 SPINC--Suitability of Project for INvestment  
 by the Customer (percentage)  
 WSCFC--Willingness to Support the project Costs  
 of the Firm by the Customer (percentage)  
 TABHL--TABLE, High-Low, a DYNAMO notation which  
 indicates that the PCSF table will be used  
 to supply the value of WSCFC corresponding  
 to the current value of SPINC. Should SPINC  
 exceed the high limit of 1 or the low of 0,  
 WSCFC will be set equal to the value which  
 corresponds to the appropriate high or low  
 extreme.  
 PCSF--Probability table of Customer Support of the  
 Firm (percentage)

The return on investment criterion of the customer, ROICC, was earlier set equal to two, indicating that the customer desired to invest in projects in which the expected value was at least twice the expected additional cost.

The willingness of the customer to support the firm depends upon the suitability of the project for investment to the customer, as defined in Equation 4-32 by the ratio of the value-cost relationship to the investment criterion of the customer. The probability of this customer support is pictured in the diagram on the next page, Figure 4-7.

Based on his willingness to support the project and upon his estimates of the total cost to complete the project, the customer determines the total amount of funds that he is willing to put into the project. The amount that he actually decides to allocate is the smaller of this total amount that he is willing to spend and the amount that has been requested by the firm, and recognized by the customer. There is some delay before the customer responds to the firm's funding requests.



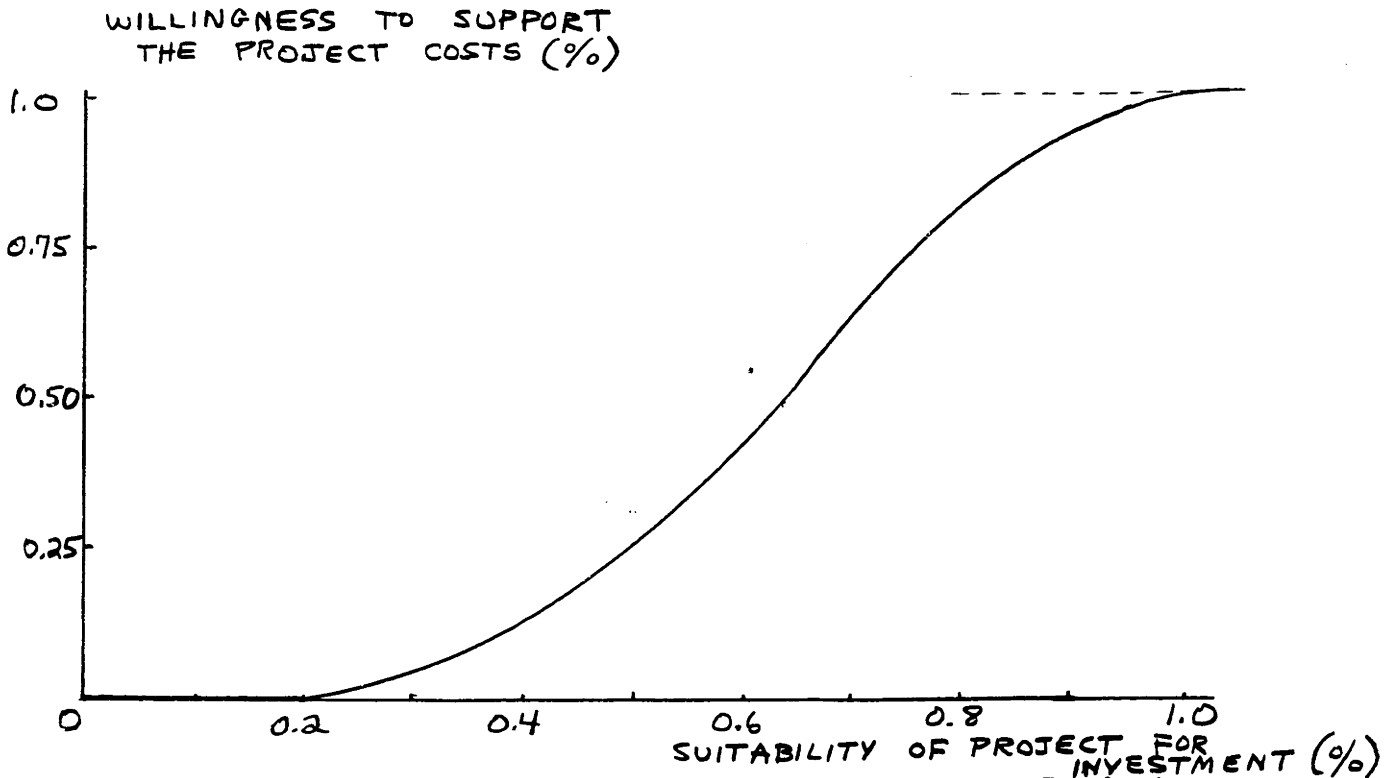


Figure 4-7 Probability of Customer Support of the Project

The values pictured in the diagram are specified at increments of 0.1 in the value of SPINC by the table for PCSF as follows:

$$PCSF^* = 0/0/0/0.1/.2/.3/.5/.75/.9/.95/1.0$$

These relationships are shown in Figure 4-8.

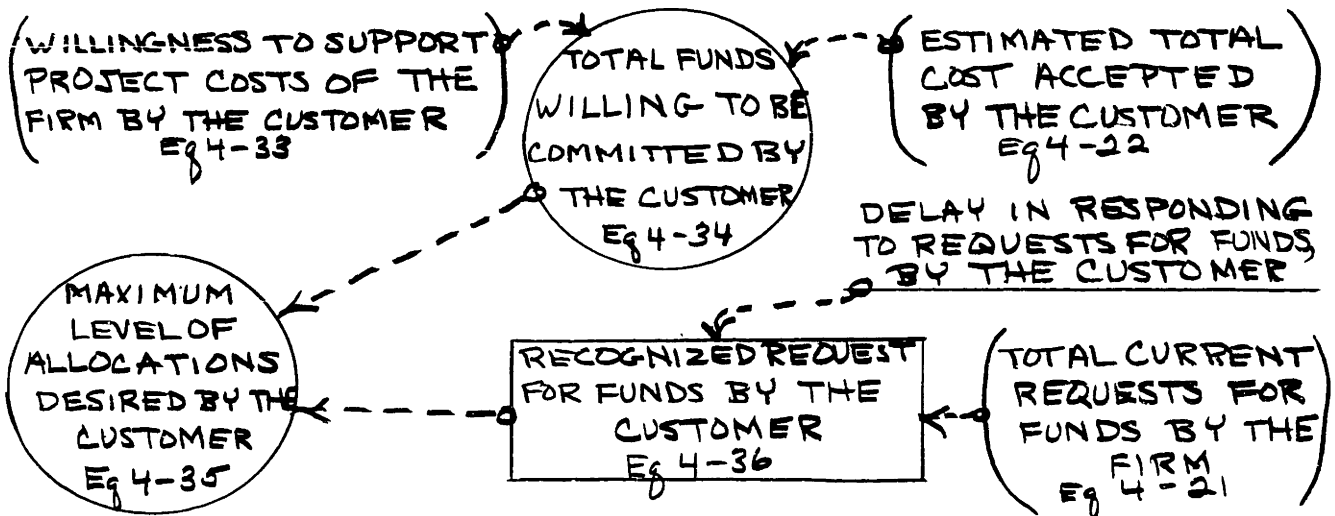


Figure 4-8 Maximum Level of Allocations Desired by the Customer

The first equation below says that the customer is willing to support a fractional part of the expected project costs, that fraction indicated by his willingness to invest that was represented in Equation 4-33. The second equation shows that the customer will not grant more than the firm has actually requested. Finally, Equation 4-36 indicates that it takes a few months before the customer is fully aware of the firm's current request for funds and can take this factor into account in its allocation decision.

$$\text{TFWCC.K} = (\text{WSCFC.K})(\text{ETCAC.K}) \quad 4-34, \text{ A}$$

$$\text{MADC.K} = \text{MIN} (\text{TFWCC.K}, \text{RRFC.K}) \quad 4-35, \text{ A}$$

$$\text{RRFC.K} = \text{RRFC.J} + (\text{DT})(1/\text{DRRFC})(\text{TCRFF.J} - \text{RRFC.J}) \quad 4-36, \text{ L}$$

$$\text{RRFC} = 0 \quad 4-27, \text{ N}$$

TFWCC--Total Funds Willing to be Committed by the Customer (dollars)  
 WSCFC--Willingness to Support the project Costs of the Firm by the Customer (percentage)  
 ETCAC--Estimated Total Costs Accepted by the Customer (dollars)  
 MADC--Maximum level of Allocation Desired by the Customer (dollars)  
 RRFC--Recognized Request for Funds by the Customer (dollars)  
 DRRFC--Delay in Responding to Requests for Funds, by the Customer (months)  
 TCRFF--Total Current Requests for Funds by the Firm (dollars)

DRRFC was established as three month, following its use in Equation 4-23.

The equations continue with the two level equations for the cumulative allocations by the customer and the funds available for additional allocation by the customer. With these two levels is also the rate equation for the financial input to the customer. This equation provides a single pulse of a very large amount of money at the input time for the customer. Financial restrictions in the customer's funds can be

considered by altering either the dollar value of VLARG or the timing of INTMC.

$AAC.K = AAC.J + (DT)(RFAC.JK)$	4-38, L
$AAC = 0$	4-39, N
$FAC.K = FAC.J + (DT)(FINC.JK - RFAC.JK)$	4-40, L
$FAC = 0$	4-41, N
$FINC.KL = PULSE (VLARG, INTMC, VLARG)$	4-42, R

AAC--Actual Allocations by the Customer  
(dollars)  
RFAC--Rate of Funds Allocation by the Customer  
(dollars/month)  
FAC--Funds Available to the Customer (dollars)  
FINC--Financial INput to the Customer (dollars/  
month)  
VLARG--Very LARGE number (dimensionless)  
INTMC--INput TIME of funds for the Customer  
(month)

VLARG is set equal to one billion, to insure no runout of customer funds in the projects to be considered. The input time of these funds is initially set at TIME = 0 and will be varied in later project simulations. Thus,

$$VLARG = 1E10$$

$$INTMC = 0$$

The following figure represents the fact that the fund allocation rate of the customer may be constrained either by the desired rate or by the available funds. The desired allocation rate reflects the customer's continuous attempt to have his actual allocations to the project equal his desired level of allocations. The customer tries to implement this attempt over a period of time designated by his variable delay in budgeting funds. Since this rate may either allocate additional monies or cancel previous allocations, the diagram also

recognizes that the customer cannot cancel more than the allocations to the firm which have not already been spent.

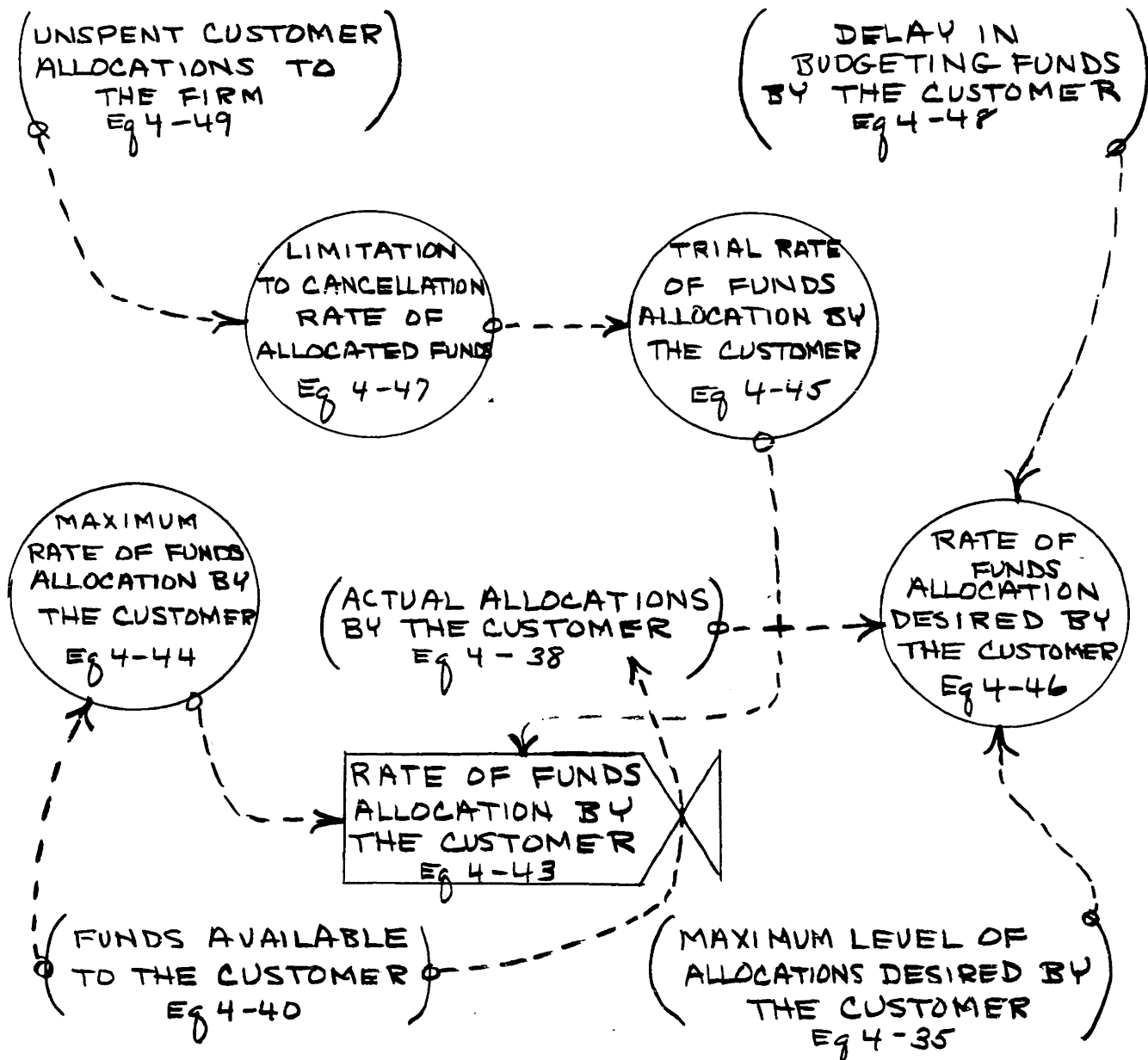


Figure 4-9 Rate of Funds Allocation by the Customer

The equation for the funds allocation rate by the customer, RFAC, takes into account the fact that the funds desired to be allocated, TRFAC, may not be available to the customer in his balance of unallocated

funds, FAC. The maximum rate that can be allocated, MRFAC, is the amount that would deplete the available funds in one solution time-interval of the equations.

$$\text{RFAC.KL} = \text{MIN} (\text{TRFAC.K}, \text{MRFAC.K}) \quad 4-43, \text{ R}$$

$$\text{MRFAC.K} = \frac{\text{FAC.K}}{\text{DT}} \quad 4-44, \text{ A}$$

RFAC--Rate of Funds Allocation by the  
Customer (dollars/month)

TRFAC--Trial Rate of Funds Allocation by  
the Customer (dollars/month)

MRFAC--Maximum Rate of Funds Allocation by  
the Customer (dollars/month)

FAC--Funds Available to the Customer (dollars)

The rate of allocation desired by the customer represents the customer's adjustment to the difference between his desired total allocation and the actual allocations that he has made thus far. His delay in actually budgeting these funds depends upon, first, the minimum delay in processing the paper work for these funds, and secondly, the extent to which the customer is enthusiastic about the project. If the customer is enthusiastic about the project, then he can push through the allocation with the minimum delay. However, if his enthusiasm is at all questionable, there is reason to believe that the customer will take much longer to make up his mind to actually allocate the funds. These factors are included in the equations below. In addition, the equations below recognize that at times the customer will feel that he has overextended himself and allocated too much money to the project under consideration. In this circumstance, the customer's allocation rate will actually be an allocation cancellation rate, which cancellation rate is limited to the amount of allocations which have not yet been spent by the firm.

$$\begin{aligned} \text{TRFAC.K} &= \text{MAX} (\text{RFADC.K}, - \text{LCRAF.K}) && 4-45, \text{ A} \\ \text{RFADC.K} &= \frac{\text{MADC.K} - \text{AAC.K}}{\text{DBFC.K}} && 4-46, \text{ A} \\ \text{LCRAF.K} &= \frac{\text{UCAF.K}}{\text{DT}} && 4-47, \text{ A} \\ \text{DBFC.K} &= \text{DMBFC} + (\text{DBFTC})(1-\text{SPINC.K}) && 4-48, \text{ A} \end{aligned}$$

TRFAC--Trial Rate of Funds Allocation by the Customer (dollars/month)  
 RFADC--Rate of Funds Allocation Desired by the Customer (dollars/month)  
 LCRAF--Limitation to Cancellation Rate of Allocated Funds (dollars/month)  
 MADC--Maximum level of Allocation Desired by the Customer (dollars)  
 AAC--Actual Allocations by the Customer (dollars)  
 DBFC--Delay in Budgeting Funds by the Customer (months)  
 UCAF--Unspent Customer Allocations to the Firm (dollars)  
 DMBFC--Delay, Minimum, in Budgeting Funds by the Customer (months)  
 DBFTC--Delay in Budgeting Funds, Time Constant (months)  
 SPINC--Suitability of the Project for Investment by the Customer (percentage)

A reasonable value for the minimum delay in the customer's processing of the allocation requests is one-half year with a probable maximum additional delay of another year. Thus,

$$\text{DMBFC} = 6 \text{ months}$$

$$\text{DBFTC} = 12 \text{ months}$$

In any case the customer's own desired maximum level of allocation, MADC, serves as a restraint on the allocation rate.

Figure 4-10 completes the pictorial presentation of those factors which relate to the customer's continuing evaluation of the project and his response to these evaluations. This diagram specifically examines the aspects relating to the customer's project control measures. The customer attempts to exercise control over the project through his

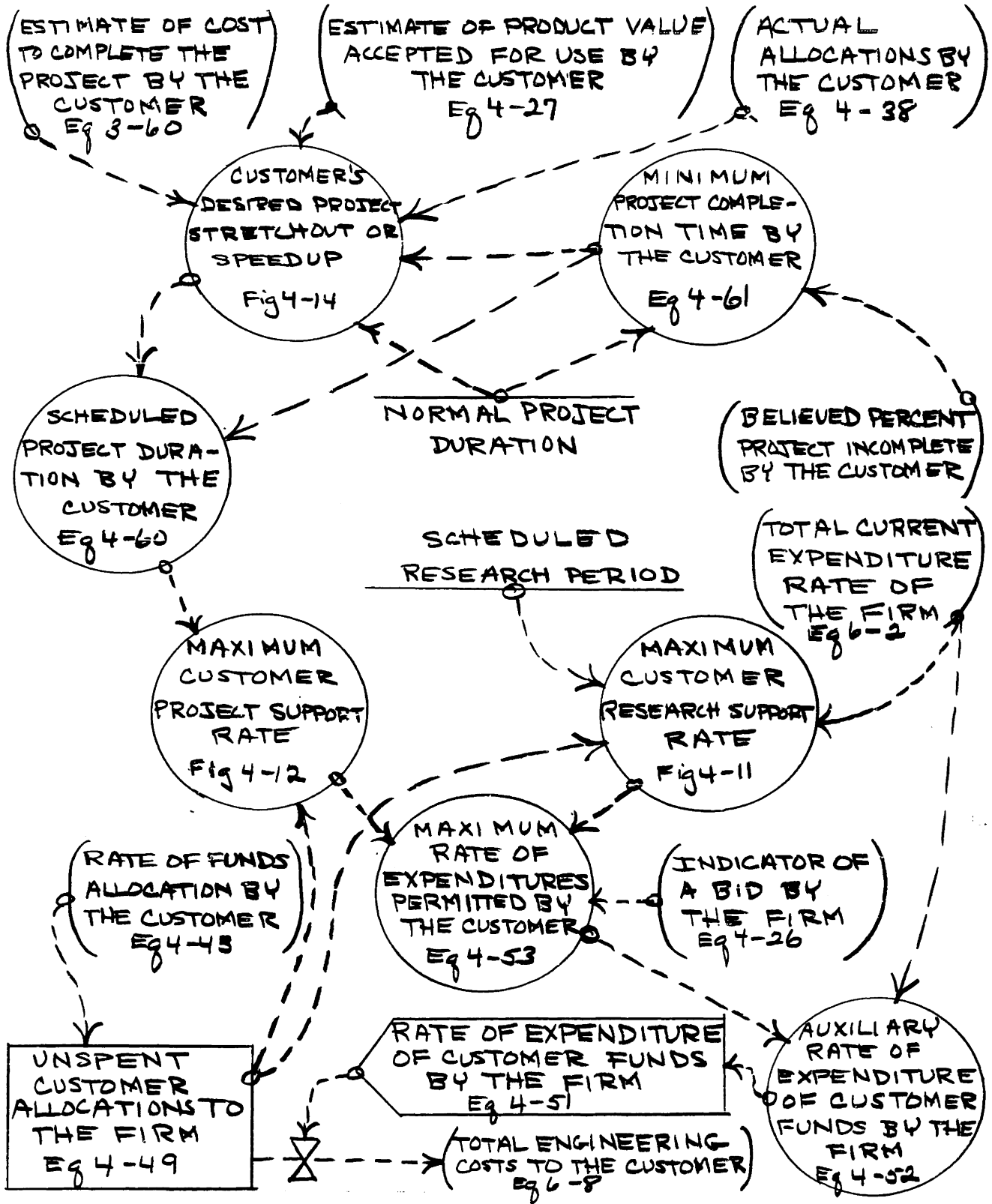


Figure 4-10 Customer Project Control

scheduling of the duration of the project and through his control over the release of his own funds for reimbursement of the firm's expenditures. Both of these measures are, of course, indirect and can therefore have only indirect effects on the actual control of research and development progress. In determining the scheduled project duration, the customer takes into account the completion time that he would normally expect for the project, given the normal total project duration and the believed amount of project left to be done. In addition, the customer takes into account his desires for stretch-out or speed-up of the project. These are the customer's responses to his continuing evaluation of the relationship between the expected costs and the expected value of the project. If the project seems to be very worthwhile in terms of the value-cost relationship, the customer may desire to speed up the project and get the benefits of these results somewhat earlier. On the other hand, if the value-cost relationship of the project begins to look poor, the customer may react by starting to stretch out the expenditure of funds on the project. This is accomplished by extending the project duration while maintaining the same total amount of allocated funds. The customer thereby induces pressure upon the firm to cut back its level of activities, and the customer will then perhaps gradually eliminate the project from his funding support. These schedule considerations determine the rate at which the level of unspent customer allocations will, in fact, be spent during the life of the research and development project.

During the earlier phases, prior to approval of large grants of development funds, the customer's support of the firm's research activities will similarly be dependent upon the amount of total allocations



that have been made to the firm, but will be restricted more by the firm's own rate of activity. As was mentioned earlier in this chapter, the customer will generally feel that the firm ought to support a certain amount of research activity out of its own funds. In addition to this, the customer will in general not support more than about 50 percent of the total research expenditures of the firm. These factors determine the customer's expenditure rate out of the pool of unspent allocation money that had been allotted to the firm. These factors are included in the equations listed below.

We shall begin with the level equation for the unspent customer allocations.

$$\text{UCAF.K} = \text{UCAF.J} + (\text{DT})(\text{RFAC.JK} - \text{RECFJ.K}) \quad 4-49, \text{ L}$$

$$\text{UCAF} = 0 \quad 4-50, \text{ N}$$

UCAF--Unspent Customer Allocations to the Firm (dollars)  
 RFAC--Rate of Funds Allocation by the Customer (dollars/month)  
 RECFJ.K--Rate of Expenditure of Customer Funds by the Firm (dollars/month)

Out of this pool of unspent but designated funds comes the rate of actual expenditures on the project by the customer. This rate, as is shown by Equation 4-52, will never exceed the total current expenses at the firm, and in general will be limited below this amount either, during research, because of the customer's policies of inducing the firm to support its own research efforts, or during development, by the customer's considerations of the scheduled project duration.

$$\text{RECFJ.KL} = \text{ARECF.K} \quad 4-51, \text{ R}$$

$$\text{ARECF.K} = \text{MIN} (\text{TCEF.K}, \text{MREPC.K}) \quad 4-52, \text{ A}$$

$$\text{MREPC.K} = \text{SWITCH} (\text{MRERC.K}, \text{MPERC.K}, \text{IBF.K}) \quad 4-53, \text{ A}$$

RECF--Rate of Expenditure of Customer Funds  
 by the Firm (dollars/month)  
 ARECF--Auxiliary, Rate of Expenditure of Customer  
 funds by the Firm (dollars/month)  
 TCEF--Total Current Expenditure rate by the  
 Firm (dollars/month)  
 MREPC--Maximum Rate of Expenditures Permitted  
 by the Customer (dollars/month)  
 MRERC--Maximum Research Expenditure Rate by the  
 Customer (dollars/month)  
 MPERC--Maximum Project Expenditure Rate by the  
 Customer (dollars/month)  
 IBF--Indicator of Bid by the Firm (dimensionless)

Equation 4-53 indicates that the limitation of customer expenditures permitted is determined by one policy during the research phase and another policy during the phase of larger-scale developmental activities.

Let us now go on to first looking at the customer support policies in existence during the early phase of the project life cycle, which, for the sake of convenience, we have called the research phase. The diagram and equations below incorporate the fact that the customer allocations for research are usually for some scheduled period of research which period will therefore be a determinant of the maximum research expenditure rate permitted out of the customer's funds. Secondly, they show that the customer will not support more than 50 percent of the current expenditures of the firm during the research period. The rest of the expenditures must be absorbed out of the firm's own funds. Figure 4-11 and Equations 4-54 through 4-56 represent the above description.

$$\text{MRERC.K} = \text{MIN} (\text{MREDC.K}, \text{MREAC.K}) \quad 4-54, \text{ A}$$

$$\text{MREDC.K} = \frac{\text{UCAF.K}}{\text{SRP}} \quad 4-55, \text{ A}$$

$$\text{MREAC.K} = (0.50)(\text{TCEF.K}) \quad 4-56, \text{ A}$$

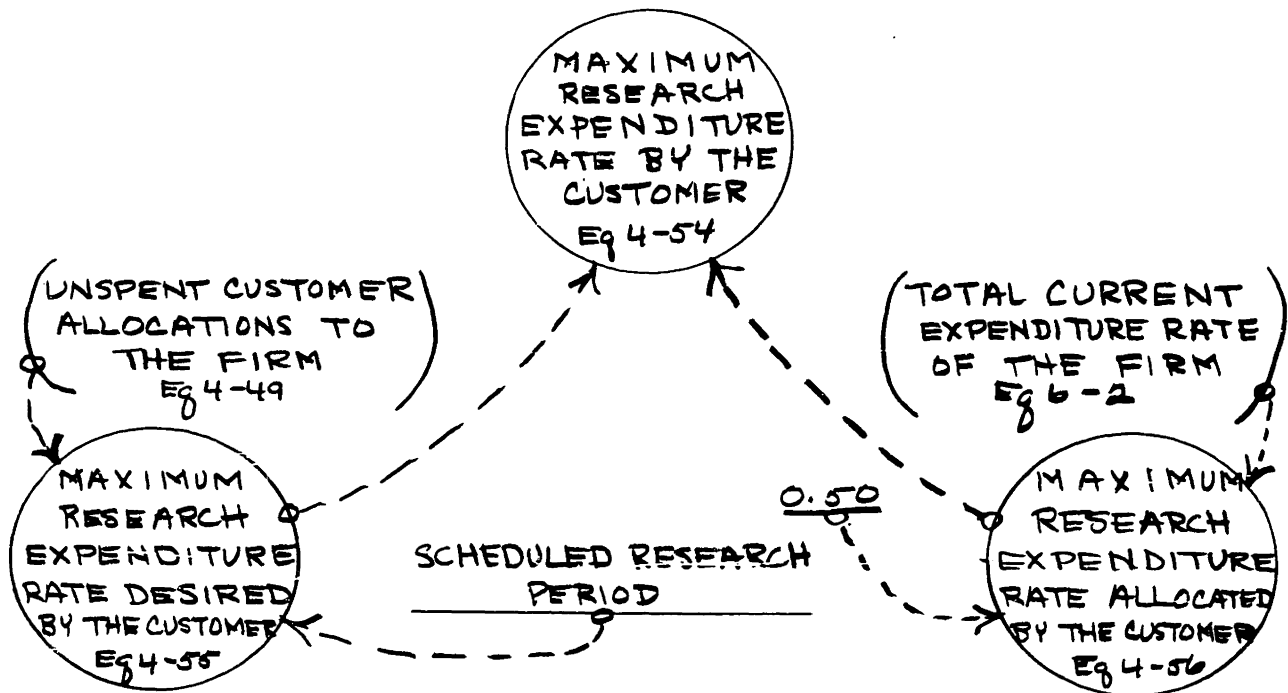


Figure 4-11 Maximum Customer Research Support Rate

- MRERC--Maximum Research Expenditure Rate by the Customer (dollars/month)  
 MREDC--Maximum Research Expenditure rate Desired by the Customer (dollars/month)  
 MREAC--Maximum Research Expenditure rate Allowed by the Customer (dollars/month)  
 UCAF--Unspent Customer Allocations to the Firm (dollars)  
 SRP--Scheduled Research Period (months)  
 TCEF--Total Current Expenditure rate by the Firm (dollars/month)

The type of funding covered by the above equations is of the nature of continuing study contracts, usually granted on an annual basis.

Thus,

$$SRP = 12 \text{ months}$$

During the development period, the maximum permitted allocation rate of the customer's funds is determined by the customer's determination of the scheduled project duration. This fact is modified only by the policy that in general the customer will not support a very small

project, here indicated to be one whose cost magnitude is that incurred by the effort one man per month or less. The diagram and equations for this consideration follow:

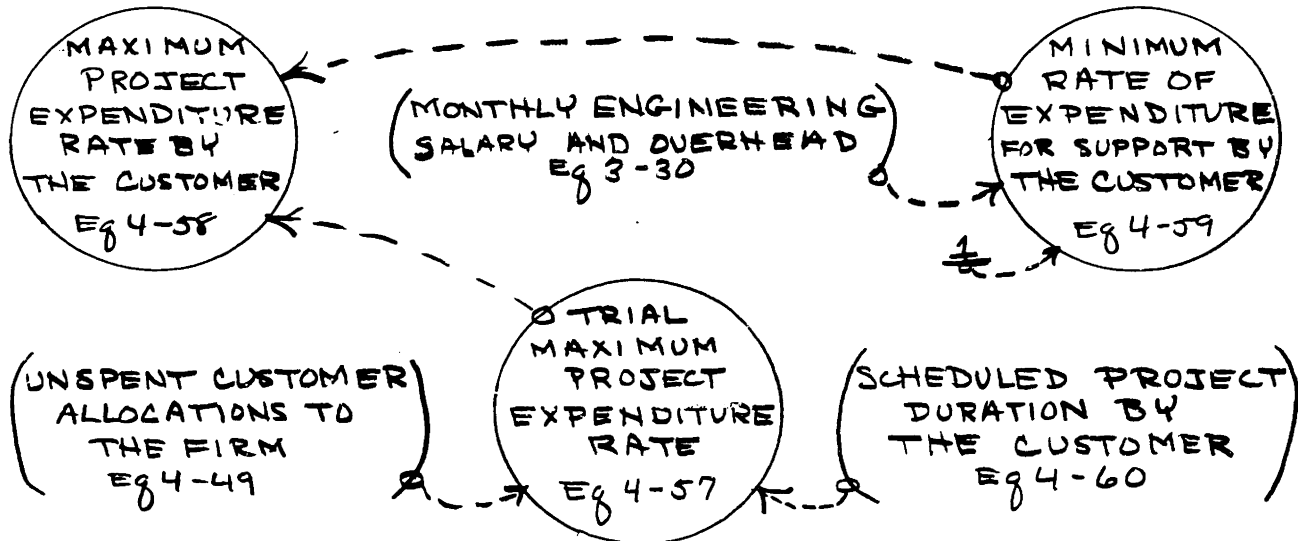


Figure 4-12 Maximum Customer Project Support Rate

$$\text{TMPER.K} = \frac{\text{UCAF.K}}{\text{SPDC.K}} \quad 4-57, A$$

$$\text{MPERC.K} = \text{CLIP}(\text{TMPER.K}, 0, \text{TMPER.K}, \text{MRESC}) \quad 4-58, A$$

$$\text{MRESC} = (1)(\text{MESOH}) \quad 4-59, N$$

- TMPER--Trial Maximum Project Expenditure Rate  
(dollars/month)
- UCAF--Unspent Customer Allocations to the Firm  
(dollars)
- SPDC--Scheduled Project Duration by the Customer  
(months)
- MPERC--Maximum Project Expenditure Rate by the  
Customer (dollars/month)
- MRESC--Minimum Rate of Expenditure for Support by  
the Customer (dollars/month)
- MESOH--Monthly Engineering Salary and OverHead  
(dollars/man-months)

The scheduled project duration consists of two parts--the normal project completion time, which at any time depends upon how much of the project is left to be done, and the changes in this scheduled completion

time, which depend upon the customer's relative satisfaction with the progress on the job. Figure 4-13 pictures this relationship. As the customer's lack of satisfaction with the job increases, as indicated by the percent overexpenditure expected by the customer, the customer stretches out the job schedule according to the curve shown.

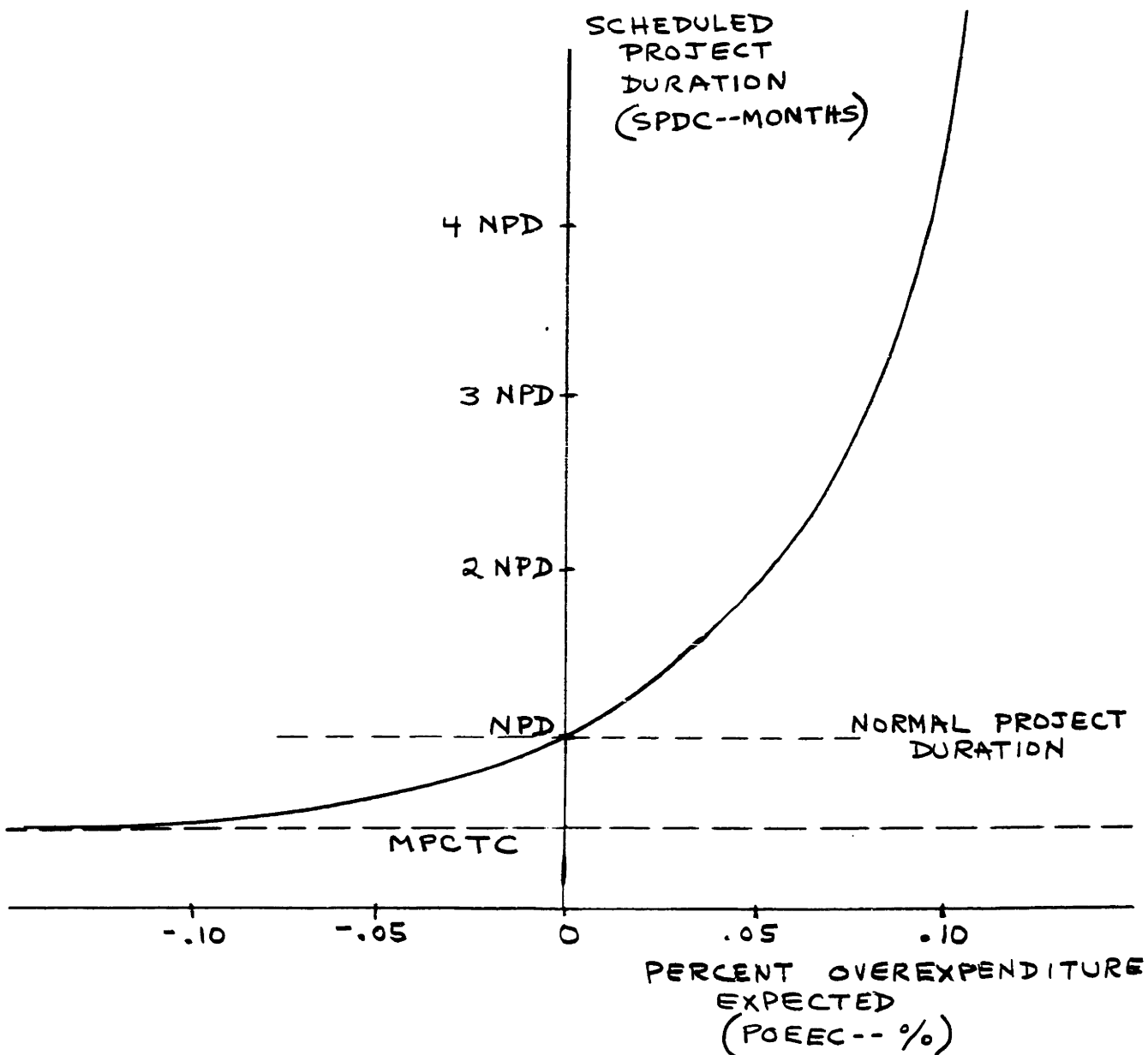


Figure 4-13 Scheduled Project Duration (for a Given Value of  $MPCTC = \frac{1}{2}NP$ )

When no overexpenditure is expected, the scheduled completion time is just the normal project duration. When the relationship is reversed, and the customer actually expects to have a very favorable relationship between project value and cost, the project schedule may be accelerated and the project duration decreased to the minimum project value, pictured as MPCTC.

The scheduling phenomenon of Figure 4-13 is represented in the model by the equation for the scheduled project duration. This duration consists of the sum of the believed minimum project completion time and the additional scheduled project duration, which is responsive to the customer's funding desires. The minimum project completion time is here represented as half the expected normal completion time, which in turn equals the normal project duration multiplied by the fraction of the project believed remaining to be completed.

$$SPDC.K = MPCTC.K + ASPDC.K \quad 4-60, A$$

$$MPCTC.K = \text{MAX} (MPTC1.K, DT) \quad 4-61, A$$

$$MPTC1.K = (BPPIC.K)(NPD)(0.5) \quad 4-62, A$$

SPDC--Scheduled Project Duration by the Customer  
(months)

MPCTC--Minimum Project Completion Time by the  
Customer (months)

ASPDC--Additional Scheduled Project Duration by  
the Customer (months)

MPTC1--Minimum Project Completion Time, 1 (months)

BPPIC--Believed Percent of Project Incomplete by  
the Customer (percentage)

NPD--Normal Project Duration (months)

Equation 4-61 keeps the schedule at least as long as one equation solution interval. The normal project duration was initially set in Chapter 3 at two years.

The customer's desired stretchout or speedup of the project is

diagrammed in Figure 4-14. The diagram serves as an accessory to Equations 4-63 through 4-69 which will now be described.

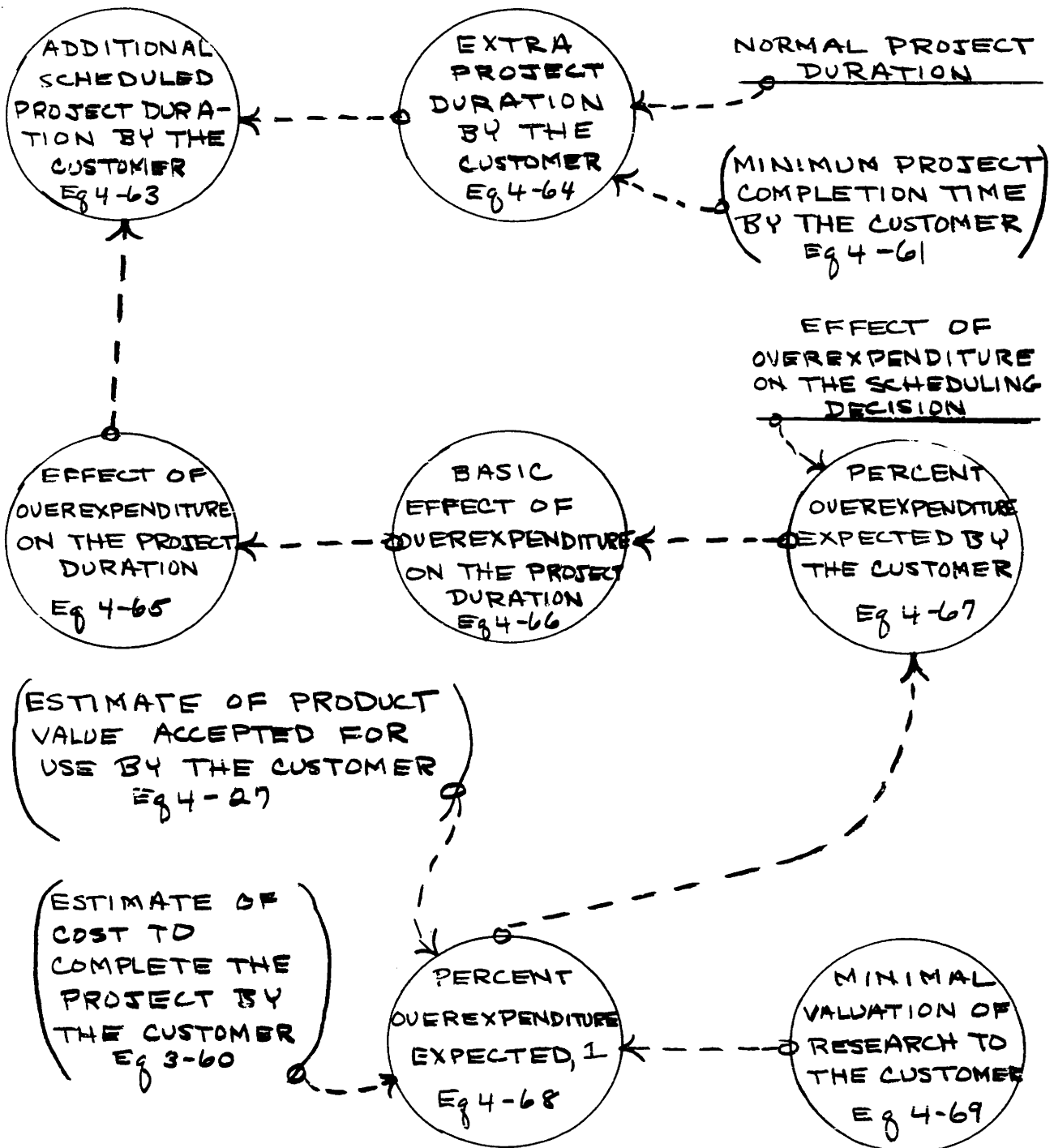


Figure 4-14 Customer's Desired Project Stretchout or Speedup

The first two equations below indicate that the additional scheduled project duration is exponentially related to the effect of expected overexpenditure on the project. If the overexpenditure effect, EXPD, is zero (when expected additional project cost equals the expected value), then the additional scheduled duration just equals  $NPD - MPCTC.K$ . Under this condition of value of the total scheduled project duration, Equation 4-60, would just equal the normal project duration. If the ratio of expected value to cost is very high, indicating an exceptionally good project situation, ASPDC will be approximately zero and the customer will be desirous of speeding up the project to its minimum duration, MPCTC, so as to benefit sooner from the completed product. However, if expected cost begins to exceed expected product value, the customer will respond by gradually stretching out the project funding period without increasing the total project allocation, thus cutting back on the customer support rate for the firm's expenses.

$$ASPDC.K = (XPDC.K) e^{EXPDC.K} \quad 4-63, A$$

$$XPDC.K = NPD - MPCTC.K \quad 4-64, A$$

ASPDC--Additional Scheduled Project Duration  
by the Customer (months)  
XPDC--eXtra Project Duration by the Customer  
(months)  
EXPDC--Effect of overeXpenditure on the Project  
Duration (percentage)  
NPD--Normal Project Duration (months)  
MPCTC--Minimum Project Completion Time by the  
Customer (months)

The next two equations produce the effect of overexpenditure expectations as a multiple EOESD of the percent overexpenditure expected. EOESD indicates the extent to which the customer responds to such expectations. Equation 4-65 limits this effect to 75 or less, since DYNAMO



will not calculate an exponential which has a power much greater than 75.

$$\text{EXPD.K} = \text{MIN} (\text{BEXPD.K}, 75) \quad 4-65, \text{ A}$$

$$\text{BEXPD.K} = (\text{EOESD})(\text{POEEC.K}) \quad 4-66, \text{ A}$$

EXPD--Effect of overexpenditure on the Project Duration (percentage)

BEXPD--Basic Effect of overexpenditure on the Project Duration (percentage)

EOESD--Effect of Overexpenditure on the Scheduling Decision (dimensionless constant)

POEEC--Percent Overexpenditure Expected by the Customer (percentage)

The multiplier which partially designates the amount of effect that overexpenditure expectations shall have on the scheduling decision of the customer will be set equal to 20. Thus,

$$\text{EOESD} = 20$$

This means that when additional project cost is expected to exceed value by five percent, EXPD will equal one, and ASPDC will approximately equal  $(2.7)(\text{XPDC.K})$ .

Finally, the last three equations of this section represent the fact that until the customer has actually allocated some funds to the project, he is not concerned with possible overexpenditures. But after he has funds committed, the customer continuously thinks about the cost versus the value of the project, relating the difference between the two to the estimate of value of the work. Here the customer recognizes that even if the product value itself dropped to zero, there is still at least gained some very small benefit from the research work performed.

$$\text{POEEC.K} = \text{SWITCH} (0, \text{POEE1.K}, \text{AAC.K}) \quad 4-67, \text{ A}$$

$$\text{POEE1.K} = \frac{\text{ECCPC.K} - \text{EVAUC.K}}{\text{EVAUC.K} + \text{MVRC}} \quad 4-68, \text{ A}$$

$$\text{MVRC} = \text{VSMAL} \quad 4-69, \text{ N}$$

POEEC--Percent Over Expenditure Expected by the  
 Customer (percentage)  
 POEEL--Percent OverExpenditure Expected, 1  
 (percentage)  
 AAC--Actual Allocations by the Customer  
 (dollars)  
 ECCPC--Estimated Cost to Complete the Project  
 by the Customer (dollars)  
 EVAUC--Estimate of product Value Accepted for  
 Use by the Customer (dollars)  
 MVRC--Minimum Valuation of Research by the Cus-  
 tomer (dollars)  
 VSMAL--Very SMALL number (dimensionless)

The percentage overexpenditure, just as the customer's earlier compari-  
 son of expected value and cost of the project, is determined by com-  
 paring the relative gap between the expected costs to complete the  
 project and the expected value of the project. Thus, again, sunk  
 costs are ignored in the anticipation of project overexpenditures.  
 Though this is theoretically justified, some readers may prefer an  
 alternate formulation of the overexpenditure equation. Such could be  
 tested in other simulation runs.

So that results are not influenced by the customer's minimum  
 evaluation of research, this shall be set almost equal to zero. VSMAL  
 shall be chosen for this purpose as one hundred-thousandth.

$$VSMAL = 0.00001$$

The final portion of Chapter 4 discusses the firm's investment  
 decision and is pictorially indicated by Figure 4-15. Starting from  
 the bottom of the diagram, we see that on the basis of the firm's expec-  
 tations of the customer's willingness to support the project, the firm  
 estimates what its expected profitability might be on the project. This  
 factor, combined with the firm's willingness to accept risk, determines  
 the maximum investment which the firm will be willing to put into the

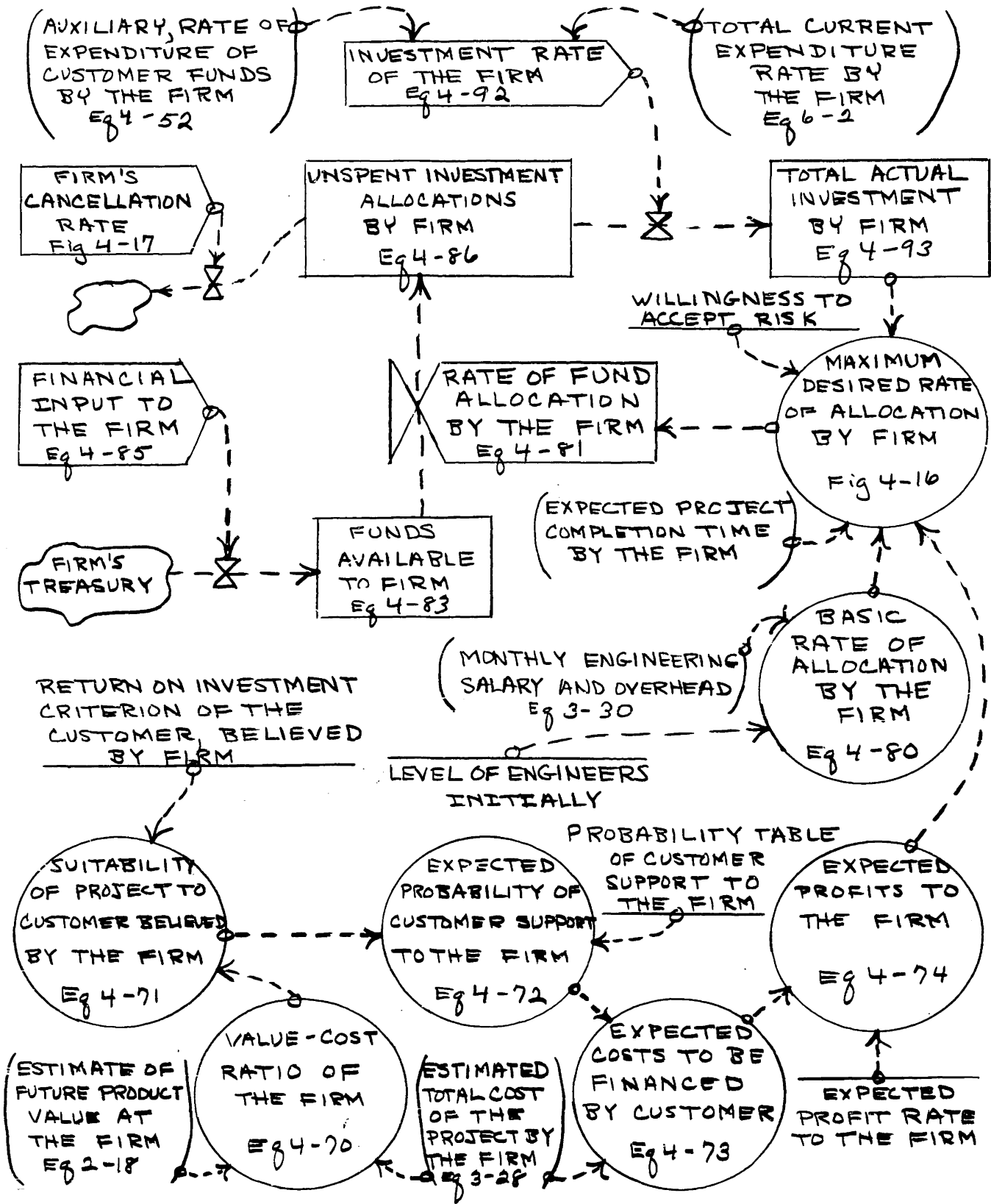


Figure 4-15 Firm's Investment Decision

project. Limited only by the funds available to the firm, this maximum desired investment and the firm's anticipation as to the expected duration of the project determine the firm's rate of allocation of funds for the project. The employment of engineers on the job creates the total current expenditure rate on the project, which expenditures, when not covered by the customer's support rate, bring about the residual rate of actual investment by the firm.

Let us start with the equations which describe the firm's expectations as to the suitability of the project to the customer. The value-cost ratio of the project, Equation 4-70, compared to the return on investment criterion that the firm believes the customer uses will determine the suitability of the project, Equation 4-71. This produces an expectation as to the probability that the customer will support the project costs.

$$VCRF.K = \frac{EFPVF.K}{ETCPF.K} \quad 4-70, A$$

$$SPCBF.K = \frac{VCRF.K}{ROICF} \quad 4-71, A$$

$$EPCSF.K = \text{TABHL} (\text{PCSF}, \text{SPCBF.K}, 0, 1, 0.1) \quad 4-72, A$$

VCRF--Value-Cost Ratio of the Firm (percentage)

EFPVF--Estimate of Future Product Value at the Firm (dollars)

ETCPF--Estimated Total Cost of the Project by the Firm (dollars)

SPCBF--Suitability of the Project to the Customer, Believed by the Firm (percentage)

ROICF--Return On Investment criterion of the Customer, believed by the Firm (percentage)

EPCSF--Expected Probability of Customer Support to the Firm (percentage)

PCSF--Probability table of Customer Support to the Firm (percentage)

We shall start with the firm correctly estimating the investment criterion of the customer. This criterion was shown by the value of

ROICC, which was set equal to two. Thus,

$$\text{ROICF} = 2.00 \text{ (decimal percentage)}$$

This correct perception will be changed in later project simulations. The probability of customer support of the firm was earlier sketched out in Figure 4-7 and the accompanying table of PCSF values.

The expected profitability on the job is the product of the expected profit rate, the expectations that the customer will support the project, and the expected total costs of the project.

$$\text{EXCFC.K} = (\text{EPCSF.K})(\text{ETCPF.K}) \quad 4-73, \text{ A}$$

$$\text{EXPRF.K} = (\text{EPRF})(\text{EXCFC.K}) \quad 4-74, \text{ A}$$

EXCFC--Expected Cost to be Financed by the Customer (dollars)

EPCSF--Expected Probability of Customer Support to the Firm (percentage)

ETCPF--Expected Total Cost of the Project by the Firm (dollars)

EXPRF--Expected PROfits to the Firm (dollars)

EPRF--Expected Profit Rate to the Firm (percentage)

The contract profit rate allowed to the firm on a research and development project usually varies over the range from about 6 to 12 percent. Let us initially use a nominal value of 10 percent.

$$\text{EPRF} = 0.10 \text{ (decimal percent)}$$

The firm is willing to invest a certain fraction of its expected profits on the project, the fraction being determined by the degree of conservatism, or conversely, the willingness to accept risk, of the firm. The firm's release of this potential allocation takes place over a period of time determined by the firm's expectations as to the project duration. In no event, however, does the firm cut its allocation rate below the amount necessary to support a minimum continuing research activity whose level is determined by policy of the firm. These factors

are incorporated in the following diagram, Figure 4-16.

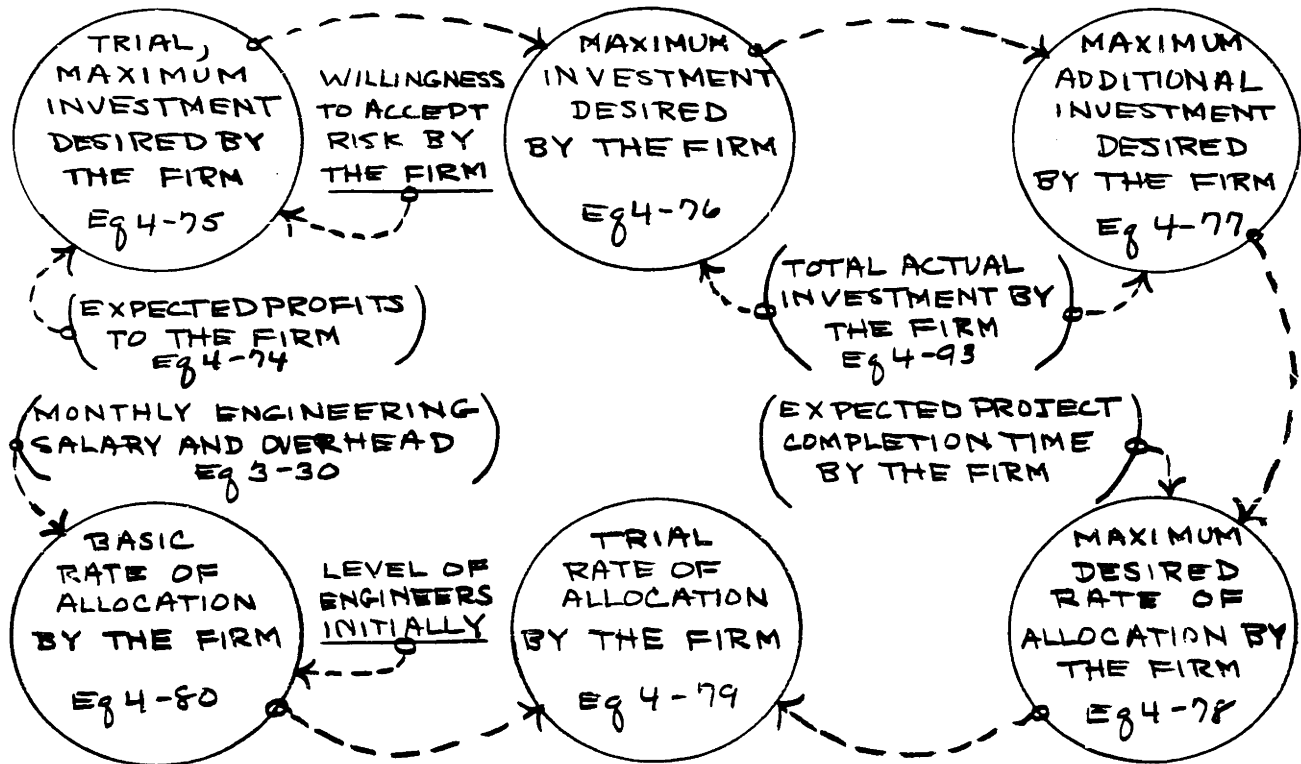


Figure 4-16 Maximum Desired Rate of Allocation by the Firm

Equations 4-75 and 4-76 express the maximum investment level desired by the firm. As a trial amount, 4-75 indicates that the firm is willing to invest that fraction of its expected profits which corresponds to its risk-taking propensity coefficient. Equation 4-76 for MIDF recognizes that sometimes the firm will already have invested more than that desired amount.

$$TMIDF.K = (WARF)(EXPRF.K) \quad 4-75, A$$

$$MIDF.K = \text{MAX} (TMIDF.K, TAIF.K) \quad 4-76, A$$

TMIDF--Trial, Maximum Investment Desired by the Firm (dollars)

WARF--Willingness to Accept Risk by the Firm (percentage)

EXPRF--Expected Profits by the Firm (dollars)

MIDF--Maximum Investment Desired by the Firm (dollars)

TAIF--Total Actual Investment by the Firm (dollars)

In Chapter 2 the firm's willingness to accept risk, WARF, was initially set equal to 1.00.

The additional amount the firm wishes to invest is the difference between its desired and actual investment levels. The firm desires to invest this amount over a period of time EPCTF, as shown in Equation 4-78. Equation 4-79 shows that this trial allocation rate by the firm does not drop below the basic rate needed to support the monthly engineering salary and overhead cost of LEI engineers (Equation 4-80)

$$\text{MAIDF.K} = \text{MIDF.K} - \text{TAIF.K} \quad 4-77, \text{ A}$$

$$\text{MDRAF.K} = \text{MAIDF.K}/\text{EPCTF.K} \quad 4-78, \text{ A}$$

$$\text{TRAF.K} = \text{MAX} (\text{MDRAF.K}, \text{BRAFF}) \quad 4-79, \text{ A}$$

$$\text{BRAFF} = (\text{MESOH})(\text{LEI}) \quad 4-80, \text{ N}$$

MAIDF--Maximum Additional Investment Desired  
by the Firm (dollars)  
MIDF--Maximum Investment Desired by the Firm  
(dollars)  
TAIF--Total Actual Investment by the Firm  
(dollars)  
MDRAF--Maximum Desired Rate of Allocation by  
the Firm (dollars/month)  
EPCTF--Expected Project Completion Time by the  
Firm (months)  
TRAF--Trial Rate of Allocation by the Firm  
(dollars/month)  
BRAFF--Basic Rate of Allocation by the Firm  
(dollars/month)  
MESOH --Monthly Engineering Salary and OverHead  
(dollars/man-month)  
LEI--Level of Engineers Initially (men)

As has often been mentioned the firm is assumed to begin with but one engineer working in the area related to the project under consideration.

This means that

$$\text{LEI} = 1 \text{ man}$$

The actual rate of fund allocation by the firm is dependent upon

its desired rate, expressed by TRAF above, and any constraints that may be placed upon it by the availability of funds in the firm.

$$\text{RFAF.KL} = \text{MIN} (\text{TRAF.K}, \text{MFRAF.K}) \quad 4-81, \text{ R}$$

$$\text{MFRAF.K} = \text{FAF.K}/\text{DT} \quad 4-82, \text{ A}$$

RFAF--Rate of Funds Allocation by the Firm  
(dollars/month)  
TRAF--Trial Rate of Allocation by the Firm  
(dollars/month)  
MFRAF--Maximum Fund Rate of Allocation by the  
Firm (dollars/month)  
FAF--Funds Available to the Firm (dollars)

The level of funds available to the firm for allocation to the project is increased by receipts of financial inputs to the firm and depleted by the firm's rate of investment in the project. Initially the firm is regarded as having available a base research budget, and receiving a very large financial input (VLARG) at month INTMF. The amount and timing of this input can readily be changed.

$$\text{FAF.K} = \text{FAF.J} + (\text{DT})(\text{FINF.JK} - \text{IRF.JK}) \quad 4-83, \text{ L}$$

$$\text{FAF} = \text{BRBF} \quad 4-84, \text{ N}$$

$$\text{FINF.KL} = \text{PULSE} (\text{VLARG}, \text{INTMF}, \text{VLARG}) \quad 4-85, \text{ R}$$

FAF--Funds Available to the Firm (dollars)  
FINF--Financial Input to the Firm (dollars/month)  
IRF--Investment Rate by the Firm (dollars/month)  
BRBF--Base Research Budget of the Firm (dollars)  
VLARG--Very Large number (dimensionless)  
INTMF--Input Time of the Firm (month)

The level of unspent investment allocations at the firm is simply the accumulation of the new rate of fund allocation minus the expenditure of these funds minus the cancellation of previous allocations by the firm. This initially is just the base research budget, which in turn provides the basic monthly rate of allocation for the length of the budgeting period.



$$\text{UIAF.K} = \text{UIAF.J} + (\text{DT})(\text{RFAF.JK} - \text{IRF.JK} - \text{CAF.JK}) \quad 4-86, \text{ L}$$

$$\text{UIAF} = \text{BRBF} \quad 4-87, \text{ N}$$

$$\text{BRBF} = (\text{BPER})(\text{BRAf}) \quad 4-88, \text{ N}$$

UIAF--Unspent Investment Allocations at the Firm (dollars)  
 RFAF--Rate of Funds Allocation by the Firm (dollars/month)  
 IRF--Investment Rate at the Firm (dollars/month)  
 CAF--Cancellation of Allocations at the Firm (dollars/month)  
 BRBF--Base Research Budget at the Firm (dollars)  
 BPER--Budgeting PERiod (months)  
 BRAf--Basic Rate of Allocations by the Firm (dollars/month)

The firm probably reviews its engineering budget periodically, at quarterly or semi-annual intervals. For this purpose, let

$$\text{BPER} = 6 \text{ months}$$

The equations below add the possibility that at the end of each budgeting period the firm can cancel the excess of the previously allocated funds. In other words, if the firm allocates the funds for the purpose of supporting engineering costs on a project, but either does not acquire sufficient engineers to cover these expenditures or has some of the expenditures supported by the customer, the firm will not accumulate the unused allocated funds indefinitely. Rather, the firm will cancel the excess of funds and continue to review the investment budget on this periodic basis. Equation 4-91 determines the difference between the level of unspent funds and the base research budget, Equation 4-90 checks to see that it is an excess and not a deficiency, and the CAF equation, 4-89, cancels this amount at the appropriate budget periods.

$$\text{CAF.KL} = \text{PULSE} (\text{CXAF.K}, \text{BPER}, \text{BPER}) \quad 4-89, \text{ R}$$

$$\text{CXAF.K} = \text{MAX} (\text{XUAF.K}, 0) \quad 4-90, \text{ A}$$

$$\text{XUAF.K} = (1/\text{DT})(\text{UIAF.K} - \text{BRBF}) \quad 4-91, \text{ A}$$

CAF--Cancellation of Allocations at the Firm  
(dollars/month)

PULSE--a function indicating that for the duration of one DT the amount specified by CXAF will be used to determine the value for the variable, CAF; the timing of this occurrence will be at each successive interval specified by the length of BPER, starting for the first time at TIME = BPER.

CXAF--Cancellable eXcess Allocations at the Firm  
(dollars/month)

BPER--Budgeting PERiod (months)

XUAF--eXcess Unspent Allocations at the Firm  
(dollars/month)

UIAF--Unspent Investment Allocations at the Firm  
(dollars)

BRBF--Base Research Budget at the Firm (dollars)

Finally, we recognize the fact that the actual investment rate by the firm is not directly controlled by the firm, but rather is the indirect result of its own policy of acquisition and employment of engineers and of the customer's policy with respect to supporting the firm's expenses. Thus the investment rate at the firm is the difference between the total current engineering costs and the current rate of support by the customer. This rate of investment by the firm accumulates over a period of time as the level of total actual investment by the company. Initially this investment equals the total engineering costs to-date, since the customer has provided no support prior to TIME = 0.

$$\text{IRF.KL} = \text{TCEF.K} - \text{ARECF.K} \quad 4-92, \text{ R}$$

$$\text{TAIF.K} = \text{TAIF.J} + (\text{DT})(\text{IRF.JK}) \quad 4-93, \text{ L}$$

$$\text{TAIF} = \text{TECF} \quad 4-94, \text{ N}$$

IRF--Investment Rate at the Firm (dollars/  
month)

TCEF--Total Current Expenditure rate by the  
Firm (dollars/month)

ARECF--Auxiliary, Rate of Expenditure of  
Customer funds by the Firm (dollars/  
month)  
TAIF--Total Actual Investment by the Firm  
(dollars)  
TECF--Total Engineering Costs to the Firm  
(dollars)

This completes the specifications of the equations for the variables, initial conditions and parameters describing the funding of the research and development project.

## CHAPTER V

### THE ACQUISITION AND UTILIZATION OF ENGINEERING MANPOWER

The activities described in the preceding chapter result in the provision of funds to the firm either from the customer's support of the firm's engineering activities or from the firm's own investment moneys. Regardless of their source of origin, available funds are necessary in order for the firm to undertake the acquisition of the productive resources that will be needed for a research and development project. These productive resources include men, materials, machinery, and facilities. Of these, the most critical element is the engineering manpower, the personnel vital to the conduct of any new product development enterprise. This chapter will, therefore, discuss the activities related both to acquiring and then productively utilizing engineers in the pursuit of the research and development project objectives. The chapter will be divided into two parts, discussing first the flow of engineering manpower, both into and out of the research and development firm, and secondly the factors influencing the productivity of the engineering work force employed by the firm.

#### The Flow of Engineering Manpower

Earlier chapters have pointed out that in all research and development companies one or two engineers, or perhaps only a "fraction" of an engineer, are doing work in areas of potential new product possibilities. These people are the first who occupy the pool of productive engineering employees in the firm. As these engineers work the activities

of value perception (Chapter 2), cost and effort estimation (Chapter 3), and the provision of funds (Chapter 4) are all being undertaken. As funds are obtained for work in the project area under consideration, whether from external or internal sources, the firm can begin to hire the manpower it is able to support or to transfer present employees from other work to the project. The first question to be asked in regard to the firm's policy for acquiring engineers is, "What determines the number of engineers that the firm desires to have on the project?" An obvious answer to this question is that the amount of financial support that the firm has available determines the desired engineering employment level. But even here the question can still be raised as to whether the firm should wait until it receives support before beginning the recruiting process. If it plans ahead, recognizing the long length of the hiring time, the company might begin to hire engineers in anticipation of future funding. One factor creating the lengthy average delay in hiring new personnel is the phenomenon of college graduation, whereby most of the new engineers and scientists are provided to the recruiting firms. Companies must anticipate their needs long in advance and begin their work early in the school year. Marcson points out in regard to recruiting, "The purpose of the contacts made is to plant a seed with the young scientists who are nine months away from getting their degrees."<sup>1</sup> One writer suggests that the real delay in college recruiting is even longer than the nine months spoken of above. He recommends that a company "maintain a cooperative educational

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<sup>1</sup>Simon Marcson, The Scientist in American Industry (Princeton, New Jersey, Industrial Relations Section, Princeton University, 1960), p. 53.

program with a recognized university which gives you the opportunity to acquaint technical students with your company, its operations, and your product...[and further that it] maintain relations with the engineering colleges in your area, acquainting them with your needs, thereby enabling them to refer previous graduates to you who may be particularly skilled in your line of work."<sup>2</sup> Such recommendations clearly indicate that the effective delay in recruiting engineers is quite lengthy. Thus, the firm which waits until the funding is provided before it begins seeking recruits may well lose much valuable time from the project. This delay in engineering acquisition is, of course, shortened when engineers are available for transfer from other parts of the company.

But even beyond the points raised thus far is the question of whether the firm does hire up to the maximum support level that has been provided. Most engineering firms are concerned with the problem of providing labor stability, especially to their professional employees. Therefore, such firms are unwilling to hire new engineers unless they feel fairly certain that they will be able to utilize these personnel for a reasonable length of time. Thus, to many firms, the stability of the engineering support over a long duration is a more important influence on their hiring policies than is their current support level. Most firms adopt a mid-road policy by taking account not only of the amount of support that they have available (or can expect soon to become available) but also of the expected duration of such support.

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<sup>2</sup>Richard C. Swander, "Proselyting---Good Business?", IRE Transactions on Engineering Management, Vol. EM-6, No. 1 (March 1959), p. 38.

However, even after the firm has decided how many engineering employees it wishes to acquire, it still has to concern itself with determining the rate of acquiring these people. In all likelihood, the firm is not able to even attempt to hire all the people it needs right away. The first reason for this is the limited size of the personnel department in the usual engineering-type firm. This restricts the amount of recruiting and interviewing activities that can be supported at any given time. To some extent, experienced engineers have to be taken off their current jobs in order to go to the colleges or other prime sources of trained manpower for the purpose of recruiting. As evidence Marcson found in his study of the "P. E. C." laboratory, "Systematic visits are made to universities which produce graduates in the fields of research of interest to the P. E. C. laboratory. These visits are invariably made by members of the scientific staff."<sup>3</sup> Some firms may therefore also limit their rates of acquiring new engineers because of unwillingness to take current employees away from other productive duties. For these reasons, a firm at any given time is probably actively recruiting only a fraction of the gap between the desired and the expected numbers of engineers. The number of expected employees of course is merely a summation of the firm's present employees plus those expected to join the company as a result of offers already made minus those whom the company feels are leaving either voluntarily or by the company's own decision.

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<sup>3</sup>Simon Marcson, "Role Adaptation of Scientists in Industrial Research", IRE Transactions on Engineering Management, Vol. EM-7, No. 4, (December 1960), p. 159.

One final influence upon the rate at which the firm attempts to hire new engineering employees is the firm's policy for training its new personnel. Most firms recognize that whether the new employee comes fresh out of college or has been obtained after much experience with another company, there is no doubt a strong need for orientation, and training of the new individual. In order to train these new employees, more experienced personnel have to at least in part be diverted from their current activities to act as trainers. Different companies vary greatly in their attitudes towards the need for or usefulness of training programs for their new employees. Some companies will severely restrict their rate of engineering hiring so that they will be able to fully indoctrinate and train their new personnel under their available experienced and particularly competent engineers. Other companies regard training in a much more casual manner and are not so concerned with the problem of providing extra coaching or on the job instruction to their recruits. "For example,... in the best lab circumstance [in twenty-three selected laboratories surveyed by the management consulting firm of Booz, Allen, and Hamilton], about a third of the personnel seldom or never were given on the job instruction, and in the poorest, almost two-thirds did not receive it. In view of the relative youth and immaturity of lab personnel, this would appear to be severe neglect of an expected supervisory function."<sup>4</sup>

The basic problem in determining a policy regarding a company training

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<sup>4</sup>C. Wilson Randle, "Problems of R and D Management", Harvard Business Review, January-February 1959, p. 134.



program is the "double-edged-sword" nature of the situation. On the one hand, if the firm does not provide adequate training to its new people, the longer run ability of these people will be hindered rather greatly. On the other hand, however, an attempt to provide a thorough training program for these personnel will force the firm to take away its most effective people from the product-oriented work which they had previously been doing. Different firms solve this enigma in different ways, some of them by burying their heads in the sand and ignoring the existence of the problem. Whatever the policy finally adopted by the company, however, it will in effect determine both results--the future productivity of the firm's engineers as well as the current availability for project work of their experienced personnel.

At the completion of their training program (even one of zero duration) the new engineers of the firm enter the status of fully employed and experienced personnel. They are available on essentially a full time basis to apply themselves to the process of accomplishing progress on the research and development project. These full time people constitute the category of worker about which the firm constantly thinks when estimating the amount of engineering effort that is required to get the job done. On the other hand, these people serve as the resource pool from which both trainers are drawn to assist the new people and managers are selected to supervise the work of the research and development operation. As discussed earlier the company's policy towards its training program largely determines the number of "fully experienced engineers" who will be siphoned off into the training function. However, the need for managers is not as easily dismissed as being dependent

solely on an overt policy decision by the firm. The employment of a number of people requires some concept of supervisory, administrative, or managerial functions, and therefore the people necessary to carry out such functions. "The supervisory structure of engineering organizations, according to a survey of 395 laboratories, requires at least 25% of all the engineers in the organization."<sup>5</sup> This study finding clearly shows the manner by which the very hiring and utilization of engineers requires the transferring of other engineers away from performing direct engineering design and development work into the less direct areas of contribution to the task objectives. Both types of functions are essential to the research and development project.

The preceding paragraphs have discussed some aspects of the problems of recruiting, hiring, training, fully utilizing, and transferring to non-engineering functions the people who originally entered the firm as part of the engineering manpower. To complete a discussion of this nature, the question of leaving the firm or the project must also be considered. It was earlier mentioned that many firms consider the maintenance of engineering work stability as an important part of their policy for hiring new engineers. Some companies do not hire any new engineers unless they are fairly confident that they will be able to productively utilize these people for a lengthy period of time. Whatever the company policy toward the initial requisition of these engineers, however, most companies face a considerable problem when the

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<sup>5</sup>I. Hirsch, W. Milwitt, W.J. Oakes, and R.A. Pelton, "The Relation of Utilization to the Shortage of Scientists," IRE Transactions on Engineering Management, September 1958, p. 94.

services of some fraction of their engineering work force are no longer required. This difficulty most often occurs during the final phases of a research and development project when the job is coming to an end and fewer engineers are needed to complete the finishing touches on the project or to go on to some further effort. Because of the anticipated harmful effect on their later ability to hire engineers, most companies are very reluctant to lay off or fire engineering employees. An additional reason for the reluctance in releasing an engineer from the firm's employ is that research and development companies usually consider their greatest asset to be the productive ability of their engineering work force, which they often regard as a team that has required a number of years to build to high effectiveness. Such companies, therefore, hesitate before getting rid of an individual whose technological knowledge can produce further profitable ventures for the firm. "It takes approximately three years before the average new employee in a company can become fully productive, and this makes it impracticable to hire and fire R and D people on a short term basis and still retain the competence necessary for successful development."<sup>6</sup> These difficulties often influence the amount of funds that the firm is pressured to appropriate for what amounts to company-sponsored research efforts. These efforts, when instituted under such pressures, are really stop-gap measures to maintain the employment of the company's current engineers. In many situations, however, the firm which has

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<sup>6</sup>Ellis A. Johnson, "The Crisis in Science and Technology and its Effect on Military Development", Operations Research, January-February 1958, pp. 23-24.

done a good job of planning, and has been successful in making its plans materialize, is able to transfer the engineers being freed from one project to work on another project activity. Dependent on the managerial ability of the firm a company will take a long or a short time to recognize that engineers are no longer needed on the project and will then transfer them to some other work. The more able firms will anticipate availability of engineers long enough in advance so that they can make plans to utilize the engineers on another job. Some inefficiencies will usually enter in such a transfer process because of the time delays necessary for the firm to recognize the availability of the engineer, to arrange for his transfer to some other work, or if necessary to give the engineer a reasonable notification of lay-off or firing.

Voluntary transfers by individual engineers rather than company-instituted transfers dominate job turnover in the research and development industry. Marcson's study found, "Technical staff members are rarely discharged...[but voluntary movements occur such] that about half the laboratory's staff turns over every five years."<sup>7</sup> Hirsch found even higher turnover rates in his larger sample. "According to survey results, the average engineer changes jobs once in every 3.3 years. Therefore, an average engineering organization would have a 30% turnover per year."<sup>8</sup> Financial considerations certainly do seem to be important in the voluntary decisions by individuals to leave an organization.

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<sup>7</sup> Marcson, The Scientist in American Industry, p. 83.

<sup>8</sup> Hirsch, et al, p. 86.

However, considerations of motivation, prestige, family desires, individual satisfaction with the job, personal aspirations, and other factors all enter into the decision of the individual to quit a job and move elsewhere.

The first section of this chapter has discussed the flow of engineering manpower through the firm. Before going on to discuss the nature of engineering productivity, it seems appropriate to summarize at this point the nature of this flow. Initially, once the firm has (or expects to obtain) funds to support an engineering effort, it must consider the decision as to the number of engineers it wishes to hire or transfer from other jobs in the firm. This decision as to desired number of engineers is in part based on the level of the company's funding and in part on its concern for providing stable employment to the new recruits. Once the company decides the number of engineers it desires to have, it begins to attempt to recruit engineers for the purpose of filling this desired quota. It usually takes a lengthy time for the company to hire such people and often several months are required even to effect an internal transfer. After being hired, new recruits report to the firm where they undergo, generally, a training program, formal or informal, to orient them to the company and to their new work environment. The second company policy area that was discussed in the chapter concerns this point, namely, the determination of a company policy towards training. Companies are perplexed by the fact that in order to train people to produce more effectively in the future, they must take engineers away from current productive effort. The managerial ability of the firm is the strongest influence on the wisdom

of the training policies adopted. As engineers are trained, they come into the status of fully employed and experienced engineers and begin to work full time on the research and development project. However, out of this full-time group some engineers must be transferred to be used as trainers for the training program even if only on a part-time basis; and other engineers, often a large fraction of the engineering work force, must be transferred to handle administrative and managerial duties. Finally, after residing in the category of experienced engineers, many engineers are fired, laid off, or more usually, transferred to other jobs when their services are no longer needed on the current project. Company attitudes as to this problem were also discussed in the preceding paragraphs. The last topic that was discussed before closing the section on engineering manpower was the question of voluntary turnover of engineering employees. Here it was pointed out that a vast number of considerations affect the individual's decision to leave his job and go to work for some other firm.

### Engineering Productivity

Any discussion of engineering productivity tends inherently to become highly complex. This tendency is caused by two basic factors. First, there exists little sound knowledge as to the nature of human productivity, especially in those areas tending towards the more creative endeavors, such as the engineering and scientific work utilized in research and development projects. Secondly, the factors which can readily be seen to bear on the productivity of engineers constitute a group which is both large and highly unstructured. This segment of the chapter will attempt to bring most of these factors into focus,

then will discuss those factors which seem of most consequence in the determination of the effectiveness of an engineering work force.

The first factor to be discussed is the basis of productivity, that is, the level of related technological knowledge that can be applied to the problem area in question. This topic was discussed quite thoroughly in Chapter 3, where it was pointed out that the level of technological know-how determines essentially the degree of potential effectiveness of the engineering work force. As technology grows over a period of time, at least the potential effectiveness of an engineering staff also grows. This chapter will not attempt to repeat the lengthy discussion of Chapter 3, but will just mention some important points regarding the utilization of technology.

First, there is a delay before the knowledge of the technological state of the art becomes available to the firm. This delay is dependent upon the amount of effort the firm is itself putting forth in this technological area. It may more directly be related to the firm's policy of obtaining and transferring into its own usage knowledge which is being developed outside of the firm's own activities. Many different factors relate directly or indirectly to determining the delay in bringing outside information into the firm. The most obvious of these is the extent to which the engineers in the firm exchange technical information with other professional colleagues. Perhaps one of the less obvious factors is the number of years away from college of most of the staff. (The younger people have been taught the new techniques in college and often bring these methods into the firm.) Encouraging continuing education can also aid in bringing new know-how into the firm more

quickly. The alternatives available were neatly summed up by one writer's questions: "Are you adding to the skills and capacities of the engineers and technical people you have now by sponsoring after-hours scholarships for advanced undergraduate and postgraduate work? Do you encourage membership and committee activities in scientific and professional societies, independent research, and the writing of technical papers? Have you ever talked with your men about teaching, or invited other scientists and educators to meet with your staff?"<sup>9</sup>

In addition to the delay in becoming cognizant of the new technical state of the art, there is the additional delay of actually absorbing the information and making use of it. The time taken for absorption of outside discoveries and developments is quite lengthy. It constitutes the longer portion of the delay between the discovery of new knowledge in one place and the actual utilization of this know-how at some other time and location by engineers in another firm.

The actual changing state of the art and the delay in becoming aware of and utilizing this know-how do form the basis for the potential productivity of an engineering team. However, many other factors affect the actual productivity that is achieved by a group of engineers working on a research and development project. The first of these to be discussed is the effect of on-the-job experience on the abilities of the engineers. One article discussed the increased productivity resulting from experience as being analogous to the "learning curves" that have been applied to manufacturing organization efficiencies.

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<sup>9</sup>Swander, loc. cit.



"The engineer, whose job is much more complex than that of a production worker, becomes more proficient when he knows the company procedures and policies; has learned the important formal and informal communication channels; has determined where he can obtain assistance in solving critical problems; is familiar with the technical aspects of the company's products; and has learned the technical errors which were made previously so that he can avoid the same pitfalls. This learning process continues at a diminishing rate as long as the engineer is associated with the company. The learning curve takes account of the diminishing learning, since it increases by a smaller factor each year."<sup>10</sup> Of course, some companies have already learned that this diminishing rate of growth of an engineer's effectiveness need not set in. Through symposia, seminars, attendance at university "short courses", and even more extended sponsored and encouraged graduate and post-graduate education and research programs, companies such as IBM in particular seek to maintain the rate of personal development of their employees.

In addition to these general benefits which can be attributed to greater experience with the company or on the particular project, there are certain factors which tend towards increasing productivity which result from the development of specific know-how on a given project. To a high degree, many of the problems which are encountered throughout a project life cycle are similar in content or in the factors contributing to them. Thus, as knowledge is built up during the earlier

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<sup>10</sup>Hirsch, et al., p. 96

phases of the project life cycle, the firm's engineers are gathering information and new techniques that will be applicable to some parts of the later phases of the project. In the aggregate, then, the productivity of the engineers working on the job tends to increase as the job progresses from the influence of these job experience factors.

In addition to the effect that job experience has on engineering productivity, one should also consider the effects on productivity that can readily be associated with the various worker categories. As discussed in the first half of this chapter, there are basically four categories of engineering employees: engineers being trained, those doing the training and supervision, those who are more or less fully employed and experienced, and finally those men who are in the process of quitting, being laid off, transferred, or fired. The work classification of the engineer is no doubt a good indicator of his relative average productivity. For example, the new recruit just joining the firm cannot be expected to be nearly as effective as the engineering employee who has been fully employed by the firm for a period of time. This is not due merely to the over-all number of years of engineering experience of the various engineers, since new recruits may very well come from other jobs with many years of engineering background. The survey which has already been quoted several times goes into this question of trainee productivity in great detail.

Turnover is costly and wasteful to engineering utilization, primarily because of the time which must be spent in becoming re-oriented to the new environment. No matter how skilled and proficient a scientist or engineer may be, some time must be spent on learning the operating system of the new company, its physical layout, and his new associates;

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understanding the requirements of the new job; and determining communication paths both to his superiors and subordinates.

There are other significant factors involved when relocating in new geographic locations; probably not the least of these concerns the family and psychological adjustments that inevitably affect output of work.

Surely the time lost in reorientation varies greatly with the individuals and the organizations, but assuming a 30 percent turnover per year it is our estimate that losses directly attributable to job-changing represent a decrease of output of about 20 percent.<sup>11</sup>

An earlier study of the RCA Laboratories found a similar result. "One-half year was...[used] as an estimate of the time it takes for a new staff member to get acclimated and to achieve some result upon which he can report. This six-month adjustment period represents the median based on the records of the persons employed after the start of the sample period."<sup>12</sup>

In general those engineers who are working as trainers or managers also have their direct job productivity decreased substantially. Looking first at the trainer, few can question the necessity or importance of his role in the organization. In the long run his contributions to the project show up in the enhanced productivity of the engineers whom he helps to develop. In the short run, however, the trainer's direct contributions to the solution of the design and development problems of the project are decreased substantially because of the smaller portion

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<sup>11</sup>Hirsch, et al., p. 86

<sup>12</sup>Alexander G. Grasberg, "Merit Rating and Productivity in an Industrial Research Laboratory: A Case Study", IRE Transactions on Engineering Management, Vol. EM-6, No. 1 (March 1959), p. 34.

of his time available for this direct engineering work. The amount of effective engineering (rather than training) work that the trainer will be able to do depends to a large extent upon the number of trainees who have been placed under his guidance or directions.

Those engineers who have been made "engineering managers" also usually have their task-oriented productivity decreased substantially. This is not a necessary, but is rather a usual, result of the job position change. The highly effective manager of an engineering organization applies himself to laying out the direction of attack on the problem, clarifies the job requirements to save the time and effort of others, provides systems coordination, etc., all of which are very much a part of the engineering task in a research and development project. He stays close to the critical job problems through council with his engineers and sometimes through participation in the making of key design decisions. However, very few engineering managers have such high effectiveness. Most managers do not manage at all. Instead they administer. They typically spend vast amounts of time on performance ratings of their engineers and on pay raise evaluations. They prepare multiple budgets which serve not as job planning tools, but rather for organization accounting purposes. They entertain customer visitors, attend higher-level staff meetings, file and collect reports in such numbers and details that the meaningfulness of these to the real management of the project seems only a remote possibility. Those who express concern for the underutilization of engineers might more profitably examine the underutilization of engineering managers who waste much time and talent on such administrative trivia. To be sure, the functions

performed may well be important to the organization, but they have little direct relevance to the project task. Thus, except for the few engineering managers who do perform the managerial role outlined, the others have their task-oriented productivity severely decreased by their work activities.

The third category of workers whose effectiveness is decreased because of the nature of their work situation is that group of engineers who are in the process of leaving the company or project, whether for voluntary or involuntary reasons. The time informally consumed by transfer activities, the loss of enthusiasm for the job which is being completed, and very often the poor attitude towards the organization or project which the engineer is leaving, all contribute to a decreased technical efficiency of the engineer while he is working in this status.

Finally, one can consider the so-called fully-employed engineer. He has been selected as the standard of engineering productivity who on the average is supposedly able to manifest in his work the available and utilizable engineering productivity which was discussed earlier. However, the job experience effect, mentioned earlier, also influences the fully-employed engineer, as do the effects of management which will be discussed below.

To an extent, one can recognize another, partly over-all category of worker, namely the engineer not on the job due to sickness, vacations, holidays, or incidental personal reasons. Though this appears basically as random noise in the system, it does have a strong seasonal component due to vacations. An earlier study by the author in an engineering department of the General Electric Company showed that this

off-the-job time amounted to an average of about 12 percent of the year's total potential work-days.<sup>13</sup>

Now turning to other factors which influence engineering productivity, "Experience has shown that the leader is probably the most important single factor influencing team performance."<sup>14</sup> Despite the apparent breadth of this generalization as to the next-to-be-discussed factor of productivity, many other researchers have agreed. "The engineering supervisor may be considered the most vital factor in achieving the full utilization of engineering potential"<sup>15</sup> It is easy to see the poor organization of work, the hiring of less competent personnel, lack of proper utilization of outside technological resources, and many other factors all are attributable to the quality of management of a firm. This can lead to lower utilized technological effectiveness than that which is potentially available to the firm. Thus, "Good supervision is basic to high R and D effectiveness. In this respect, research does not differ materially from other company areas. Yet management often excuses poor supervision on the basis that R and D work does not lend itself to direction, that the scientist works better when unrestricted, or that the experience and education of the scientist poorly fit him for handling others.

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<sup>13</sup>Edward B. Roberts, "The Digital Computer as an Element of a Financial Control System", unpublished Master's thesis, M.I.T., June 1958, p. A.1-27, 28.

<sup>14</sup>Fred E. Fiedler, "The Leader's Psychological Distance and Group Effectiveness" in Group Dynamics, Research and Theory, Second Edition, edited by Dorwin Cartwright and Alvin Zander (Evanston, Illinois: Row, Peterson and Company, 1960), p. 586.

<sup>15</sup>Simon Marcson, "Role Concept of Engineering Managers", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 30.

Here is where many companies run into trouble."<sup>16</sup>

There are many ways in which the quality of management enters in determining the effectiveness of the engineering work team. Principle among these is that the able management will effect policies that enable group leaders and working engineers to see their particular task in the perspective of an over-all organizational objective. This assists everyone in the project to see the forest as well as the trees thus providing a more intelligent basis for individual engineering decisions. The capable management will establish a penalty-reward system in the firm which encourages initiative and creativity, not for their own sakes, but towards defining and accomplishing project goals. Management of high quality will design a penalty-reward system which encourages objectivity and the organizational integrity that permits quick recognition and communication of project problems and bottlenecks. Such a set of attitudes allows the people of the organization to be the communication and control system needed for effective project management, without dependence on the artificial and ineffective devices for project evaluation and review whose proponents currently clutter both the management literature and mailbag.

Such an environment both establishes good leaders and effective working engineers. It provides worker motivations which derive from pride and involvement in the work group, and the effective performance which results from such motivations. Through policies which enhance these characteristics, the quality of the firm's management creates a

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<sup>16</sup>Randle, p. 134.



major effect on engineering productivity.

A second managerially-related effect upon the productivity of engineers in the firm is the size of the engineering work force. In an article specifically oriented to the difficulties relating to the size of engineering groups, Kershner said, "Above a certain level, the assignment of additional personnel to a large project may not only not reduce total time proportionately, but in fact may increase total time to accomplishment, and....many organizations today engaged in complex engineering tasks are operating at a level in which this fact is true.... They could speed up the accomplishment of their tasks by reduction of engineering personnel."<sup>17</sup> From his studies at the Army Operations Research Office, Ellis Johnson also found that **having too many engineers** working on a project increases the length of time for development.<sup>18</sup>

The communications problem is particularly great as the size of the engineering team increases. "While the laboratory was a small organization, the research executive would participate knowledgeably in the on-going research and so influence its direction personally. As the laboratory grew in size, knowledge about specific on-going research projects grew away from him, and he seemed to spend more time on budget and personnel matters."<sup>19</sup>

Finally, as the organization solidifies into this large engineering group, the next thing that happens because you have too many people is that you become

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<sup>17</sup>R.B. Kershner, "The Size of Research and Engineering Teams", IRE Transactions on Engineering Management, June 1958, p. 35.

<sup>18</sup>Johnson, op. cit., p. 25.

<sup>19</sup>Marcson, The Scientist in American Industry, p. 99.

heavily involved with the well-known problem of organizational inertia...A large organization simply moves more slowly. There are more elaborate controls; there is much more paperwork; there is more sitting down and writing memos that must go through several channels and finally wind up on a desk that is already overwhelmed with memos; there is more waiting three weeks before the proper signature can be obtained to authorize purchase of a paper clip to hold all the memos. This process is a very well-known one, but it is, of course, very extremely serious.<sup>20</sup>

There is strong reason to believe that the tight organization, that is the one that has both a meager budget and staff, can in fact accomplish objectives significantly out of proportion to its size.

There have been a few cases of major programs carried out very successfully with extremely small engineering staff, which might serve as indications of the appropriate level of effort. Notable among these is the Sidewinder program. This program, with a tiny engineering staff at NOTS, led to an extremely successful guided missile. The group was small enough that the approach could be kept completely coordinated and all major technical decisions were made by one man, William McLean. Mr. McLean was recently awarded a special Civil Service prize for his accomplishment in this program and richly deserved it. But in addition to being a testament to the brilliance of one individual, the program serves also as a striking illustration of the efficiency achievable with a small engineering staff.<sup>21</sup>

Another relatively recent example of the ability of a tightly organized team to perform efficiently and effectively is the feat of the Von Braun rocket group at Huntsville, Alabama. After a long and rather typical development program for the Vanguard satellite had failed in its first two attempts to launch a satellite for the United States, the

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<sup>20</sup>Kershner, p. 37.

<sup>21</sup>Ibid., p. 38

Von Braun group was given the go-ahead to make an attempt under Army auspices. Eighty-four days after receipt of the authorization, the Von Braun group successfully launched America's first satellite, the Pioneer I. To be sure the satellite and rocket were not developed in this brief period. The organization had many years of experience in related areas, had previously developed the launch vehicle, and had thought about and done preliminary work on the problems of earth satellites. But this type of background is exactly that which is necessary to an effective project team. The people need deep understandings of each other, of the technical problems, of the related science and, more important, of the required art. These elements enable a group, such as Von Braun's, to run with the ball once given an opportunity. Both the Sidewinder and Pioneer I provide good examples, of the effects of a small, well-directed work team combined with top-notch managerial capability and the presence of strong motivation for accomplishment to produce the impressive results that were achieved.

A third way in which the ability of the manager can affect the overall productivity of the work force enters in the manager's decision to allocate engineering effort to the different types of work that have to be done on a project. From unwise decisions of this class arises gross waste of scientific and engineering talent, not only in the use of engineers for jobs which could more effectively and efficiently be done by someone else. More importantly, such waste comes from the poor decisions which provide engineering resources to the vast percentage of projects, cited in the Introduction, which never result in satisfactory finished products. In the same vein, the engineering manager's

allocation of his own time also can have a great effect on the work productivity of his group.

The study on engineering utilization by Hirsch and others, cited several times earlier, went into great detail on the reasons behind the misallocation of manpower.

We believe that the mass engineering philosophy represents the most serious waste of engineering manpower today. Mass engineering is an expression used to describe a situation where several engineers are assigned to a job which could be adequately accomplished in the same length of time by any one competent engineer properly supported by technicians. Much of the incentive for the mass engineering approach seems to stem from the flexibility permitted under the cost-plus-fixed-fee type of contract. Under this type of contract, which is used almost universally by the military and defense projects, the normal competitive stimulus is removed. The efficient engineering organization is penalized to an extent, because with reduced costs come reduced profits.<sup>22</sup>

Hirsch relates this difficulty to the quality and training of the managers of such engineering firms. "Many modern engineering executives are products of the cost-plus-fixed-fee era. As such, they have not obtained a true appreciation of the value of running an efficient organization. The competitive stimulus where profits are proportional to efficiency does not exist. Because of this, the executive lacks a desire, and sometimes the ability, to increase the productivity of his scientists and engineers."<sup>23</sup>

The last few paragraphs have examined the effect of the management of the engineering company on the productivity of its engineers. Management aspects relating to general organizational effectiveness, engineering motivation, the effects of size of the work force on efficiency,

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<sup>22</sup>Hirsch, et. al., p. 90.

<sup>23</sup>Ibid., pp. 91-92.

and the effects of allocation of engineering manpower to different problems were all discussed. The Hirsch study summed up its findings regarding factors such as these, plus many others which they listed, as: "Our best estimates at this time indicate that improved utilization of the scientific manpower available could result in increased yields by a factor up to 100 times--with a more probable increase of about 10 times! This would mean that by improving utilization methods alone, i.e., without increasing the supply, about ten times as much output could be obtained from our scientific supply."<sup>24</sup>

In re-examining this entire last portion of the chapter devoted to the problems of engineering productivity, it suffices to say that the productivity of engineers in any research and development project is based upon the technology available to them plus many modifying factors. These modifiers include the engineers' experience on the job, their work status within the engineering organization, and the effects of management of the firm. These managerial effects, in turn, relate to the areas of a penalty-reward system. These in turn effect motivation, size of the organization, and allocation of effort. All of these combine to produce the existing level of effectiveness of the engineers who are working for the company on the research and development project at any given time, and the changes in this effectiveness from time to time. The integration of the applied man-hours of work with this level of effectiveness produces the progress on the job which will be further discussed in the next chapter.

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<sup>24</sup>Ibid., p. 88.

## APPENDIX TO CHAPTER V

The presentation of the flow diagrams and model equations in this appendix shall follow the breakdown used in the descriptive part of the chapter. First we shall discuss the flow of engineering manpower and then delve into the question of engineering productivity. Figure 5-1 presents visually the flow of engineering manpower. As a result of recruiting activity by the firm, new engineers are recruited and join the firm. They go through a formal training or informal indoctrination period during which their skills gradually increase to those of the average longer-term employee of the firm. Some of the more experienced engineers are reassigned to training and supervisory roles as these needs arise. Similarly, when their services are no longer required on the particular project under consideration they are transferred to another job, or occasionally are actually fired from the firm's employ. Those who are being transferred out require some period of time for paper work before they actually leave the project. This continuing inflow and outflow of engineers into and from the firm cumulatively produces the level of engineers actually, as well as those expected, on the project.

All of these basic changes take place in response to the firm's efforts to adjust its actual engineering level to the number it desires. These desires are based on considerations both of maintenance of a stable engineering work force and of the firm's ability to profitably support the engineering force.

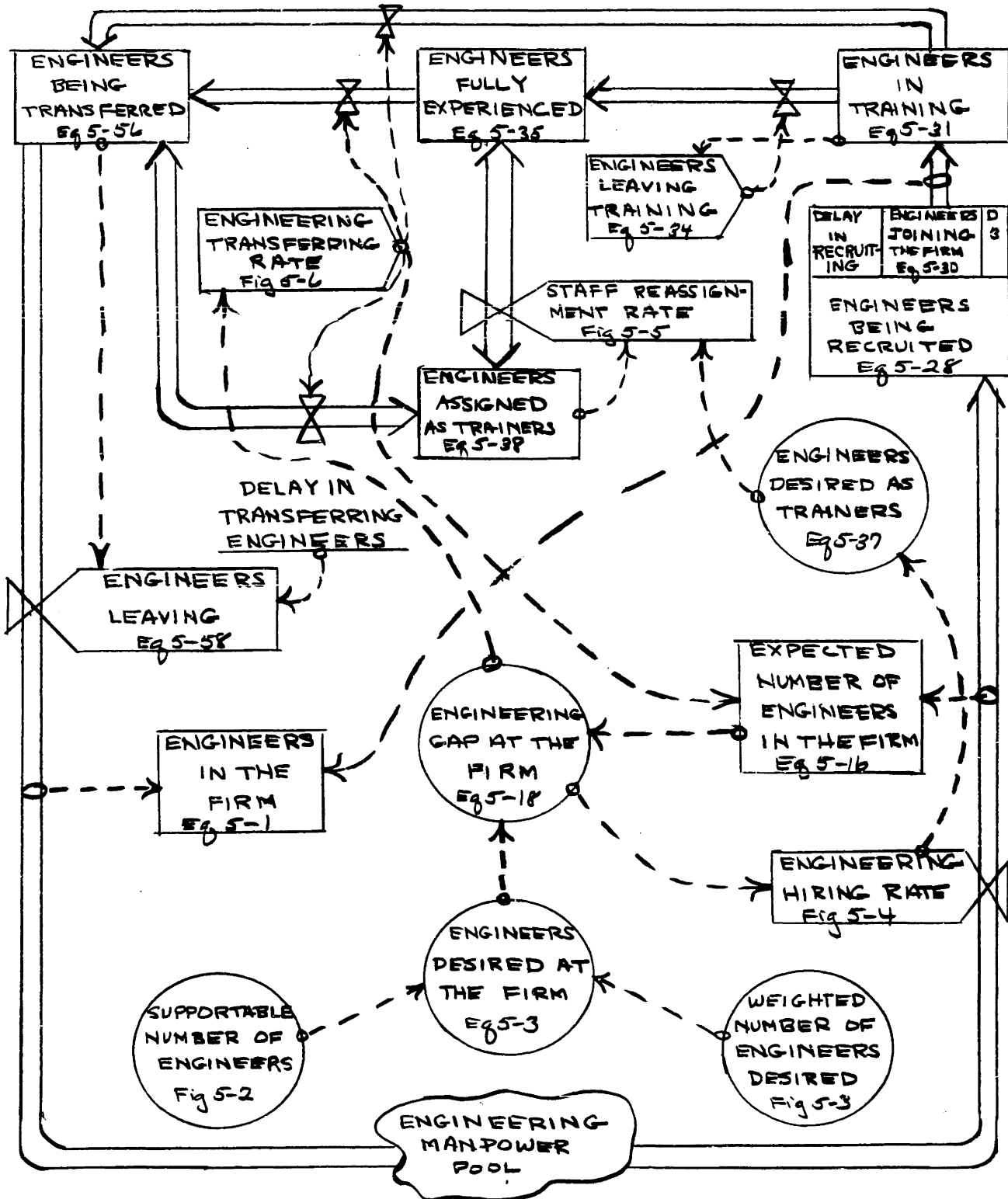


Figure 5-1 The Flow of Engineering Manpower

Let us start the equations of Chapter 5 with the information-level equation for the engineers actually employed by the firm on the project, regardless of their status. This level is a continuous summation of the engineers joining the firm minus those leaving the firm.

$$\text{ENGRF.K} = \text{ENGRF.J} + (\text{DT})(\text{ENCJF.JK} - \text{ENCLF.JK}) \quad 5-1, L$$

$$\text{ENGRF} = \text{LEI} \quad 5-2, N$$

ENGRF--ENGINEERS in the Firm (men)  
 ENGJF--ENGINEERS Joining the Firm (men/month)  
 ENGLF--ENGINEERS Leaving the Firm (men/month)  
 LEI--Level of ENGINEERS Initially (men)

The engineers desired, as contrasted to the actual ones, certainly cannot exceed those whom we expect to be able to support financially. However, in some cases the project needs or other policies may restrict the desired level to less than our supportable level.

$$\text{ENGDF.K} = \text{MIN}(\text{SENGF.K}, \text{WENGDF.K}) \quad 5-3, A$$

ENGDF--ENGINEERS Desired at Firm (men)  
 SENGF--Supportable number of ENGINEERS at Firm (men)  
 WENGDF--Weighted number of ENGINEERS Desired at Firm (men)

The number of engineers considered supportable is based on the estimated funding that will be available in the future. This estimate rests on two factors: the average funding that has recently been available from the customer and/or the firm itself; and the recent changes in the funding which are expected to continue. The period of future planning on this funding takes into account the hiring lead-time (if available funds are increasing) and the engineering transfer time (if funding is on the decline). **These considerations**



are shown in Figure 5-2.

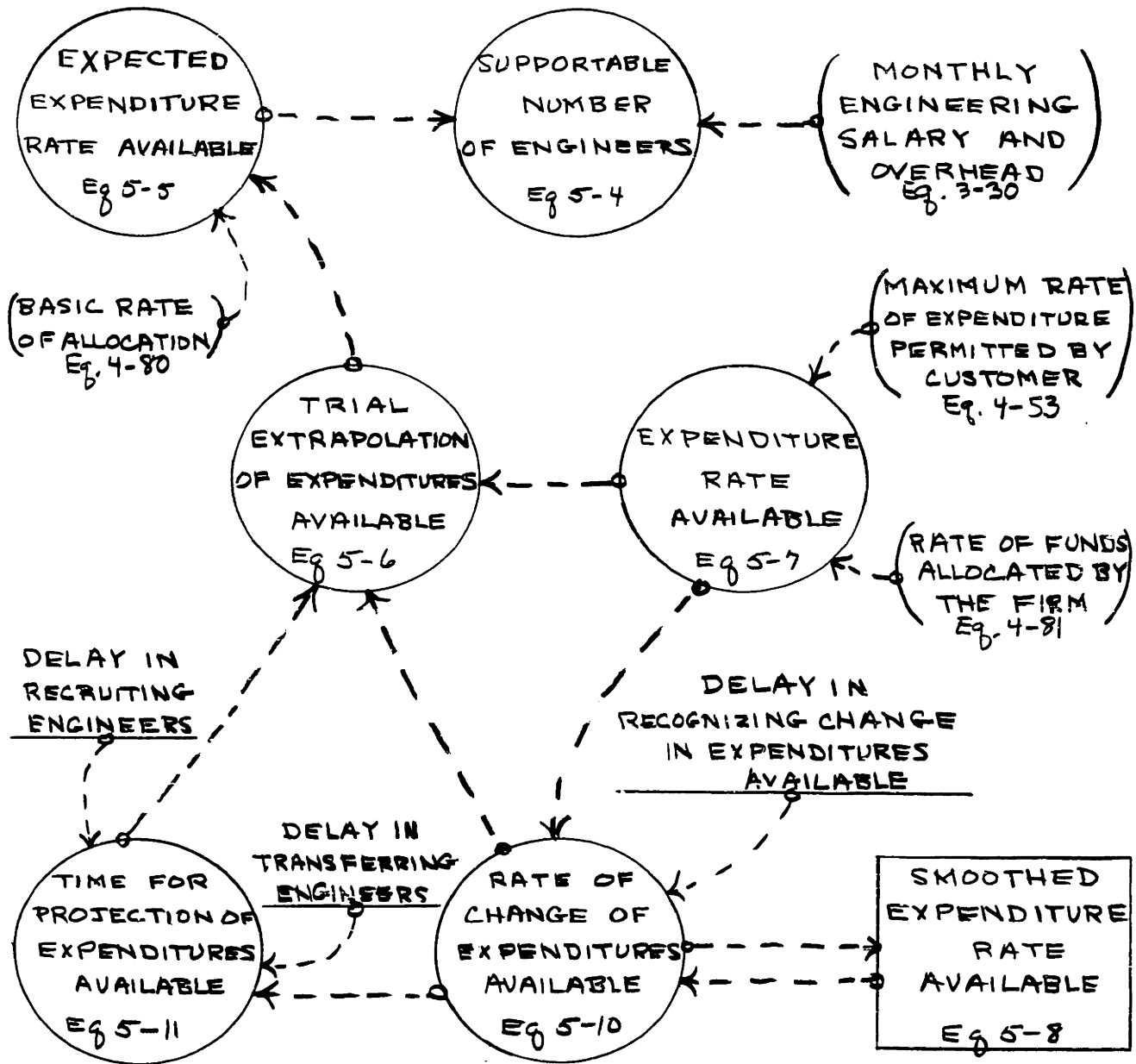


Figure 5-2 Supportable Number of Engineers

The first equation of this group, Equation 5-4, indicates that the number of engineers who can be supported on the expected funding equals the expected monthly funding rate divided by the average monthly support cost per engineer.

$$\text{SENGF.K} = \frac{\text{EERAF.K}}{\text{MESOH}}$$

5-4, A

SENGF--Supportable number of ENGINEERS at the Firm  
(men)  
EERAF--Expected Expenditure Rate Available to the Firm  
(dollars/month)  
MESOH--Monthly Engineering Salary and Over Head  
(dollars/man-month)

The expected expenditure rate available is, in general, an extrapolation of the recent changes in funding from the customer. Should this support from the customer be falling, the firm knows that his own basic support rate can be provided if necessary. The expected funding from the customer, Equation 5-6, is equal to the current expenditure rate available plus any change in this funding which is expected in the next few months. The firm anticipates that the changes in the near future will be similar to the recent changes in the funding available. The last equation listed below says that the expenditure rate available is the larger of the amount permitted by the customer and that being allocated by the firm.

$$\text{EERAF.K} = \text{MAX}(\text{TEEAF.J}, \text{BRAAF}) \quad 5-5, \text{ A}$$

$$\text{TEEAF.K} = \text{ERAF.K} + (\text{RCEAF.K})(\text{TPEAF.K}) \quad 5-6, \text{ A}$$

$$\text{ERAF.K} = \text{MAX}(\text{MREPC.K}, \text{RFAAF.JK}) \quad 5-7, \text{ A}$$

EERAF--Expected Expenditure Rate Available to Firm  
(dollars /month)  
TEEAF--TriaI Extrapolation of Expenditures Available  
to Firm (dollars/month)  
BRAAF--Basic Rate of Allocations by Firm (dollars/month)  
ERAF--Expenditure Rate Available to Firm (dollars/month)  
RCEAF--Rate of Change of Expenditures Available to Firm  
(dollars/month/month)  
TPEAF--Time for Projection of Expenditures Available  
to Firm (months)

MREPC--Maximum Rate of Expenditure Permitted by  
Customer (dollars/month)  
RFAF--Rate of Funds Allocated by the Firm  
(dollars/month)

In trying to estimate the funding that will be available, the firm averages over the recent past the funding that has been available. The averaging, or smoothing, equation written below takes an exponential average of the expenditure rate available, ERAF, over the past DRCEA months.

$$\text{SERAF.K} = \text{SERAF.J} + (\text{DT})(\text{RCEAF.J}) \quad 5-8, \text{ L}$$

$$\text{SERAF} = \text{BRAAF} \quad 5-9, \text{ N}$$

$$\text{RCEAF.K} = \frac{\text{ERAF.K} - \text{SERAF.K}}{\text{DRCEA}} \quad 5-10, \text{ A}$$

SERAF--Smoothed Expenditure Rate Available to the Firm  
(dollars/month)

RCEAF--Rate of Change of Expenditure Available to the  
Firm (dollars/month/month)

BRAAF--Basic Rate of Allocations by the Firm (dollars/month)

ERAF--Expenditure Rate Available to the Firm (dollars/month)

DRCEA--Delay in Recognizing Change in Expenditures  
Available (months)

Since the firm is very quick to take cognizance of any changes in the project funding available, DRCEA is estimated at one month.

$$\text{DRCEA} = 1 \text{ month}$$

The final variable taken into account in Figure 5-2 was the time for projection of the changes in expenditure rate available. Equation 5-11 states that when funding is increasing, the firm projects ahead the duration of the recruiting time. This period is used because the firm is trying to anticipate the additional number of engineers it should acquire, if the firm relies on the expected increased support. On the other hand, if funding is falling, the firm projects the support change for the duration of time needed

to transfer engineers from the project. This is done so that the firm can effect the transfers by the time its support rate falls further.

$$\text{TPEAF.K} = \text{CLIP} (\text{DRCE}, \text{DTRE}, \text{RCEAF.K}, 0) \quad 5-11, \text{ A}$$

TPEAF--Time for Projection of Expenditures Available to the Firm (months)  
 DRCE--Delay in ReCruiting Engineers (months)  
 DTRE--Delay in TRansferring Engineers (months)  
 RCEAF--Rate of Change of Expenditures Available to the Firm (dollars/month/month)

The delay in recruiting the engineers, on the average, is on the order of several months. This takes into account the fact that some engineers will be available in a very short period from elsewhere in the firm, while others, particularly when the firm is seeking special skills, a large number of engineers, or new college recruits, will not be available for as much as a year or even more. Averaging these together the recruiting time will be set at six months. The transfers out of the project, or even completely out of the firm, can be implemented, once the firm makes the decision, in about one month. Thus,

$$\text{DRCE} = 6 \text{ months}$$

$$\text{DTRE} = 1 \text{ month}$$

When deciding upon the number of engineers it desires to have, instead of considering just the number of engineers whom they can support in the near future, the firm also takes into account the assumed need for maintaining as much stability as possible in the engineering work force. Thus before hiring additional engineers it will contemplate the duration of need for these engineers. Diff-

erent firms will weigh this factor to various extents. In general, however, the relative weighting between the support level of engineers and those who are expected to be needed for the project duration is dependent upon the stage of the project. That is, the policy that sets the number of engineers desired tends to depend on the support level during the early project phases and gradually moves towards dependence on engineering work force stability considerations as the project moves forward. These factors are illustrated in Figure 5-3.

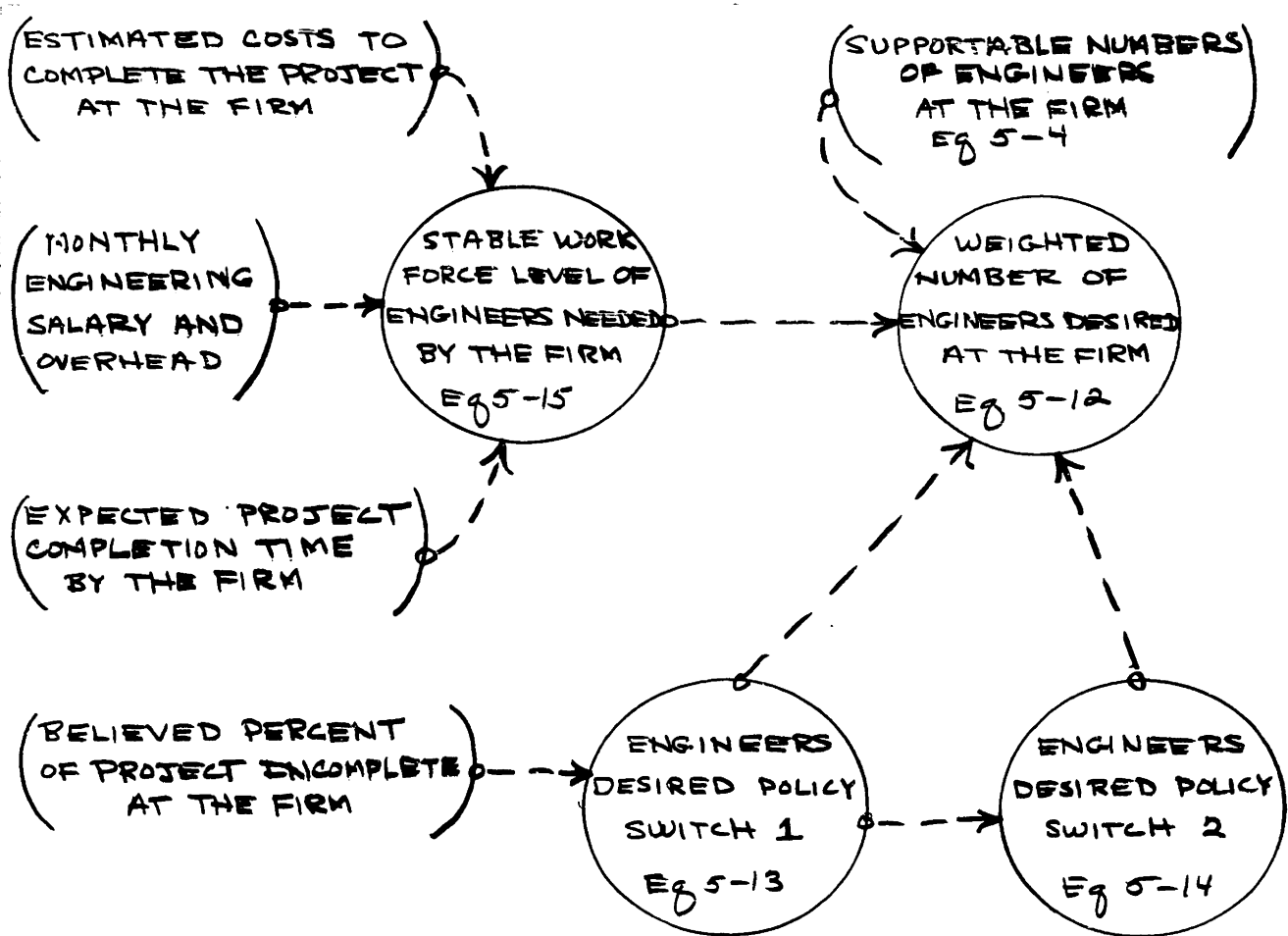


Figure 5-3 Weighted Number of Engineers Desired

Equations 5-12 through 5-14 indicate that the weighted number of engineers desired takes into account both the stable work force level of engineers (SWENF) and the number of engineers supportable on the anticipated funds (SENGF). The weighting is dependent on the stage of project progress. At the beginning of the job, the believed percent incomplete is 100%, and EDPS1 = 0 with EDPS2 therefore equal to 1. Thus at the beginning of a project the weighting considers only the support level. As the job progresses, the weighting depends more and more on stable work force considerations. By the time the project is completed, EDPS1 = 1 and EDPS2 = 0, thus causing WENGD to be wholly dependent on work force stability factors.

$$WENGD.K = (EDPS1.K)(SWENF.K) + (EDPS2.K)(SENGF.K) \quad 5-12, A$$

$$EDPS1.K = 1 - BPPIF.K \quad 5-13, A$$

$$EDPS2.K = 1 - EDPS1.K \quad 5-14, A$$

WENGD--Weighted number of ENGINEERS Desired at firm  
(men)  
EDPS1--Engineers Desired Policy Switch 1 (percentage)  
SWENF--Stable Work force level of Engineers Needed by  
the Firm (men)  
EDPS2--Engineers Desired Policy Switch 2 (percentage)  
SENGF--Supportable number of ENGINEERS at the Firm (men)  
BPPIF--Believed Percent of Project Incomplete by the  
Firm (percentage)

The equation which indicates the stable work force level of engineering determines the expected man-months of effort remaining in the project ( $ECCPF.K/MESCH$ ) and divides this by the expected time left for completion of the project. This determines the number of engineers who can be steadily employed until project completion, given the expected effort needed and the project scheduling.

$$\text{SWENF.K} = \frac{\text{ECCPF.K}}{(\text{MESOH})(\text{EPCTF.K})} \quad 5-15, \text{ A}$$

SWENF--Stable Work force level of Engineers Needed by the Firm (men)

ECCPF--Expected Costs to Complete Project by Firm (dollars)

MESOH--Monthly Engineering Salary and OverHead (dollars/man-month)

EPCTF--Expected Project Completion Time by the Firm (months)

In trying to adjust the number of engineers to its desired level, the firm needs to recognize its actions, already initiated, which will bring new engineers into the firm or separate some of the current engineering employees from the firm. Thus we need to designate the level of engineers which the firm expects to have, based on all of its hiring and transferring actions taken thusfar.

$$\text{EENGF.K} = \text{EENGF.J} + (\text{DT})(\text{ENGHF.JK} - \text{ENGTF.JK}) \quad 5-16, \text{ L}$$

$$\text{EENGF} = \text{LEI} \quad 5-17, \text{ N}$$

EENGF--Expected number of ENGINEERS in the Firm (men)

ENGHF--ENGINEERING Hiring rate at the Firm (men/month)

ENGTF--ENGINEERING Transferring rate at the Firm (men/month)

LEI--Level of Engineers Initially (men)

The gap between the number of engineers desired and those expected is next defined by a simple subtraction operation.

$$\text{ENGP.F.K} = \text{ENGDF.K} - \text{EENGF.K} \quad 5-18, \text{ A}$$

ENGP.F--Engineering Gap at the Firm (men)

ENGDF--ENGINEERS Desired at the Firm (men)

EENGF--Expected number of ENGINEERS in the Firm (men)

This gap constitutes a need for either hiring into or transferring out of the project the number of engineers indicated by ENGP.F. Let us first examine the hiring sequence. Figure 5-4 shows

that the engineering gap combines with the firm's delay in changing the level of engineers to produce a desired rate of change in engineering.

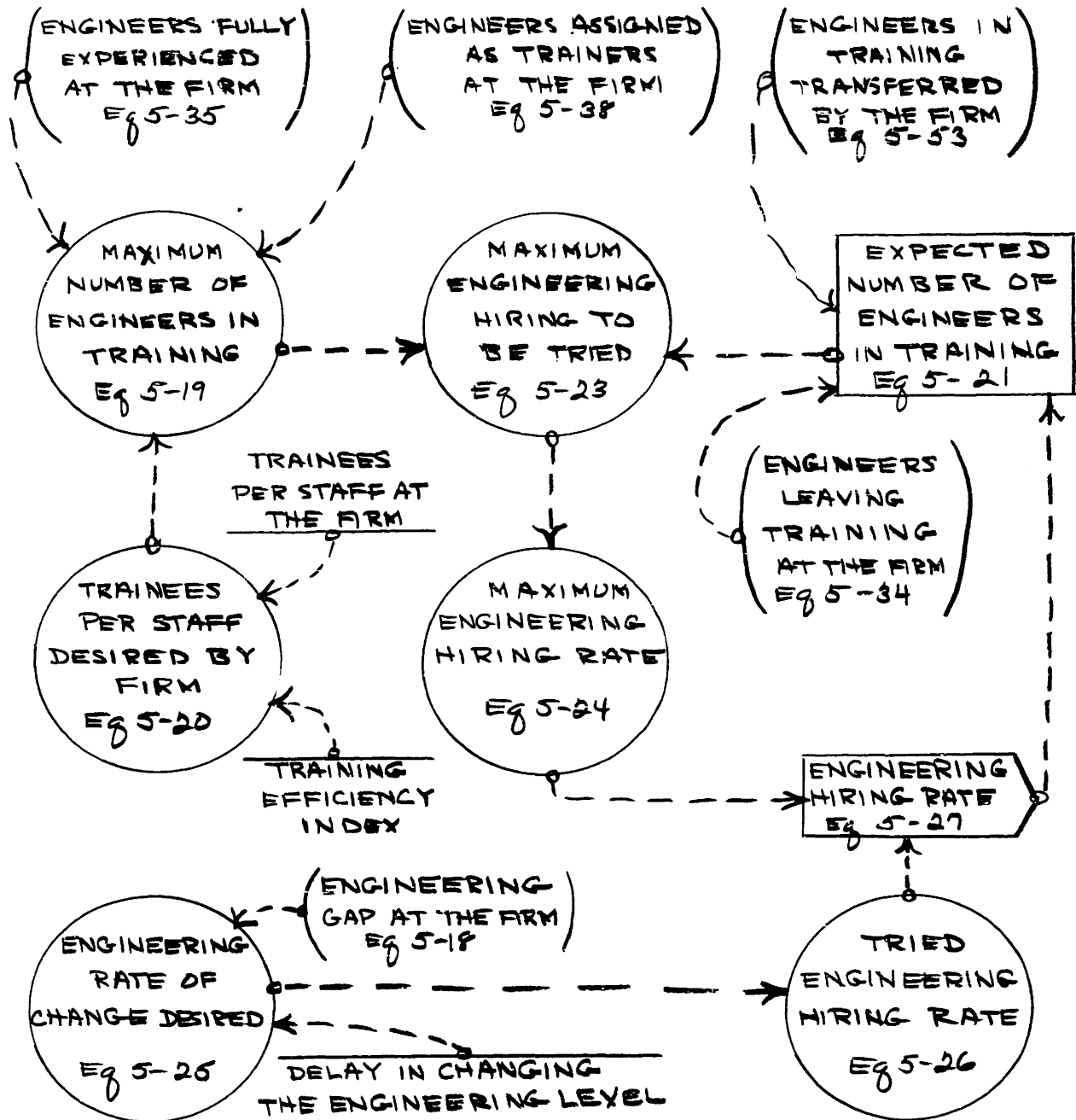


Figure 5-4 Engineering Hiring Rate

The delay represents the fact that only a fraction of the personnel requests shown by the engineering gap can be processed in



any single month. However, the firm restricts its hiring rate not only because of its own limitations in recruiting capability nor solely because of the limits imposed by the lack of immediate availability of qualified engineers. In addition to these, the firm takes account of its own ability to absorb new people into the organization, to train them and make them an integral part of a productive team. We shall here recognize a policy, formal or more usually implicit, that the rate of hiring of new engineers be restricted to that number which the firm feels its fully integrated staff can handle.

Equation 5-19 expresses this policy that the maximum number of relatively new engineers desired at any time is limited by the number of experienced engineers, both those working full time on the project task and those already partly engaged in training the new engineers on the project. The number of recruits each experienced engineer can supervise effectively is a function the number each can usually handle (TPSF) multiplied by the current training efficiency of the staff (TEI). The last equation in the group below says that the level of engineers expected in training is a continuous summation of the firm's hiring rate minus the rate of engineering completions of training minus the firm's transfers of new engineers from the project area. The following equations apply to these factors:

$$\text{MEITF.K} = (\text{TPSDF})(\text{ENFEF.K} + \text{ENATF.K}) \quad 5-19, \text{ A}$$

$$\text{TPSDF} = (\text{TEI})(\text{TPSF}) \quad 5-20, \text{ N}$$

$$\text{EEITF.K} = \text{EEITF.J} + (\text{DT})(\text{ENGHF.JK} - \text{ENLTF.JK} - \text{EITTF.J}) \quad 5-21, \text{ L}$$

$$EEITF = 0$$

5-22, N

MEITF--Maximum number of Engineers In Training at Firm (men)  
 TPSDF--Trainees Per Staff Desired by Firm (men/men)  
 ENFEF--Engineers Fully Experienced at Firm (men)  
 ENATF--Engineers Assigned as Trainers at the Firm (men)  
 TEI--Training Efficiency Index (dimensionless)  
 TPSF--Trainees Per Staff at the Firm (men/men)  
 EEITF--Expected number of Engineers In Training at Firm (men)  
 ENGHF--Engineering Hiring rate at Firm (men/month)  
 ENLTF--Engineers Leaving Training at Firm (men/month)  
 EITTF--Engineers In Training Transferred by the Firm (men/month)

The normal number of trainees which an experienced engineer can supervise (on part-time basis) will be set initially at 2.5 men. This will be modified in essence in several computer simulations by changing the training efficiency index, TEI, from its initial unity value.

$$TPSF = 2.5 \text{ men/men}$$

$$TEI = 1.00$$

The maximum hiring rate permitted under this policy is therefore the rate which (during one computational interval) would bring the expected number of trainees up to the specified limit. If, as Equation 5-24 shows, this amount is not positive, the firm will do no hiring. The desired engineering rate of change, Equation 5-25, is a fraction of the engineering gap, the fraction indicating how long it usually takes for the firm to process engineering requests. If this desired rate of change is positive, the firm will attempt to hire; if not, it will hire no one and will consider transferring some engineers from the project. The actual hiring rate, ENGHF,

is the desired hiring rate, TENHF, unless the maximum rate described above restricts hiring still further.

$$\begin{aligned} \text{MEHTF.K} &= \frac{\text{MEITF.K} - \text{EEITF.K}}{\text{DT}} && 5-23, A \\ \text{MENHF.K} &= \text{MAX}(\text{MEHTF.K}, 0) && 5-24, A \\ \text{ENGCF.K} &= \frac{\text{ENGP.F.K}}{\text{DCEF}} && 5-25, A \\ \text{TENHF.K} &= \text{MAX}(\text{ENGCF.K}, 0) && 5-26, A \\ \text{ENGHF.KL} &= \text{MIN}(\text{TENHF.K}, \text{MENHF.K}) && 5-27, R \end{aligned}$$

MEHTF--Maximum Engineering Hiring to be Tried by the Firm (men/month)  
 MEITF--Maximum number of Engineers In Training at Firm (men)  
 EEITF--Expected number of Engineers In Training at Firm (men)  
 MENHF--Maximum Engineering Hiring rate at Firm (men/month)  
 ENGCF--Engineering rate of Change desired at Firm (men/month)  
 ENGP.F--Engineering Gap at the Firm (men)  
 DCEF--Delay in Changing the Engineering level at the Firm  
 TENHF--Tried Engineering Hiring rate at Firm (men/month)  
 ENGHF--Engineering Hiring rate at Firm (men/month)

When new engineers are needed for the project, an average of about three months is needed to process the specifications. Thus,

$$\text{DCEF} = 3 \text{ months}$$

Once engineers have been hired, several months usually pass before they can free themselves of current commitments and report for duty to the firm. Their rate of joining the firm is represented as a third-order exponential delay of the hiring rate. When they join the firm, the new engineers supplement others who are in training at the firm. The number in training, ENITF, is depleted by those completing the training program and by those transferred out of training and from the project by the firm. Those not being transferred remain in training (ENRTF) until they complete the pro-

gram after a period of about DETF months. Upon completion of training the engineers take on the same responsibilities as the other experienced engineers.

$$\begin{aligned} \text{ENBRF.K} &= \text{ENBRF.J} + (\text{DT})(\text{ENGHF.JK} - \text{ENGJF.JK}) && 5-28, \text{ L} \\ \text{ENBRF} &= 0 && 5-29, \text{ N} \\ \text{ENGJF.KL} &= \text{DELAY3}(\text{ENGHF.JK}, \text{DRCE}) && 5-30, \text{ R} \\ \text{ENITF.K} &= \text{ENITF.J} + (\text{DT})(\text{ENGJF.JK} - \text{ENLTF.JK} - \text{EITTF.J}) && 5-31, \text{ L} \\ \text{ENITF} &= 0 && 5-32, \text{ N} \\ \text{ENRTF.K} &= \text{ENITF.K} + (\text{DT})(-\text{EITTF.K}) && 5-33, \text{ A} \\ \text{ENLTF.KL} &= \frac{\text{ENRTF.K}}{\text{DETF}} && 5-34, \text{ R} \\ \text{ENFEF.K} &= \text{ENFEF.J} + (\text{DT})(\text{ENLTF.JK} - \text{ENFTF.J} - \text{ENREF.JK}) && 5-35, \text{ L} \\ \text{ENFEF} &= \text{LEI} && 5-36, \text{ N} \end{aligned}$$

ENBRF--Engineers Being Recruited by the Firm (men)  
 ENGHF--Engineering Hiring rate at the Firm (men/month)  
 ENGJF--Engineers Joining the Firm (men/month)  
 DRCE--Delay in Recruiting Engineers (month)  
 ENITF--Engineers In Training at the Firm (men)  
 ENLTF--Engineers Leaving Training at the Firm (men/month)  
 EITTF--Engineers In Training Transferred by the Firm  
 (men/month)  
 ENRTF--Engineers Remaining in Training at the Firm (men)  
 DETF-- Delay in Engineering Training at the Firm (men)  
 ENFEF--Engineers Fully Experienced at the Firm (men)  
 ENFTF--Engineers Fully experienced Transferred by the  
 Firm (men/month)  
 ENREF--Engineering REassignment rate at the Firm  
 (men/month)  
 LEI--Level of Engineers Initially (men)

The equation for ENRTF takes into account the fact that engineers currently being transferred out of training will not be available for the normal completion of training that is treated by ENLTF.

Earlier in this appendix the recruitment time, DRCE, was specified

as six months. The time required to fully indoctrinate and train the new engineers up to the average effectiveness of the more experienced engineers is the subject of major disagreement. Some, quoted earlier in this chapter, estimated the time at six months; others were quoted with estimates as high as three years; still other people have privately indicated a belief that as much as five years are required for this training. As an initial compromise DETF will be set at one and one-half years, and the project will be simulated later under varying values of the DETF parameter. Therefore, initially,

$$\text{DETF} = 18 \text{ months}$$

Whether formally indicated or not, the pressures of new employees require some of the fully experienced engineers to spend a portion of their time supervising or helping to train or break in the new recruits. In the model, we shall explicitly recognize this reassignment of effort. The average experienced engineer is assumed to be able to indoctrinate (or manage) an average number (given by TPSF) of new employees. The reallocation of effort by these engineers of course results in a decreased direct personal productivity, as will be modeled later. Equation 5-37 states that the number of engineers desired as trainers equals the number of new engineers expected divided by the number of recruits each experienced engineer can train. Corresponding to this desired level, equation 5-38 gives the actual number of engineers engaged in training and/or supervisory work as a resultant of reassignments to and from the full-time engineering category, also taking into

account the transfers of some of these trainers out of the project area.

$$\text{ENDTF.K} = \frac{\text{EEITF.K}}{\text{TPSF}} \quad 5-37, \text{ A}$$

$$\text{ENATF.K} = \text{ENATF.J} + (\text{DT})(\text{ENREF.JK} - \text{ENTTF.J}) \quad 5-38, \text{ L}$$

$$\text{ENATF} = 0 \quad 5-39, \text{ N}$$

ENDTF--Engineers Desired as Trainers by the Firm (men)  
 EEITF--Expected number of Engineers In Training at the Firm (men)  
 TPSF--Trainees Per Staff at Firm (men/month)  
 ENATF--Engineers Assigned as Trainers at the Firm (men)  
 ENREF--Engineering REassignment rate at the Firm (men/month)  
 ENTTF--Engineering Trainers Transferred by the Firm (men/month)

The firm desires to reassign engineers so as to close the gap between the desired and the actual number of engineers assigned as trainers. It takes a short period of time to arrange for this, if in fact the additional experienced engineers needed are available. When the firm is transferring engineers out of the project (at the end of the project, for example), it does not bother with the formalities of first reassigning the trainers back to full-time status on the task-oriented engineering work. These actions are shown in Figure 5-5.

The equations for the reassignment follow the logic just described. The reassignment rate desired is a fraction of the gap between the desired and actual number of trainers. If enough engineers are available (ENARF), then this desired rate determines the reassignment rate possible (Equation 5-41). During periods of transfer of engineers from the project, trainers are transferred out directly without first being reassigned to the ENFEF pool. This is expressed by the equation for the reassignment

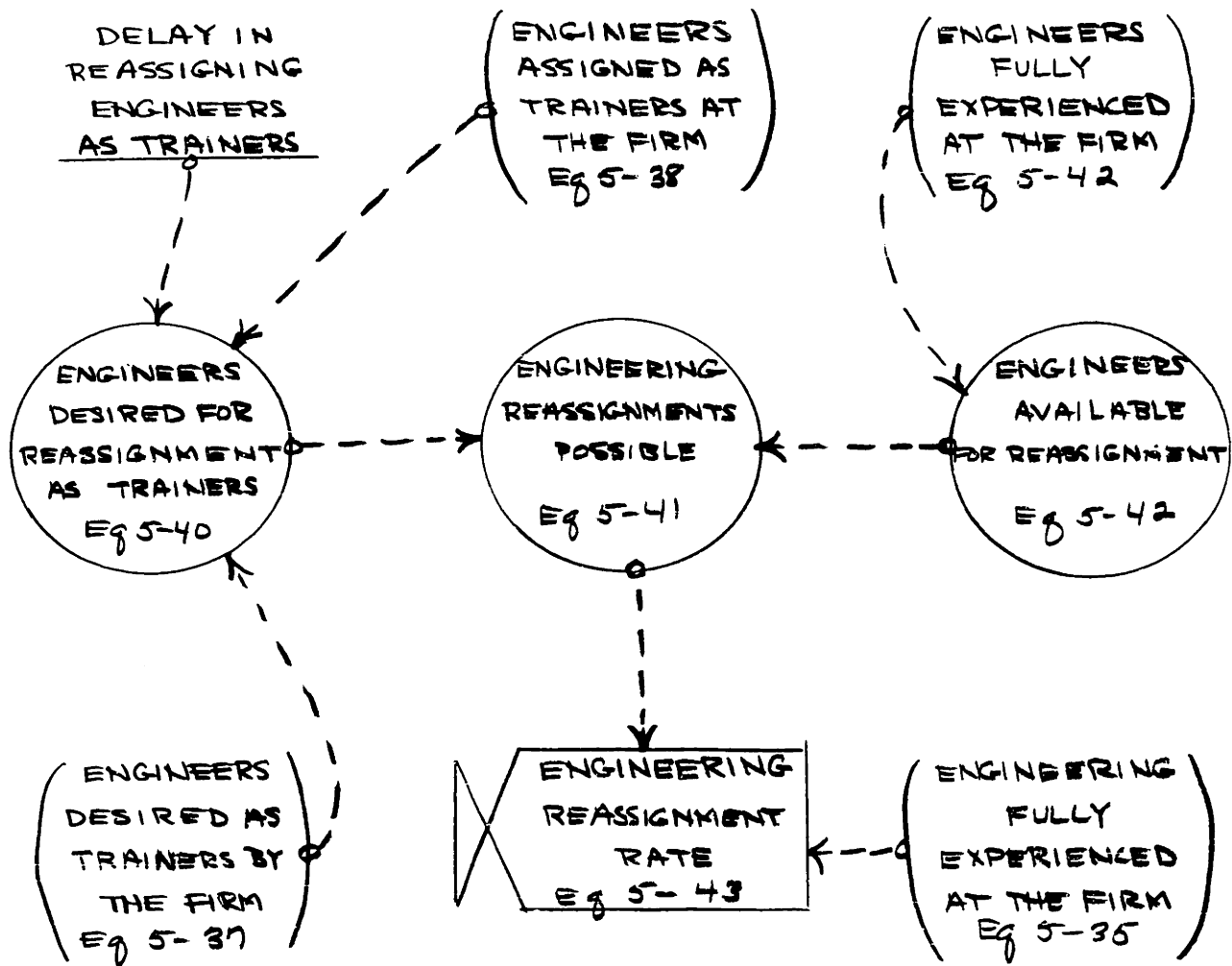


Figure 5-5 Staff Reassignment Rate

rate itself, ENREF.

$$EDRTF.K = \frac{ENDTF.K - ENATF.K}{DRET} \quad 5-40, A$$

$$ENRPF.K = \text{MIN}(EDRTF.K, ENARF.K) \quad 5-41, A$$

$$ENARF.K = \frac{ENFEF.K}{(DT)} \quad 5-42, A$$

$$ENREF.KL = \text{CLIP}(0, ENRPF.K, 0, ENGP.F.K) \quad 5-43, R$$

EDRTF--Engineers Desired for Reassignment as Trainers  
by Firm (men/month)  
 ENDTF--Engineers Desired as Trainers by the Firm (men)  
 ENATF--Engineers Assigned as Trainers at the Firm (men)  
 DRET--Delay in Reassigning Engineers as Trainers (months)  
 ENRPF--Engineering Reassignments Possible at the Firm  
(men/month)  
 ENARF--Engineers Available for Reassignment at Firm  
(men/month)  
 ENFEF--Engineers Fully Experienced at Firm (men)  
 ENREF--Engineering REassignment rate at the Firm  
(men/month)  
 ENGPF--Engineering GaP at the Firm (men)

In Equation 5-42 above ENARF is the largest possible rate of reassignment of experienced engineers into the pool of trainers. That rate would immediately utilize all engineers not yet assigned for handling training responsibilities. In general, about one month is required to arrange for ~~and~~ accomplish the reassignment of the engineers. Thus,

$$DRET = 1 \text{ month}$$

When, after taking account of all the factors discussed earlier relative to the formulation of the desired number of engineers, the firm finds itself with an excess of engineers, it transfers the requisite amount from the project (and perhaps from the firm). The diagram illustrating this transfer process is Figure 5-6. In it we can see that the firm exercises this transfer unless in fact some of the people it wants to transfer are not yet available. The total available for transfer are those experienced engineers who are currently employed full-time on the project task, those who are assigned as trainers, and those new recruits still in training. Those employed as trainers are transferred from the project first. If more transfers are needed, the engineers still in training get





transferred. Finally, if still more engineers should be removed from the project, some of the full-time experienced engineers are transferred out of the project (and, if really necessary, out of the firm itself).

The first three equations say, respectively, that: (1) when the firm expects more engineers than it desires (ENGPF is less than zero), the firm transfers at the rate of ENGTD engineers per month; (2) that transfer rate is the ENTRF unless sufficient engineers are not available for transfer; and (3) ENTRF is the amount needed to adjust the engineering gap, ENGPF, immediately.

$$\text{ENTDF.K} = \text{CLIP}(\text{ENGTD.K}, 0, 0, \text{ENGPF.K}) \quad 5-44, A$$

$$\text{ENGTF.K} = \text{MIN}(-\text{ENTRF.K}, \text{TEATF.K}) \quad 5-45, A$$

$$\text{ENTRF.K} = \frac{\text{ENGPF.K}}{\text{DT}} \quad 5-46, A$$

ENTDF--Engineering Transfer rate Decision at the Firm  
(men/month)  
 ENGTD--Engineering Transfer rate Desired (men/month)  
 ENGPF--Engineering Gap at the Firm (men)  
 ENTRF--Engineering Transfer Rate at the Firm (men/month)  
 TEATF--Total Engineers Available for Transfer by the  
 Firm (men/month)

The total engineers available for immediate transfer are those assigned as trainers, plus those in training, plus the fully-experienced engineers who are working directly on the project effort.

$$\text{TEATF.K} = \text{ETATF.K} + \text{EITAF.K} + \text{ENARF.K} \quad 5-47, A$$

$$\text{ETATF.K} = \frac{\text{ENATF.K}}{\text{DT}} \quad 5-48, A$$

$$\text{EITAF.K} = \frac{\text{ENITF.K}}{\text{DT}} \quad 5-49, A$$

TEATF--Total Engineers Available for Transfer  
by the Firm (men/month)  
 ETATF--Engineering Trainers Available for  
Transfer by the Firm (men/month)  
 EITAF--Engineers In Training Available to the  
Firm (men/month)  
 ENARF--Engineers Available for Reassignment by  
the Firm (men/month)  
 ENATF--Engineers Assigned as Trainers at the  
Firm (men)  
 ENITF--Engineers In Training at the Firm (men)

Equations 5-48 and 5-49 recognize that the maximum rate of transfer of engineers out of the two categories is that rate which would deplete the level in one computation interval.

The actual transfer rate is composed of those transferred from each of the three available pools mentioned above. First those assigned as trainers get transferred; then, if more need be shifted, those in training are taken; finally, if still more engineers are to be transferred out, the fully experienced engineers are moved. In no case, of course, can the transfer rate out of any individual sector exceed the maximum rate available from within that sector. These provisions are included in Equations 5-50 through 5-55 below.

$$\text{ENGTF.KL} = \text{ENTTF.K} + \text{EITTF.K} + \text{ENFTF.K} \quad 5-50, R$$

$$\text{ENTTF.K} = \text{MIN} (\text{ENTDF.K}, \text{ETATF.K}) \quad 5-51, A$$

$$\text{ENTAN.K} = \text{ENTDF.K} - \text{ENTTF.K} \quad 5-52, A$$

$$\text{EITTF.K} = \text{MIN} (\text{ENTAN.K}, \text{EITAF.K}) \quad 5-53, A$$

$$\text{ENTFN.K} = \text{ENTAN.K} - \text{EITTF.K} \quad 5-54, A$$

$$\text{ENFTF.K} = \text{MIN} (\text{ENARF.K}, \text{ENTFN.K}) \quad 5-55, A$$

ENGTF--ENGINEERING Transfer rate at the Firm  
(men/month)  
 ENTTF--ENGINEERING Trainers Transferred by the  
Firm (men/month)  
 EITTF--ENGINEERS In Training Transferred by the  
Firm (men/month)

ENFTF--ENgineers Fully-experienced, Transferred  
by the Firm (men/month)  
 ENTDF--ENgineering Transfer rate Decision at the  
Firm (men/month)  
 ETATF--ENgineering Trainers Available for Trans-  
fer by the Firm (men/month)  
 ENTAN--ENgineering Transfers, Additional, Needed  
(men/month)  
 EITAF--ENgineers in Training Available to the  
Firm (men/month)  
 ENTFN--ENgineering Transfers, Final, Needed  
(men/month)  
 ENARF--ENgineers Available for Reassignment by  
the Firm (men/month)

If the engineers are being transferred to another project within the same firm some time is usually taken up by the transfer arrangements. If the engineers are actually going to leave the firm's employ, a nominal notification period is usually given. These factors cause notified engineers to remain in the project for an additional short period of time while they are being transferred.

$$\text{ENBTF.K} = \text{ENBTF.J} + (\text{DT})(\text{ENGTF.JK} - \text{ENGLF.JK}) \quad 5-56, \text{ L}$$

$$\text{ENBTF} = 0 \quad 5-57, \text{ N}$$

$$\text{ENGLF.KL} = \frac{\text{ENBTF.K}}{\text{DTRE}} \quad 5-58, \text{ R}$$

ENBTF--ENgineers Being Transferred at the  
Firm (men)  
 ENGTF--ENgineering Transfer rate at the Firm  
(men/month)  
 ENGLF--ENgineers Leaving the Firm (men/month)  
 DTRE--Delay in Transferring Engineers (month)

ENGLF actually represents the engineers leaving only the project as well as those actually departing from the firm. DTRE was, at an earlier point in this appendix, set equal to one month.

Figure 5-7 treats the remaining aspect of the Chapter 5 discussion, namely the topic of engineering productivity. The diagram shows the dependence of actual effective production rate in engineering on the

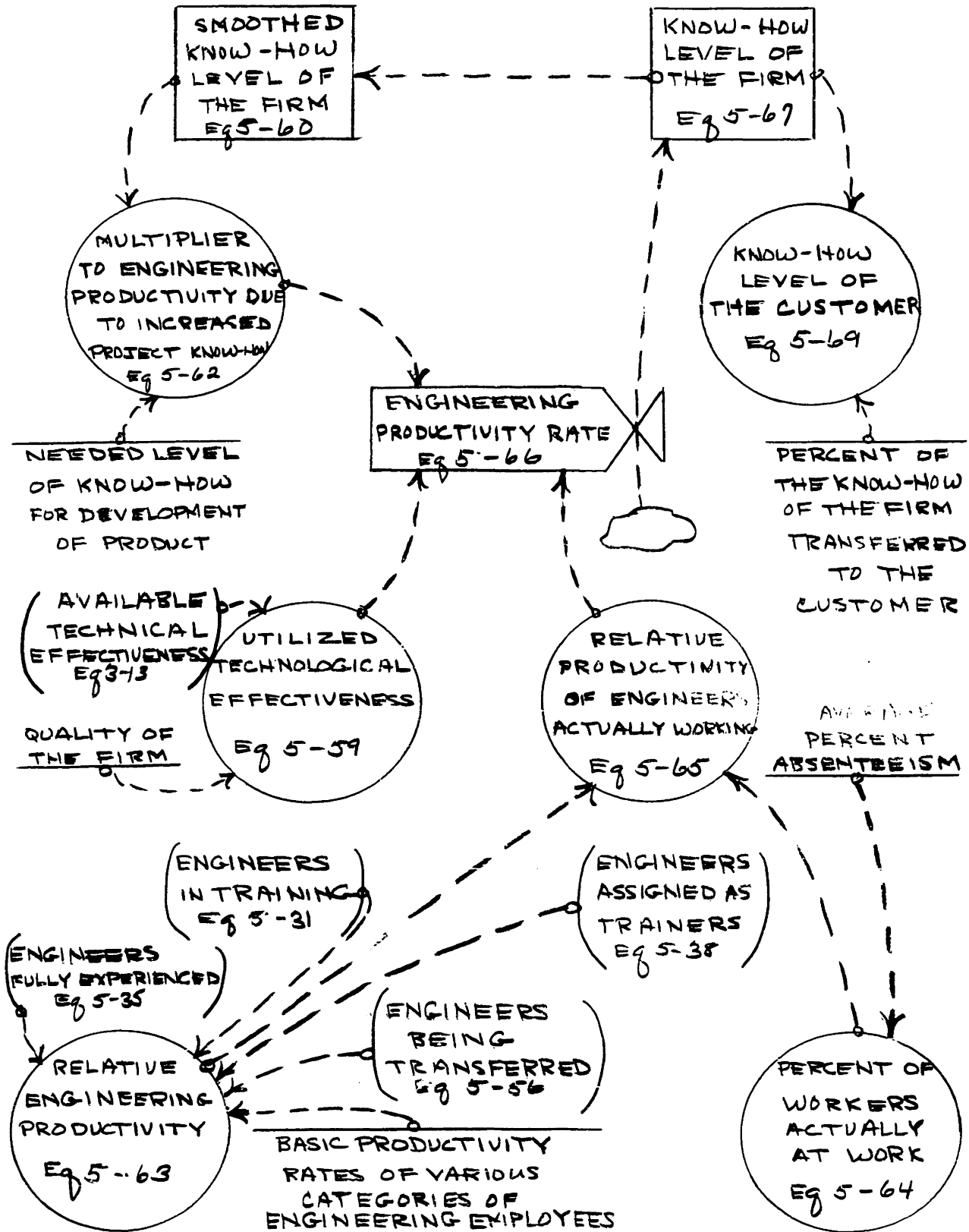


Figure 5-7 Engineering Productivity

number of engineers, the degree to which they possess utilizable skills (some are less trained than others, some have a portion of their efforts drawn off to non-directly productive tasks, etc.), and the general level of this potential engineering utilization. The latter point is shown to be based on the available state of the art and management's ability to help the engineering force make use of this potential. The final factor shown in the illustration as contributing to the engineering production rate is the firm's experience on the current project, based on the extent of its earlier accomplishments on the job which have been absorbed and made available for further exploitation.

Let us start our equations for this sector of the model with one for the utilized technological effectiveness. This was said to depend upon both the available technology and the competence of the firm.

$$UTEF.K = (QF)(ATEF.K)$$

5-59, A

UTEF--Utilized Technological Effectiveness  
at the Firm (percent)  
QF--Quality of the Firm (percent)  
ATEF--Available Technological Effectiveness  
at the Firm (percent)

Initially, this quality factor was placed at 100 percent.

Next let us treat the formulation of the contribution of current project experiences to engineering productivity. Whatever know-how is developed in solving the R and D project problems, some time is required for it to be adequately absorbed. Then, as the experiences cumulate, the firm's engineers supplement their non-project skills with these new more specific insights and approaches to the task. Increments to the engineering effectiveness are 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 project accomplishments made late in the life cycle will find still further use on this project. Thus, the multiplicative effect on the engineering productivity of the project achievements themselves probably looks like the curve of Figure 5-8.

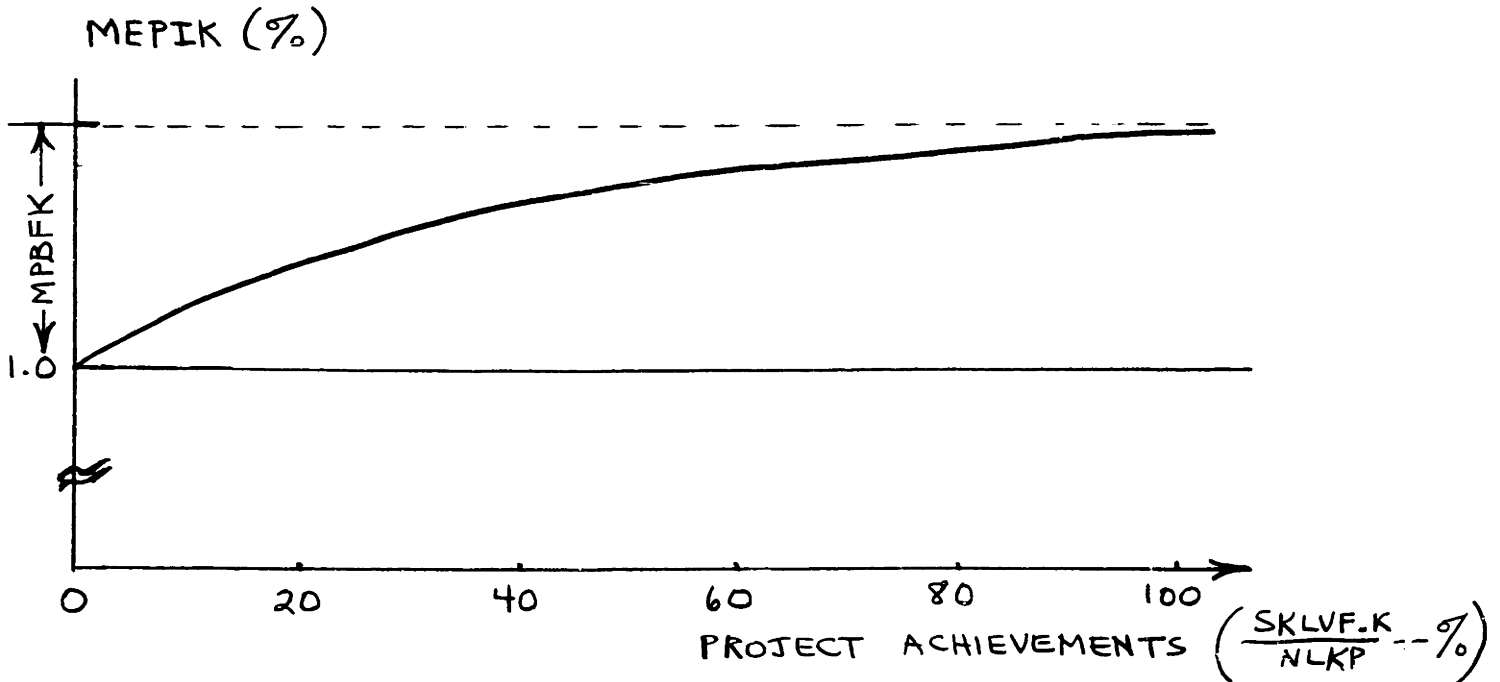


Figure 5-8 Effect on Productivity of Project Achievements

The time required to adequately absorb the know-how is represented by the smoothing equation, 5-60. It is this averaged knowledge which is used in Equation 5-62 to create the multiplicative effect of project experience on the engineering productivity, as shown in:

$$SKLVF.K = SKLVF.J + (DT)(1/DCKN)(KLEVF.J - SKLVF.J) \quad 5-60, L$$

$$SKLVF = KLEVF \quad 5-61, N$$

$$MEPIK.K = 1 + (MPBFK)(1 - e^{-(3)(SKLVF.K) / NLKP}) \quad 5-62, A$$

SKLVF--Smoothed Know-how LeVel of the Firm  
(effective man-months of effort)

DCKN--Delay in Changing KNow-how (months)

KLEVF--Know-how LEVel of the Firm (effective  
man-months of effort)

MEPIK--Multiplier to Engineering Productivity due  
to Increased project Know-how (percent)  
MPBFK--Maximum Productivity Benefit From project  
Know-how (percent)  
NLKP--Needed Level of Know-how for development  
of the Product (effective man-months of  
effort)

In all likelihood several months go by before the engineers on the project are able to effectively utilize their newly-found know-how on other project problems. This is true both because of the engineers' own learning time and because of the probable lapse in time before a problem requiring the same understandings comes up in the project. DCKN will thus be assumed as a half-year.

DCKN = 6 months

The value of MPBFK specifies the extent to which the firm's productivity benefits from its project know-how. Arbitrarily, since no data exists to guide this choice otherwise, the maximum increase will be set as sixty percent.

MPBFK = 0.60 (decimal percentage)

Before taking account of these above-defined factors, we can express the basic relative productivity of the engineers employed on the project. This recognizes the different degrees of effectiveness of the less trained from the more experienced, those fully employed on engineering from those busy with handling administrative tasks or, finally, from those preparing to transfer out of the project.

$$\text{REPRF.K} = (\text{PRIT})(\text{ENITF.K}) + (\text{PRAT})(\text{ENATF.K}) + (\text{PREBT}) \\ (\text{ENBTF.K}) + (1.0)(\text{ENFEF.K})$$

5-63, A

REPRF--Relative Engineering Productivity of the  
Firm (effective man-months of effort/month)  
PRIT--Productivity of engineers In Training  
(months of effective effort/months of work)



ENITF--Engineers In Training at the Firm (men)  
 PRAT--Productivity of engineers Assigned as  
 Trainers (months of effective effort/  
 months of work)  
 ENATF--Engineers Assigned as Trainers at the  
 Firm (men)  
 PREBT--Productivity of Engineers Being Transferred  
 (months of effective effort/months of work)  
 ENBTF--Engineers Being Transferred at the Firm  
 (men)  
 ENFEF--Engineers Fully Experienced at the Firm  
 (men)

The constants used above, PRIT, PRAT, and PREBT, all are defined relative to the base productivity of the fully experienced engineers, ENFEF. New engineers generally have some relevant experiences gained elsewhere, and they soon increase their effectiveness during their initial training period. Thus, we shall set PRIT to represent 40 percent of the effectiveness of the more experienced engineers. The more experienced engineers assigned to training will devote only part of their efforts to this indirect training work, to the extent that their effectiveness will drop by 30 percent. Finally, because of either confusion or demoralization, the engineers being transferred will be regarded as only 20 percent as effective as the fully employed engineers, used here as a standard. Therefore,

PRIT = 0.40 effective man-months of effort/  
 month of work  
 PRAT = 0.70 effective man-months/month  
 PREBT = 0.20 effective man-months/month

Equation 5-63 represents the potential base productivity of all the engineering employees. However, some are occasionally absent or not working because of a holiday or vacation period. On the average, AVABS percent of the engineers are out of work at any given time. Thus the percent of workers actually at work is 100% minus AVABS percent.

The actual relative productivity reflects this factor.

$$PWA\dot{W} = 1 - AVABS \quad 5-64, N$$

$$RPEWF.K = (PWA\dot{W})(REPRF.K) \quad 5-65, A$$

PWA $\dot{W}$ --Percent of Workers Actually at Work  
(percent)

AVABS--Average percent ABSenteeism (percent)

RPEWF--Relative Productivity of Engineers  
actually Working at the Firm (effective  
man-months/month)

REPRF--Relative Engineering PRoductivity at  
Firm (effective man-months of effort/  
month of work)

Combining all of these influences on productivity--the basic manpower and skills factors of RPEWF, the gains from experience of MEPIK, and the fundamental dependence on technology and managerial ability as expressed in UTEF--we can now write the equation for the actual productivity rate of the firm, in terms of the effective man-months of output developed per month of the firm's project activity. This rate of course changes as any of the contributing factors change during the project life.

$$ENPRF.KL = (UTEF.K)(MEPIK.K)(RPEWF.K) \quad 5-66, R$$

ENPRF--ENgineering PRoductivity rate of Firm  
(effective man-months/month)

UTEF--Utilized Technological Effectiveness at  
Firm (percent)

MEPIK--Multiplier to Engineering Productivity  
due to Increased project Know-how (per-  
cent)

RPEWF--Relative Productivity of Engineers  
actually Working at Firm (effective man-  
months/month)

This continuing rate of productivity adds to the previous job accomplishments to produce the level of real progress on the job, which we have identified here as the level of really relevant know-how of the firm. Through his communications with the customer, the firm

transmits a certain fraction of this know-how to the customer.

$$KLEVF.K = KLEVF.J + (DT)(ENPRF.JK) \quad 5-67, L$$

$$KLEVF = VSMAL \quad 5-68, N$$

$$KLEVC.K = (PKFTC)(KLEVF.K) \quad 5-69, A$$

KLEVF--Know-how LEVel of the Firm (effective man-months of effort)

ENPRF--ENgineering PRoductivity rate at Firm (effective man-months/month)

VSMAL--Very SMALl number (dimensionless)

KLEVC--Know-how LEVel of the Customer (effective man-months of effort)

PKFTC--Percent of the Know-how of the Firm Transmitted to the Customer (percent)

We shall assume that the firm is effective (due to its own or the customer's qualifications) in communicating 80 percent of the project know-how developed to the customer.

$$PKFTC = 0.80 \text{ (decimal percentage)}$$

This completes the equation-writing and parameter specification describing the firm's acquisition and effective employment of engineers on the research and development project.

## CHAPTER VI

### THE CONTROL OF RESEARCH AND DEVELOPMENT PROGRESS

#### Introduction

The purpose of control is to assure that the R and D activity is performing as expected and to provide a basis for corrective action if it is not. The control process involves these operations: (1) establishing criteria governing the information output of the R and D function....; (2) observing the information output continuously or by frequent samples; (3) comparing the actual information output with the expected output; (4) taking action to make changes in R and D activity or in the conditions under which it operates, if judged necessary. Effective control requires that corrective action be taken quickly, when indicated.<sup>1</sup>

The problems involved in measuring and responding to progress in a research and development project are central to the management of R and D. They shall be discussed in this chapter in much the same sequence as the phases listed in the quotation above.

In the same article cited above, Rubenstein introduces the problem:

Attempts to apply standard control and evaluation techniques to the research program have proved very disappointing in many companies. They have led to misunderstandings between research and management personnel and have often placed barriers in the way of effective research programming. Sometimes these difficulties arise from control and evaluation procedures which are basically inadequate for any of the company's activities, but more frequently they come from applying procedures which are effective in other parts of the company but not in research.<sup>2</sup>

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<sup>1</sup>Albert H. Rubenstein, "Setting Criteria for R and D", Harvard Business Review, Vol. 35, No. 1 (January-February, 1957), p. 102.

<sup>2</sup>Ibid., p. 96

These distinctions which show up between the research and development department and manufacturing, for example, reflect the degree of tangibility of the outputs of the two organizations. In manufacturing, cost accounting tools and physical counting of output usually serve the purpose of measurement of progress. Management somehow defines its output volume and cost goals and knows its degree of success in meeting these goals by simply looking at production records or accounting statements. To be sure, other factors of consequence to the manufacturing organization are less tangible, more difficult to measure, and therefore usually ignored. Such things as product quality and customer satisfaction can also be regarded as manufacturing outputs, but they are seldom considered until they actually cause a crisis in the organization.

The research and development manager has a situation which is perhaps similar in substance but certainly different in degree. He too has a need for measurement of his organization's progress, but he even lacks any readily-defined physical means of determination. Furthermore, in all R and D situations the intangible quality and satisfaction measures are obviously consequential but not so obviously available for measurement. Many schemes have been tried in attempting to keep track of R and D progress, including the establishment of project milestone schedules, sophisticated computer reporting techniques, as well as much just plain guesswork. But these processes are generally felt to be quite subjective, and the capability of research and development management enters more into the picture in deciding, for the record, whether or not milestones have been achieved, what types of inputs to

provide to the computer systems, and what factors ought to enter into their estimates. Perhaps it is only the folklore that such processes cannot be objective which keeps research and development managers from trying otherwise. Certainly some organizations have been successful in defining noncontroversial measures of project progress, and in using information regarding the accomplishment of these to help in their management efforts. But such successes are exceptional and not at all typical. For example, the author has examined one large company's survey of several hundred engineering progress reports, in which the project leaders were so often confounded as to what progress had actually been achieved that during about 80 percent of the actual time span of a project, the supervisors reported the job to be about 90 percent completed. It is likely that many of the predesignated stages of progress in this job were meaningless or basically undefined. It is also true that, at least in theory, a project's tasks can be defined such that tangible measures are associated with the progressive accomplishments of the project. But very few firms have yet developed their project planning skills to the extent needed.

The type of experience cited above has been shared by a good many people other than just the author. For instance, Norden writes, "It has been suggested that the spectrum from basic research to production is calibrated by the degree of accuracy with which one can specify (a priori) the nature and measure of the outcomes, and the numerous configurations of all operations required, for any task to be done. This is comparatively easy in manufacturing, and next to impossible in basic research. Applied research and development

appeared to be a twilight zone in which we are just learning to specify the methodology."<sup>3</sup>

Even those who are asserting the use of sophisticated computer methodology for keeping track of project status recognize the inherent difficulty of initially setting down the signposts to guide the way in one's evaluation technique. Early in his discussion of the PERT approach, Pearlman points out, "The planning of technical objectives and the accompanying measurement of success is perhaps the most nebulous aspect of program management. An organization whose growth depends upon innovation has difficulty in studying and measuring quantitative objectives."<sup>4</sup>

And finally, Nelson, whose writings have been cited several times earlier, addresses himself to the problem as follows:

There is considerable uncertainty as to the outcome of an R and D program, the uncertainty being, of course, closely related to the degree of knowledge in the relevant fields and to the advance sought in the programs. Attempts to develop an object that represents a marked advance in the state-of-the-art are subject to great uncertainty; attempts to improve an existing object are subject to relatively little uncertainty.

The attempt to plan a development program in detail will lead to frustration and failure if the program represents a significant leap forward. Usually, not just sometimes, unexpected obstacles are discovered, and many expected ones prove relatively easy to solve.<sup>5</sup>

To some extent in a large project the random elements which contribute to these unexpected events probably tend to cancel each other out.

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<sup>3</sup>Peter V. Norden, "On the Anatomy of Development Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960), p. 41.

<sup>4</sup>Jerome Pearlman, "Engineering Program Planning and Control Through the Use of PERT", IRE Transactions on Engineering Management, Vol. EM-7, No. 4 (December 1960), p. 125.

<sup>5</sup>Richard R. Nelson, "Invention, Research and Development: A Survey of the Literature", U.S. Air Force Project Rand Research Memorandum, RM-2146 (April 15, 1958), pp. 19-20.

However, the nonrandom elements, the deterministic bias that comes from assuming everything will go in the best possible way, is what gets so many projects into so much trouble. This was discussed in great detail in Chapter 3 and need not be further developed here. But since we are describing what takes place in today's research and development projects, we cannot act as if these planning problems can be talked out of existence. Perhaps they are present because of the failure of competent people to attempt their solution; perhaps they are present because their difficulty overwhelms even the routinely competent and in fact all but an exceptional few able R and D managers. For whatever the reasons, meaningful project planning in research and development is an almost universally lacking accomplishment.

Thus, because of these intangible, imprecise, and uncertain factors, the accomplishment of a significant research and development undertaking cannot be naively charted out as easily as one plots the best route to take in traveling between two cities in the United States. In such a map exercise, we can look at several alternate routings from source of destination, add up the links between signposts or towns, and find out which route constitutes the shortest route between the two points. If we then took one of these roads, we would feel rather certain that signposts would exist on the way to mark our progress at any given point. The map might not tell us, however, that the shortest route is also the more popular route, and therefore crowded with travelers and slow to traverse. Or it might not warn us of the bridge that washed out in one of the small highway linkages, thus creating the need for a long and time-consuming detour. But although this



analogy between attempting to plan a research and development project and attempting to select a travel route can be carried further to some degree, it is naive even to believe that a research and development project could be nearly as well defined as the markings on a highway map. In research and development each of the development linkages is uncertain; each of the roads may be marked by a potential washout, creating the necessity for major detour. And even when one selects the well-traveled development path, he may only proceed up to a certain dead-end; the same development path which has been commonly used before may be limited by its very nature against handling the particular problem being undertaken.

It is unfortunate that this survey of the literature and analysis of the state of the art of project planning has to paint such a bleak picture. But the author feels quite justified in observing this major weakness in research and development management capabilities. The hope resides in the fact that so few R and D people make any overt attempt to do the needed project planning seriously. Of the remaining large number of "uninitiated" managers, those who seriously (not superficially, as some current fads seem to encourage) undertake to lay thorough foundations for their project commitments can probably realize ten to one improvements (or perhaps even more) in their research and development effectiveness.

In addition to the fact that projects are poorly planned initially, these general problems still exist during the life of the project, when the R and D manager attempts to reassess his project goals and redefine his objectives. The remainder of the chapter will attempt

to go into each of these phases in more detail, to analyze what practices have been adopted by industry for both establishing criteria and measuring progress, and hopefully to constructively evaluate the merits of these practices.

#### Establishing Criteria for Progress Measurement

In order to control any kind of process, one must start with an objective function toward which he is aiming. As the customer and the firm in a research and development project contemplate the job before them, they too recognize an objective function--not necessarily the immediate maximization of profits, but rather the development of some particular end product. The concepts describing these technical objectives may very well change during the life cycle of the project, particularly during the early phases of relatively low level of engineering effort. But as the customer and the firm get further along in the R and D project life cycle, they begin more clearly to recognize the specific nature of the task before them, including perhaps some subset of requirements which must be met for the project to be completed. "It appears that each operational group goal has associated with it a set of 'task requirements' which must be satisfied if progress toward the goal is to take place."<sup>6</sup> But despite the fact that such a subset of tasks no doubt can be clearly seen as having existed after the fact of project completion, it is not necessarily true that before the fact the impressions of either customer and firm were other

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<sup>6</sup>Dorwin Cartwright and Alvin Zander, Group Dynamics, Research and Theory, Second Edition (Evanston, Illinois: Row, Peterson and Company, 1960), p. 354.

than highly uncertain. As argued earlier, the ability to recognize these specific requirements rests on the general managerial and technical ability of the firm and/or customer, and more particularly on their understanding as to how to use these capabilities in the initial project design.

In Chapter 3 it was stated that both the customer and the firm view the nature of the development effort under contemplation by basing their estimates on consideration of the believed job size and upon their assessments of the technological effectiveness of engineers. The combination of those two factors, the job size and the technological effectiveness, was described as producing the estimate of total effort that would be required to complete the research and development undertaking. If this be the case, then one can readily present the only meaningful definition of progress on a research and development job; i.e., the accumulation over the period of time of the project of those effective manhours contributed by the engineering work force. As discussed in Chapter 5, the rate of progress is dependent upon the number of engineers at work, their qualifications, the ability of engineering management in general, and the state of the art in the related technological areas. Thus as effective effort is applied over time, problems are solved, breakthroughs are made, sub-tasks within the job are completed, and in general, less effort remains for completion of the total project. Such statements are obvious ones, but their simplicity belies a very basic fact of research and development. There is no intrinsically correct measure either of engineering effectiveness, or of problems solved, or of the task left

to be done. For these reasons, the difficulties are encountered in attempting to control a research and development project.

Some statements made in the literature highlight the confusion regarding this problem.

Shartle...reports on the basis of extensive research in formal organizations...that responsible executives can state their perceptions of the goals of the organization and the degree of progress made toward them at any given time. He proposes that it will be possible to construct a goal achievement index which denotes the ratio of the total distance to the goal in relation to the amount of progress that has been achieved. It must be added, however, that the methodological difficulties of constructing such an index quantitatively have not yet been overcome.<sup>7</sup>

Thus we combine here the assertion that one can claim to know the state of progress with the recognition that such statements cannot quantitatively be measured or verified.

Such a situation brings us to the methods that are actually used in research and development projects, wherein people are willing to state what progress has been made but where no necessarily relevant measurements are available to verify or deny such statements. Thus, we have a case similar to the general problem referred to by Barnard. "When we are obliged in a practical sense to deal with intangible things chiefly characterized by relationships rather than by substance, we have to symbolize them by concrete things or personify them."<sup>8</sup> This is particularly unfortunate, since the obvious concrete measurable

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<sup>7</sup>Cartwright and Zander, op. cit., First Edition (1953), p. 307.

<sup>8</sup>Chester I. Barnard, The Functions of the Executive (Cambridge: Harvard University Press, 1938), p. 74.

variables may be basically unrelated to the amount of effort required to getting the job done. This can be readily seen if we talk, for instance, about a fund-raising objective to collect, let us say, \$100,000. It seems reasonable to argue that the effort required to get the first \$50,000 through such a drive may be of an entirely different order of magnitude than the effort required to get the final \$50,000. For the first part of the drive, those who have always given in the past will continue to give again. The large contributors who account for a substantial fraction of the gift may be among the first to contribute, and thereby 50 percent of the dollar goal may be achieved with a rather minimal amount of effort. The remaining 50 percent of the fund goal may require rallies and campaigning, door-to-door visitation, much time-consuming effort on the part of committee workers, and perhaps a much longer elapsed duration of time. Another campaign of the same exact sort may encounter entirely different problems. Here the rate of growth of the total funds collected may start very slowly, gradually gathering momentum, accelerating more rapidly, and finally going over the top at a very advanced pace. For such a project, many people say, "Getting organized is half the job." Thus from looking at these two different types of time histories of a fund-raising campaign, one can readily see that the amount of effort may be wholly unrelated to the most obvious physical manifestation of results of that effort, in these cases the actual dollars collected. The dangers of reliance upon the easiest-to-obtain tangible measures are significant not just in research and development but throughout the corporation. Considering the often sophisticated methods that have recently been introduced into research

and development programming, it seems rather shameful that so little is known about the basic determinants of R and D progress.

Fundamental to all attempts to establish criteria for measuring and controlling research and development progress is some plan for the actual technical accomplishment. A recent paper describing this kind of activity at the Bendix Corporation stated: "Formal planning on the part of the project engineer begins with the development of the project schedule chart, which presents in convenient form, numeric and graphic information about the project. To complete the information required on this form, it is necessary for the engineer to think out the steps he must go through to complete his project on time."<sup>9</sup> Describing the experiences at Sylvania, another writer said, "One of the first administrative measures in developing a real-time system program will be to lay out a schedule with appropriate milestones. This is not easy; and the more detail is in it, the less likely it is to represent the facts as they unfold."<sup>10</sup> At General Electric, their approach to the same problem was described as follows:

Next, the plan or operating program is established to accomplish the objective. This plan is broken down into the steps which must be performed in terms of the lead time each will take to meet the requirements of the plan. Let's call these steps operations. An operation may be a stated requirement of engineering release for the procurement of raw material. It is stated in terms of the lead

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<sup>9</sup>R. W. Haine and W. Lob, "The Application of Closed-Loop Techniques to Engineering Project Planning", IRE Transactions on Engineering Management, Vol. EM-7, No. 3 (September 1960), p. 97.

<sup>10</sup>W. A. Hosier, "Pitfalls and Safeguards in Real-Time Digital Systems with Emphasis on Programming," IRE Transactions on Engineering Management, Vol. EM-8, No. 2 (June 1961), p. 114.

time it will take to procure in order to meet the requirements of the plan. Another operation may be the requirement of an engineering release to allow manufacturing to proceed, utilizing the raw material previously released. This, too, is identified in terms of lead time.<sup>11</sup>

Trying to adhere to these types of planning procedures is very difficult indeed in research and development. The literature of R and D control is basically misleading in the general impression that it often presents as to the relative simplicity of making up such plans. As one example, "To simplify project planning, the approximate date for the completion of intermediary phases of the project is empirically established by the project engineer, as well as the final date for completion and shipment of the work."<sup>12</sup> The important question is whether such approximate dates listed in these plans have any meaningful relationship whatsoever to the actual dates that are finally achieved in the R and D projects. In an earlier chapter, the United States experiences in conducting many different product development undertakings were described. The RAND Corporation findings, as others, pointed to a great and an historical lack of ability to properly estimate the time and effort required to complete research and development jobs. There is no reason to believe that we have progressed in our ability to handle this difficulty beyond the stage reported in those studies.

The difficulties of making realistic estimates of time and effort

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<sup>11</sup>Ralph Medros, "Introducing New Jet Engine Production with Reduced Lead Times", paper presented at the SAE National Aeronautic Meeting, April 2-5, 1957, p. 4.

<sup>12</sup>Haine and Lob, p. 97.

requirements was recently cited in a letter written by a reviewer for the IRE Transactions on Engineering Management in his comments about the PERT system. "We have taken the time to study a great many trees of research....and even when these relate to the 'development' of new drugs, we have found that you could not with knowledge available at the time have predicted the sequencing of events, a priori. We have checked this in other labs....At any given stage, you have the probability of new knowledge--which is why you do the research--but you do not know how many steps or what specific events are going to take place before the new knowledge appears."<sup>13</sup>

All the evidence cited merely strengthens the initial point made, that it is extremely difficult though not impossible to establish criteria for measuring progress in research and development effort. Even a system of project milestones, which system basically states the subtasks required to complete the end result, still has the potential failings due to the uncertainties inherent in research and development. Nevertheless, most companies do go ahead in their planning efforts to map out such a set of project linkages or milestones which will be met before the job has been completed. The capable managers of Rand D can use this approach effectively. For example, when the milestones themselves are noncontroversial in their measurability, the likelihood that the firm will have at least some form of tangible guideposts increases. One report gives a good example of a basis for the

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<sup>13</sup>Editorial column, IRE Transactions on Engineering Management, Vol. EM-7, No. 3 (September 1960), p. 81.



kind of milestones to which we are referring. "Turning now to the rate of engineering development: the design of an axial type turbo-jet of 8,000 to 10,000 pounds static thrust absorbs about one year, and a further 12 months or more will be required to build the first prototype engine--or, say, two years from the first line on the drawing board to the test bench, ready to run. Then, in the following three years, there should be completed 8,000 to 10,000 engine hours of bench running and about 2,000 hours of flight testing. From 3,000 to 4,000 engine hours of bench running is a good yearly figure in the 4th and 5th years."<sup>14</sup>

These expected project performance data, if acceptable as milestones, can be checked as the project proceeds to determine whether or not the job is behind normal schedule for such an undertaking. But variables other than the percent of job completion are of importance to those who are managing a research and development project. "In addition to the technical problems, the elapsed time and the amount of money spent must be considered. It is evident that all three---technical accomplishment, elapsed time, and the remaining funds--are of concern to the project engineer."<sup>15</sup>

In regard to this, Nelson says,

The scheduling of man-hours, money, expenditure, and progress by project is apparently becoming increasingly popular. However, these schedules seem to be taken seriously only for projects

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<sup>14</sup>F. R. Banks, "The Birth of an Engine", Aeronautical Engineering Review, Vol. 12, No. 6 (June 1953), p. 39.

<sup>15</sup>Haine and Lob, p. 97.

involving relatively little uncertainty; they are seldom if ever taken seriously for broadly defined research projects. The use of periodic reports is even more common than the use of schedules. About 75 of the laboratories responding to a Harvard Business School questionnaire said that regular checks were made on project costs, manpower, and estimated completion date.<sup>16</sup>

One grand approach to the measurement of progress in research and development seems, unintentionally, to use the management mistakes which created previous project life cycles as the standard of excellence for current projects. In the originator's words:

"Normalized curves" represent a means of evaluating the relationships of time, total expenditures, sub-contract expenditures, and a number of activities and events. They represent data on previous contracts that have been categorized and reduced to common scales. "Normalized curves" can indicate that on a research and development contract for product "X" which will result in the delivery of one system, the following should have occurred when 50 percent of the time has passed from the start of the contract until the delivery of the system: 30 percent of the total anticipated funds should have been expended; 22 percent of the anticipated subcontract funds should have been expended; 40 percent of the total contract direct man-months to completion should have been utilized; all of the bread-boards should have been previously fabricated; and 87 percent of the preliminary schematics should have been released.<sup>17</sup>

To a great extent such efforts as these described seek relationships between the superficialities of a few projects while neglecting to recognize that fundamental reality of research and development projects--the great uncertainty to which so much time has been devoted

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<sup>16</sup> Nelson, "Invention, Research and Development: A Survey of the Literature", p. 59.

<sup>17</sup> D. W. Kornreich, "Utilization of Normalized Data for Defense Contracts", Proceedings of the Nineteenth National Meeting of the Operations Research Society of America, May 25-26, 1961, pp. 3-4.

in this discussion. It is easy to criticize these various approaches to establishing measures of progress in research and development. It is much more difficult to propose an alternative which has both substance and validity, rather than just theoretical merit. The author himself admits to having been responsible for one of the earliest of the sophisticated computer-oriented approaches to help control progress in R and D projects.<sup>18</sup> This effort, the author now feels, was equally as devoid of substance relevant to real progress in research and development as are the methods criticized in the preceding pages.

The articles cited thusfar do not even provide a clue as to an alternative approach to the problems of establishing criteria for progress measurement. However, the passing comment of a writer from Hughes Aircraft Company does suggest some ideas. "Speculation as to the degree of difficulties involved in solving a new problem is particularly vulnerable to emotional thinking, since the assumed factors tend to be exaggerated disproportionately when the speculator has an emotional motivation for wanting to take a certain route."<sup>19</sup> This motivational factor, which has been largely ignored in the design of R and D control systems thusfar, can certainly serve to modify behavior of engineers and managers in research and development projects. Much of the key to the project planning and measurement planning problems may well lie in the lack of incentive for bettering the R and D plans. There is no

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<sup>18</sup>Edward B. Roberts, "The Digital Computer as an Element of a Financial Control System", unpublished Master's thesis, M.I.T., June, 1958.

<sup>19</sup>A.L. Stanley, "Logic and Illogic in Engineering and Management", IRE Transactions on Engineering Management, Vol. EM-5, No. 4 (December 1958), p. 147.

real reward for success in planning or penalty for failure. Therefore, planners or managers do not use their failures as a basis for learning. This comes largely from the McGregor "Theory X" difficulty<sup>20</sup>--the attempt to exert exterior control and authority on research and development, without incentives for the R and D people to strive toward the same ends.

When we recognize that people normally react to pressures, even those from measurement and evaluation systems, from the viewpoint of their own objectives, we can begin to better understand the causes for failure of many progress evaluation schemes. Let us examine some of the current R and D progress comparison schemes from this motivational-factor perspective. Rubenstein's survey of 37 laboratories found that "to appraise progress, 15 companies used comparisons of actual and budgeted expenditures; 6 used proportion of budget spent; 3 used output of information to groups that applied for research data."<sup>21</sup> With only slight exaggeration to help make the basic point clear, comparing "actual to budgeted expenditures" creates an incentive to increase budgets, regardless of need, and to hold down expenditures, regardless of progress; checking "proportion of budget spent" creates pressures on the manager or engineer to be sure he spends the money, whether or not on something useful; and counting "output of information to groups which applied for research data" emphasizes long reports about work on

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<sup>20</sup> Douglas McGregor, The Human Side of Enterprise (New York: McGraw-Hill Book Company, 1960), pp. 33-57.

<sup>21</sup> Rubenstein, "Setting Criteria for R and D", p. 98.

short-term crises in which the rest of the company is currently involved. The encouragements provided by other R and D progress measures are also obvious, for instance, the results of counting the number or square feet of engineering drawings released. None of these criteria relate to the excellence of engineering accomplishment. Some of these measures in fact create incentives detrimental to good project performance. Obviously, the company ability which shows up in the design of its incentive-evaluation system, can have great bearing on research and development success.

### Progress Measurement

The approach to control outlined at the beginning of this chapter presented a four-step process: (1) establishing criteria, (2) observing, (3) comparing, (4) taking action. To this point in the chapter, only the first aspect, the establishment of criteria for the measurement of research and development progress has been discussed. The difficulty of separating the observation phase from the comparison phase will be illustrated in this section. It will also try to take into account the underlying elements in the process of observing and comparing progress in a research and development operation. Let us start with a critique of some of the detailed methods for research and development measurement.

The determination of the physical completion at any given time presents some problems. Asking each engineer at a given time ( $t_i$ ) what the physical completion of his work is, would constitute a major problem. First of all, each engineer would have a different judgment factor; second, the number of engineers involved may make such a task prohibitive; and third, having gathered the various percentages of physical completion, one may now know whether such percentages are additive,

form a series, or have any other kind of relationship. Furthermore, it is not known what segment of the budgetary curve pertains to the reported physical completion.<sup>22</sup>

Thus, one measurement suggestion has been made and discarded by its own author. The collection of completion estimates by each individual engineer working on a job and their aggregation into some over-all measurement is not recommended.

Another suggestion was presented thusly: "Technical objectives are difficult to define. Measuring their attainment has posed even greater problems. The solution to this problem has been the design review."<sup>23</sup> Pearlman goes on to say that in one department of the General Electric Company six design review sessions are held for each project, one each at the end of six defined-as-distinct phases of engineering development. The desire is to intensely examine each portion of the design at these reviews, highlighting observed shortcomings for correction. Thus the majority vote or the consensus of the group acts as the determinant of the progress or lack of progress that is measured by the design review committee.

A third observer reports his company's difficulties in gaining periodic measurements of progress.

Prior to the use of project schedule charts, a monthly progress report for each project was prepared by project engineers. This report included a statement of the project's completion

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<sup>22</sup>H. Versteeg, "Analysis of Engineering Performance", IRE Transactions on Engineering Management, Vol. EM-8, No. 2 (June 1961), p. 72.

<sup>23</sup>Jerome Pearlman, "Engineering Program Planning and Control Through the Use of PERT", IRE Transactions on Engineering Management, Vol. EM-7, No. 4 (December 1960), p. 125.

percentage. Our experience with this method indicated that the shortcomings of the concept, 'percent complete', were sufficiently great to negate its value. While projects tended to make rapid progress towards completion when work first began it took an inordinately long time to get from 90 percent to 100 percent complete. The 'percent complete' limitation has been circumvented by having the project engineer subdivide his project into the milestones of technical accomplishment by which progress can be evaluated. For ease of recognition, these milestones usually have definite identifiable beginning and end points....In addition to subdividing each project into milestones, each segment is limited to a relatively short time period, which results in two important advantages. Breaking the project down into bits and pieces allows the preparation of more accurate project estimates. It also permits us to evaluate progress functionally in terms of the task requirement and accomplishment.<sup>24</sup>

The experiences described are evidently taken from a company which formerly used for their progress measurements estimates of percent completion that were devoid of consideration of the accomplishment of particular technical achievements. Milestone charts are here treated as something wholly distinct from percent completion reports. What the writer seems to ignore are two things. First, milestone charts have been used in the aerospace industry for many years with no notable success in the industry in terms of the two important advantages cited in the quote above. Secondly, even if an engineer could wholly objectively report the accomplishment or the lack of accomplishment of a particular milestone, the achievement of one or any number of milestones is no indicator of the extent of the project work that has been done, or, more importantly, of the extent of project work that is remaining. Thus even with milestone reporting, one has to estimate how

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<sup>24</sup>Haine and Lot, p. 99.

many more man-months of engineering effort are left to be done, and how many more dollars are to be spent before the contracted job will be finished. Furthermore, milestones do not just have the two-fold state of either being accomplished or not being accomplished. At any given time, many tasks are partially complete. This is true even if one breaks the task down into smaller bits and pieces. How does an engineer estimate the additional time and effort that he expects will be required to complete the current milestone on which he is working? There is no magic sure-fire formula for success in such estimations. It seems, then, that the continuous nature of work effort and work accomplishment in a research and development project denies separation of the concept of percent complete from the concept of project milestone achievements. The two are linked together, whether or not one recognizes this fact explicitly or not.

The apparent current rage in methods of planning and measuring progress in research and development projects is the system known as PERT--Program Evaluation and Review Technique. Pearlman, cited earlier, discusses the utilization of this approach.

Program time status is readily obtainable from the PERT/PEP networks. Every two weeks the following information, which has been found most useful, is obtained: (1) status of those events that should have been started or completed during the reporting period, (2) a forecast of the start or completion date of the next most immediate events, and (3) any major network alterations. This information is obtained on a personal basis by program-planning engineers. These data are used to calculate a new critical path, and a status is forecasted. The time to attain the end event on the critical path is compared to a contractual requirement. Hence, the program is classified as to whether it will be 'ahead', 'equal to', or 'behind' schedule.



On a monthly basis, a report.....is generated for management.<sup>25</sup>

The statement of this procedure is clear, but whether or not one has gained much from it is still questionable. The fundamental reason for questioning this is the second category of "information" that is listed above as obtained for PERT reports. All forecasts of the start or completion dates of the next events have within them uncertainties at least as great as do any attempts to report either percent completion of a job, or percent of milestone accomplishment of a job, or engineering hours or dollar costs left to be spent for completion. All of these estimates, regardless of label, amount to the same thing. For any one of these procedures, the engineer or engineering manager providing these estimates must guess at where he is and must also guess as to where he has to get. The more venture-some or uncertain the research and development program, the less certain these estimates are going to be, whether they are reported verbally, in written reports, or in sophisticated computer output sheets. This criticism is not intended to deny the fact that the careful planning and scrutiny of research and development projects, perhaps induced by some of these techniques, might be helpful for management of R and D. But the companies which have reputations for having been successful in the area of military and commercial product development have carefully planned and watched over research and development progress even before the advent of the computer and of the sophisticated techniques (like PERT) that have accompanied it.

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<sup>25</sup>Pearlman, p. 127.

But enough discussion of the formal superficialities of research and development progress measurements. Let us ask instead what of a fundamental nature is really taking place in these many apparently so-varied attempts to gain assessments of the progress that has been achieved in any R and D project. First, let us recognize that despite biases that may be present due to evaluation of his own work, the engineer closest to the scene knows the difficulties that have been encountered and has at least a feeling for the kinds of problems he expects to encounter before completing his own job. "In the case of individual projects, good results have been attained by a number of laboratories which push control down to the lowest possible level--to those people who are closest to the work."<sup>26</sup> The reason for this is that the engineer is concerned with his own work and wants to accomplish his technical mission. "As time passes and effort is applied to the project, the engineer becomes more and more concerned with where the project stands in relationship to his plan and the project completion date. At least once a month, he sets aside a few minutes to review what has been accomplished on each task detail."<sup>27</sup> With all of this attention focused down the line in the engineering organization it seems natural that Marcson should report: "In the conduct of research, day-to-day decisions are in the hands of the scientist. It is he who decides he has a finding or failure to report."<sup>28</sup>

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<sup>26</sup>Rubenstein, "Setting Criteria for R and D", p. 103.

<sup>27</sup>Haine and Lob, p. 99.

<sup>28</sup>Marcson, pp. 33-34.

Thus, the process of supposedly controlling R and D ought to take into account this real source of control--the individual engineer. If the individual engineer or engineering manager is given a company environment which encourages initiative and integrity, then the people in the organization will themselves supply the progress evaluation information that is needed by top management. In a very few places the channels of upward communication in the organization contain information mostly about problems and troubles. This data is transmitted on the common understanding that the primary purpose of higher management is to help where the lower levels have problems. It also rests on an organizational penalty-reward structure that encourages such integrity and allays the fears that exist in most firms. In the more usual case the structure is such that only "sales presentations" are communicated upward to impress management with how successfully the engineering department is functioning. Once such presentations which overstate actual accomplishment have been put in writing or made to a formal project review board, it becomes even more difficult to admit problems that have been long in the making. Almost by definition one would think that the company which understands these facts of life and develops the desirable organizational attitudes is a firm with high quality management.

But even in the company in which integrity is high, the effectiveness of engineers in recognizing problems varies as the project gets further along. One particular difficulty is that during the very early phases of a project, the milestones have a tendency to be less precisely definable and hence less accurately measurable than

during later phases of the project. "Many aspects of unit operation never become apparent until they have to work together; so that even if units have not yet been polished to the utmost, they can be more efficiently revised after early ensemble operations."<sup>29</sup>

Thus in many projects the impressions of the engineer or the manager in charge might well be that the project is going along at a reasonable pace until quite late in the project history. Then the manager suddenly discovers that his previous optimistic estimates have to be strongly revised, that rework on earlier "completed" tasks might be necessary, and that problems exist which have shown up in later phases of development, which problems were not tackled during the earlier stages. A recent major rocket engine project proceeded despite great difficulties up to the "final" stage of design completion, and the sequence of milestones on the path toward that completion had been recorded as successfully completed by the time the rocket engine was placed on the test pad. However, at the first test and at two successive tests the engine blew up, thus causing "agonizing reappraisal" of the project accomplishment to date. This kind of difficulty is seldom rigorously documented in the literature, but other examples of the same problem can still easily be found. For instance, is it not likely that the development engineers on the Lockheed Electra would have said their job was completed, long before the wings started to fall off? To take another case, how far along towards completion was the Project Vanguard program, before the United States' first satellite

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<sup>29</sup>Hosier, p. 112.

"launching"? The problems in being able to identify the stage of progress in the development of a new product are enormously difficult ones, with the basic information inputs often lacking until most people might think the job is just about over. As the Electra example above shows, sometimes it is even difficult to determine the state of completion of a job long after it is apparently working well. But, in general, this difficulty eases as the product takes physical form and begins to undergo performance testing.

Fundamentally, then, it seems that the engineer working on the job and the engineering manager supervising the job are continuously assessing the believed rate of progress on the engineering project. They are continuously assuming that by applying time and effort they are gradually accumulating the solutions to the numerous problems which confront them in the project undertaking and gradually narrowing the gap between what they have accomplished and what they are going to have to accomplish before the job is done. However, there is always the problem that these estimates of completion might completely differ from the real facts of the matter. The later phases of research and development, wherein the assembled product is tested for its operation and performance, begin to reveal to the design team whether or not their estimates of completion were correct. Thus, it is often only after considerable testing has taken place, including the testing which takes place at certain of the critical milestones within the project, that both customer and firm can closely estimate the progress which has been made to that point in time. The lag between assuming that something is right and having a noncontroversial test prove that the

effort was correctly handled is oftentimes quite long. In many cases, the problems of the product are never discovered until the product has completely left the laboratory and even in many cases the manufacturing plant and is being used in the field.

On the other hand, to some extent, the organization, at least at the operating level, often knows that "things are not well" with the project, even during its early phases. The handwriting on the wall is often evident to those with the motivation to look. But the low-integrity-based attitude that produces hoping-for-the-best instead of providing-for-the-worst is what often prevents recognition of these problems. The fact that similar difficulties arise at basically similar places in different projects of a given company indicates that these difficulties are built into the company's system, and are not part of the general uncertainty of research and development. Such factors reflect the inherent ability of the management group.

The entire process whereby the customer and firm estimate the effort and cost required to complete the job, which process is to a great extent involved in this phase of progress measurement and evaluation, was very thoroughly discussed in Chapter 3. Such problems exist throughout the life cycle of the project, even down to the very end of the job. Even when a job has in fact reached completion the engineering reports may not quite say so.

This uncertainty with regard to the actual time scale, together with the problems discussed above, associated with the difficulty of precisely defining when engineering of a particular item has been accomplished, leaves the engineer responsible for specific sub-items to look for other guides to determine when he must say that he is ready to release drawings. Obviously, he

wishes to spend as long as possible on the engineering job because the more time he spends, the more assurance he has that all bugs have been discovered and ironed out and no difficulty will arise due to inadequate engineering in his area. A commonly-used criterion is to release them as late as possible without putting himself in a position of being criticized for delaying the completion of the over-all job. In other words, as long as the engineer responsible in one area can assure himself that other critical items are not yet ready for release, he feels under no obligation to release his own portion. What results, then, is a rather strange process in which the man responsible for releasing drawings in each area keeps half an eye on the progress being made in the neighboring area with a view to accomplishing his own release as late as possible, just so long as he is not last. The dynamics of this situation are quite comparable to those of a horse race in which every jockey has heavily bet on himself to come in next to last.<sup>30</sup>

This description, which seems appropriate for most R and D organizations, indicates that typically the individual engineer has almost no incentive to hold down costs on his work. To be sure the situation would seem to encourage continuous product improvement, but this results as an accident and not as an objective of the system. The goal for the engineer in such an organizational environment is to avoid criticism, rather than to produce a more efficient output. This kind of difficulty is evidently very common to developmental type work, as is shown by the following quote: "Computer programmers differ little from engineers, in general, in their reluctance to stop tinkering with and improving their creations. This is a laudable [??] trait; but as delivery dates approach and time grows short, it has to be restrained. Definitive test versions of the program must be established, and tight

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<sup>30</sup>R.B. Kershner, "The Size of Research and Engineering Teams", IRE Transactions on Engineering Management, June 1958, p. 37.

control exercised over changes, so that all effort can be directed at those which are really necessary to meet specifications."<sup>31</sup>

The problems found in getting someone to admit completion of a job, plus sloppy control in phasing engineers out of a job, may in the project that actually finishes its objective lead to an overcompletion of the objective. This too can be a problem both in terms of money to the contractor as well as in unreimbursed overexpenditures by the firm. The problem results from the incentives seen by the individual engineer or manager, which in turn derive from the penalty-reward structure of the organization. Such a structure is an important aspect of top management design of the business and reflects the true ability of the company management.

This problem of overachievement is hardly as serious as the major difficulty that has been discussed in this section, the difficulty in getting meaningful periodic measurements of progress and problems in research and development projects. Several methods that have been commonly used in industry have been discussed in this preceding section and to some extent evaluated critically. The fact that indications of progress become much clearer at later phases of product accomplishment than during the earlier phases of project life was also pointed out. And, finally, the lag between actually accomplishing an objective and the information derived from testing of such an accomplishment was mentioned as being in many cases quite a lengthy delay.

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<sup>31</sup>Hosier, p. 114.



Response Mechanisms in Research and Development Control

To close the research and development control loop (and also to complete this chapter), we shall now discuss the actions which organizations take as a result of their measurements of progress. "This is the 'so-what?' part of management coordination. The manager periodically compares and analyzes actual performance and status against the program and objectives. From this, he can determine the need for and direction of new action. The situation may indicate the need for revision of the program, or a relative increase or decrease in certain operating activities in order to balance out the whole utilization of resources."<sup>32</sup>

Problems arise in trying to decide what kind and how much action ought to be taken in response to the deviations that are sensed in the progress of the project.

It is necessary that the schedules and budgets have meaning. If they are not being followed, it is important that some decisions be made in order to increase the resources, modify the requirements, and reduce the costs. Unfortunately, the decision is oftentimes to reschedule and budget without taking any actions that affect the conduct of the project. Such actions indicate that the project office really does not believe in its own schedules and budgets. Thus, schedules and budgets become window-dressing for management and the customer, as well as objects of ridicule within the project.<sup>33</sup>

But despite such exhortations, it is quite difficult to compare the dollar cost of a project versus the scheduled expenditures to date, or the effort allocation versus the expected effort allocation to date, or the anticipated technical achievement versus the sensed

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<sup>32</sup>Medros, p. 4.

<sup>33</sup>Kornreich, p. 1.

technical achievement. The figure below

shows this basic method and the inherent difficulties that the analyst faces in interpreting the performance.

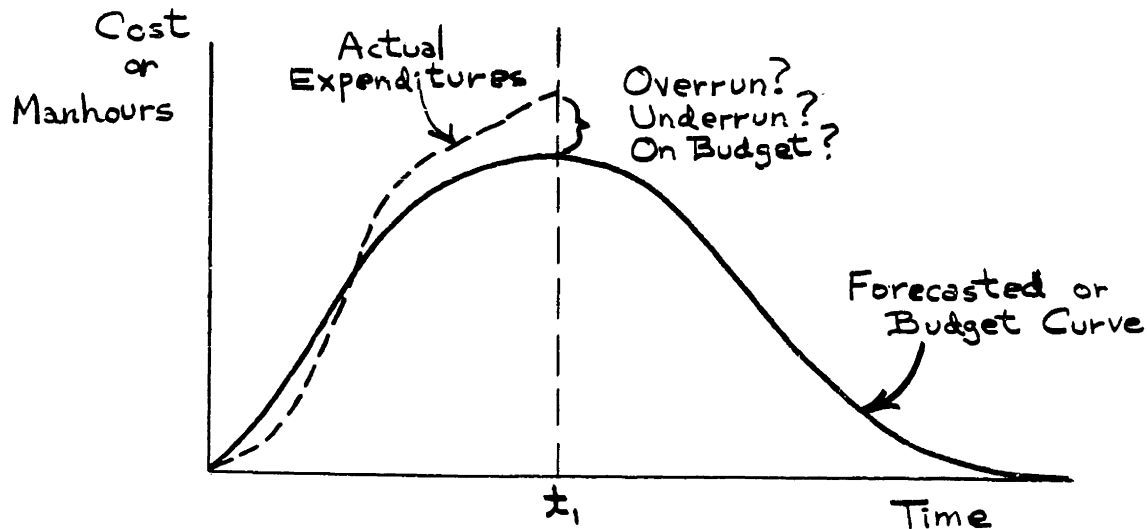


Figure 6-1 Contract "A"

On the basis of a comparison of an expenditure curve and a budget curve, no intelligent decision can be made as the following questions arise: (1) Are both curves compatible? (2) Do segments of both curves represent the same work? (3) Is there acceleration or deceleration of performance? For instance, a finance department will consider the distance between the two curves as an over-run condition. But based on the answers to the questions posed, the distance between the two curves could be any of the following three possibilities: over-run, under-run, or on-budget.

To find the meaning of the distance between the two curves, the correlative properties of the curves must be established. The most significant of these correlative properties is the physical completion of the work at  $t_1$ . In addition to being most significant correlative property, physical completion knowledge is one of the fundamentals necessary in the decisionmaking process by management. Decisions, such as additional or reduced manpower, increased or decreased overtime to finish the

effort based on the current physical completion, are of importance to engineering management.<sup>34</sup>

Thus, the various ways in which managements respond to indications of errors in their job estimates can well be critical determinants of the behavior of research and development projects. Two examples of apparently different policies will be mentioned here, both of which are commonplace among R and D project histories. In both examples, let us assume that the management of the firm uses periodic project review sessions perhaps on a quarterly basis. At the first quarter-year project review of a new undertaking, management finds that only half as much progress has been made as was initially expected. The basic question is, "How does management respond to this?" Under one familiar set of policies, management might say that this error only indicates some of the problems of getting the project under way; that there is no real reason to change the initial over-all estimate of project magnitude. The old platitudes, "We don't have to worry about encountering that kind of problem again", or "We often get into trouble when we're just starting up", are easily used as the excuse for such behavior. Furthermore, this same general response might very well be elicited at the next review period, and the one after that, and so on. Finally, after perhaps several reviews and a year or two have gone by, management might finally recognize that the series of error indications which they have ignored thus far do in fact dictate a radical revision in the projected effort requirements for getting the job completed. Thus, in this case the managerial

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<sup>34</sup>Versteeg, p. 72.

policy for responding to problems pointed up by their progress measurement procedures seems to be a policy which really ignores the error indications. Such an approach might well doom the project to failure, or at least to serious difficulties.

On the other hand, management policy might well decree immediate response to any apparent error in the estimates that is shown up in such project review sessions. In such a case, the deviation from estimate indicated at the first quarter-year review might cause management to change radically its initial estimate of project magnitude and to begin to take actions to acquire more people and facilities. Once a company acts to increase the scope of its activity, there is built-in momentum deriving from the purpose and commitments of these initial activities. The Parkinsonian attributes of an organization are thus given a boost by deliberate management action and, once moving, actions to recruit or transfer engineers onto the job or to acquire additional funds and expanded facilities are very difficult to stop. Of course, if the error signal to which management responded was in fact due solely to "the difficulties of starting the project", then such difficulties were not a sign of the inherent scope of the project or level of effectiveness of the people. In this case, the response will force overexpansion and wasteful haste in the job performance. It will result in an unnecessarily large and ultra-expensive project, much greater than is really required by the basic situation.

Both of these examples, which were presented as two opposite poles of a situation, are really just points on a long continuing relationship which basically describes how rapidly the management of a research

and development project responds to problems shown by comparison, whether graphical, tabular or mental, of their measured progress with their previously-expected progress. The company which has an extremely long delay in responding to error indications might well be characterized by the first example given, while a radical decrease in this response delay would produce the second example cited above. Without advocating either one of the two extremes cited, it is nevertheless important to recognize the striking contrasts in the results produced by the interaction of these managerial decisions with the rest of the research and development system. The way a company typically responds to problems of this sort is probably a characteristic of the firm based upon its own previous experiences and upon the intrinsic insight and ability of its management to understand the underlying situation in the project.

As a result of the response mechanisms utilized in a research and development project, the firm will sometimes anticipate that it is going to require greater effort and hence greater cost in accomplishing the job. As discussed in Chapter 4, this will often result in a request for increased funds from the customer and might similarly result in a decreased willingness on the firm's own part to invest its money in the project. But in the same way that the firm might begin to get skeptical about the likelihood of success of a project after it has begun to respond to its error estimations, so too the customer might have his doubts as to the wisdom of continuing the project.

The decision to terminate a research project is often a difficult one to make. This is especially true if it has been a long project with a considerable investment. Extending a nonprofitable venture, however, not only wastes research dollars, but it also delays starting work on potentially profitable

projects. Occasionally one hears comments such as 'Why didn't we drop that project six months ago?' or 'Why did we ever start research on that project?' Sometimes the answer is that no one asks the question at the proper time, and if it has been asked, the project might have been dropped.<sup>35</sup>

Having taken this into account, we have basically also finished closing the loop that was started at the beginning of this chapter.

### Summary of Chapter

This chapter has discussed the nature of measurements in research and development projects. Most existing measurements systems seem intrinsically unsuitable because of the uncertain nature of research and development and because the existing systems ignore the vital role of the individual in the project control system. Fundamental to the process of attempting to design controls for an R and D project is the recognition that often masking the real progress which is taking place are much accompanying bias, noise, and random elements. These factors are partly caused by the experience, ability, and insight of the project managers. The backgrounds of these people, as well as their personal motivations, tend to distort the ability of managers (or engineers) to identify and/or report the real progress that is being accomplished. Lags due to system testing, lack of accurate milestone assessment, and similar nonexistence of timely and carefully designed reporting systems all help produce inaccuracies in project progress estimations.

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<sup>35</sup> Carl R. Gloskey, "Research on a Research Department: An Analysis of Economic Decisions on Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 4 (December 1960), p. 168

Above all, there seems to be a need on the part of the management of the firm and of the customer for what Professor Zaccharias of M.I.T. (for many years a member of The President's Science Advisory Board) refers to as "taste and judgment". This kind of management ability is vitally needed to help clarify the usually floundering attempts to define, measure, review, and perhaps redefine the project goals and objectives. This taste and judgment is intrinsically related to the over-all quality and ability of the management and the technical personnel of the company and of the customer. It derives in part from the general experience that these people and organizations have encountered and from the insight and intuition of their personnel. To some extent it relates to an organization's courage to face up to failure, an organizational characteristic very closely related to the integrity that was discussed in the section on bidding within a project. If the environment of the organization can be so established that each individual engineer has the attitude that his own personal goals are best met by helping the corporation to succeed in the current research and development endeavor, then he will be little pressured by the fears of admitting problems and facing up to difficulties that he personally is encountering in an R and D project. If this sort of attitude exists throughout the organization, the communication systems of the company will serve to transfer valuable information as to the real state of progress and the real expected state of difficulties, and not serve as a means of distortion, bias, and delay in the transmission of valuable information and in taking of action in response to it. To a great extent, such problems relate to the reward-penalty structure that exists

within the organization, and in part to the same structure which exists within the contractual relationships between the customer and the firm. Very few careful studies have been made which would indicate the nature of how these relationships affect decision-making within research and development projects, although the author has recently begun such an undertaking under N.A.S.A. sponsorship. However, it seems rather obvious that the cost-plus-fixed-fee contracting approaches (commonly known as CPFF) create very little incentive for honesty by the firm or even for success (from the customer's viewpoint) within an individual project on which the firm is working. Longer-range objectives, different types of incentive systems, more concern for the motivations both of corporations and of the individual engineers and managers within these corporations can probably radically affect the ultimate success achieved within a given research and development project. These considerations can, no doubt, also greatly modify the outcome of the long-term research and development programs of our government or of any industrial corporation. As studies on these relationships are made and reported, our ability to comprehend better the problems in measuring and responding to progress indicators in research and development will be greatly enhanced.



## APPENDIX TO CHAPTER VI

The diagram of Figure 6-2 incorporates all of the elements described in the preceding portion of Chapter 6 and completes the visual presentation of the general model of research and development project life cycles. The figure indicates that the level of real job accomplishment (defined in the Chapter 5 appendix) and the intrinsic effort demanded by the complexity of the job produce a real measure of actual percentage completion of the project. This, when contrasted with the believed percent complete (to be discussed shortly), creates a pressure gap influencing change in the completion estimates of both the firm and the customer. The strength of this potential influence depends upon the fraction of this gap which is recognized, which fraction was earlier explained to be dependent upon the stage of the project. Correction of the previous estimate of completion also forces revision in the estimate of current progress, since this believed progress rate had to be in error in order for the cumulative estimate to have gotten out of line.

Other aspects of the diagram show that the accumulation of engineering expenditures is produced by the current rate which depends upon the number of engineers and their average monthly cost, including overhead expenses. The level of cumulative engineering effort (not considering the productivity of this effort, as was done in Chapter 5) merely sums the current rate of effort exerted by the engineers who are actually on the job. This current effort rate expended combines with the Chapter 3 estimate of total effort required for the job to produce a base believed progress rate. The progress rate's accumulation,

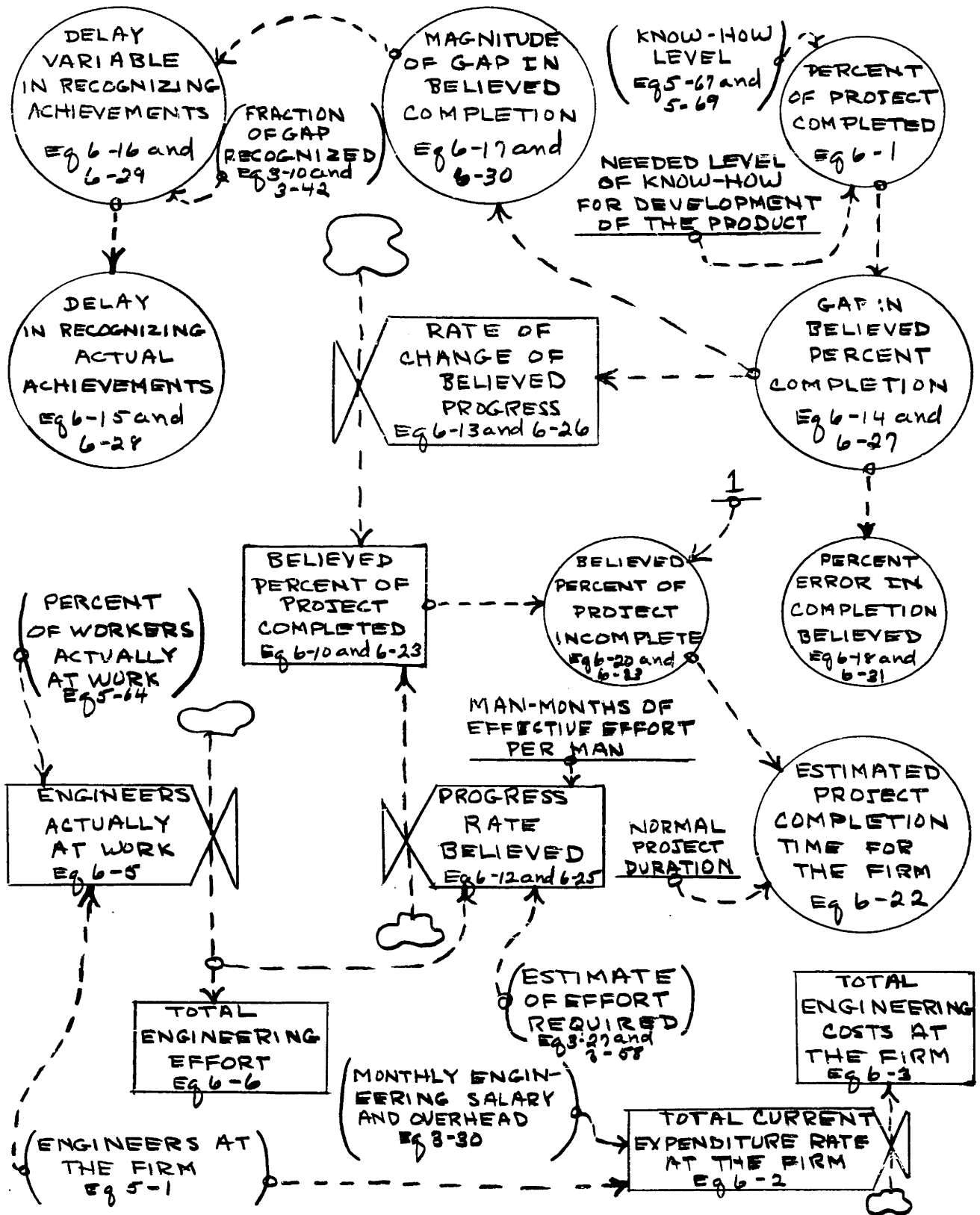


Figure 6-2 The Control of Research and Development Progress

as revised (see discussion above), gives the believed percent completion to date. The complement of this is the percent of the job believed to be yet incomplete. The latter finally helps determine the estimate of the remaining time needed for completion of the project, under normal conditions.

The equations shall begin with one for the actual percent of project completed, as indicated by the amount of know-how developed as a fraction of that which is needed (intrinsically) for product completion.

$$\text{PPC.K} = \frac{\text{KLEVF.K}}{\text{NLKP}} \qquad 6-1, A$$

PPC--Percent of Project Completed (percentage)  
 KLEVF--Knowhow LEVel at the Firm (effective  
 man-months of effort)

NLKP--Needed Level of Knowhow for development  
 of the Product (effective man-months of  
 effort)

Other "actuals", as contrasted to "beliefs", are also accumulating as the project evolves. These are the readily measurable variables of expenditure and effort rates, and cumulative costs of engineering efforts on the project. The first equation below, 6-2, shows that the current engineering expenditure rate is determined by the number of engineers in the firm and the average monthly cost factor per engineer. Equation 6-3 cumulates this rate into the level of total engineering costs. Equation 6-5 indicates that the number of engineers actually working equal the number of engineers in the firm multiplied by the factor which accounts for the average absenteeism from work. The TEEF equation cumulates this expended effort to-date. Finally Equation 6-8 cumulates as the total costs to the customer the continuing rate of customer expenditures on the project.

$TCEF.K = (MESOH)(ENGRF.K)$	6-2, A
$TECF.K = TECF.J + (DT)(TCEF.J)$	6-3, L
$TECF = (TEEF)(MESOH)$	6-4, N
$ENAWF.K = (PWAU)(ENGRF.K)$	6-5, A
$TEEF.K = TEEF.J + (DT)(ENAWF.J)$	6-6, L
$TEEF = \frac{KLEVF}{UTEF}$	6-7, N
$TECC.K = TECC.J + (DT)(RECFJ.K)$	6-8, L
$TECC = 0$	6-9, N

TCEF--Total Current Expenditure rate at  
           the Firm (dollars/month)  
 MESOH--Monthly Engineering Salary and Over-  
           Head (dollars/man-month)  
 ENGRF--ENGINEERs at the Firm (men)  
 TECF--Total Engineering Costs at the Firm  
           (dollars)  
 TEEF--Total Engineering Effort at the Firm  
           (man-months)  
 ENAWF--Engineers Actually at Work at the Firm  
           (men)  
 PWAU--Percent of Workers Actually at Work (per-  
           centage)  
 KLEVF--Know-how LEVEL of the Firm (man-months  
           of effective effort)  
 UTEF--Utilized Technological Effectiveness at  
           the Firm (percent effectiveness)  
 TECC--Total Engineering Costs paid by the Cus-  
           tomer (dollars)  
 RECFJ.K--Rate of Expenditure of Customer Funds by  
           the Firm (dollars/month)

Now we move into the formulation of the "believed" variables,  
 rather than the "actual" ones. Of course these beliefs form the basis  
 of decision-making in the project for both the customer and the firm.  
 Therefore, the discussion and determination of these equations for  
 the firm will immediately be followed by similar equations for the  
 customer. First, we have the believed level of project completion,  
 composed of the previous completion estimate plus revisions due to

changed beliefs as to the stage of progress and beliefs as to new progress made. The believed rate of new progress is merely the ratio of the amount of effort being produced by the engineers at work on the project to the number of man-months of effort believed to be required for project completion.

$$BPPCF.K = BPPCF.J + (DT)(PRBF.JK + RCBPF.JK) \quad 6-10, L$$

$$BPPCF = PPC \quad 6-11, N$$

$$PRBF.KL = \frac{(ENAWF.K)(MMEEM)}{EERF.K} \quad 6-12, R$$

BPPCF--Believed Percent of Project Completed by the Firm (percentage)

PRBF--Progress Rate Believed by the Firm (percent of project/month)

RCBPF--Rate of Change of Believed Progress by the Firm (percent of project/month)

PPC--Percent of Project Completed (percentage)

ENAWF--ENgineers Actually at Work at Firm (men)

MMEEM--Man-Months of Effort per working-Engineer per Month (man-months/man-month)

EERF--Estimate of Effort Required by Firm (man-months)

The factor **MMEEM** translates the manpower count into a manpower effort. Obviously, each engineer who is working contributes one man-month of effort (not necessarily effective) per month that he works. Therefore,

$$MMEEM = 1 \text{ (man-month of effort) / (man-month-of work)}$$

The rate of changes in the estimates relate to the pressure magnitude created to modify the earlier commitment. This pressure depends on the gap between the actual and the believed level of completion, and the extent to which this gap is made potent by the degree of recognizability of the error. The latter, of course, determines the delay in recognizing the actual achievement on the job and depends on how near completion (or believed completion) the project has approached.

$RCBPF.KL = \frac{GBPCF.K}{DRAAF.K}$	6-13, R
$GBPCF.K = PPC.K - BPPCF.K$	6-14, A
$DRAAF.K = DMRAF + DVRAF.K$	6-15, A
$DVRAF.K = (DRAAT)e^{-(50)(FOGRF.K)}(MGBCF.K)$	6-16, A
$MGBCF.K = \text{MAX}(GBPCF.K, -GBPCF.K)$	6-17, A

RCBPF--Rate of Change of Believed Progress by the Firm (percent of project/month)  
 GBPCF--Gap in Believed Percent Completion by Firm (percent)  
 DRAAF--Delay in Recognizing Actual Achievements by Firm (months)  
 PPC--Percent of Project Completed (percentage)  
 BPPCF--Believed Percent of Project Completed by the Firm (percentage)  
 DMRAF--Delay, Minimum, in Recognizing Achievements by the Firm (months)  
 DVRAF--Delay, Variable, in Recognizing Achievements by the Firm (months)  
 DRAAT--Delay in Recognizing Actual Achievements, Time constant (months)  
 FOGRF--Fraction of Gap Recognized by the Firm (percent of gap recognized/month)  
 MGBCF--Magnitude of Gap in Believed Completion by the Firm (percent)

We have said, in Equations 6-16 and 6-17, that the rate of recognition of the error in completion estimate depends on the magnitude of the error gap, regardless of the direction of this error.

On the average it seems unlikely that the progress estimate revision could take effect in any less than one month after the cause for revision exists. This minimum delay is likely to exist only when the job is almost or actually completed, in which case,

$$DMRAF = 1 \text{ month}$$

On the other hand, if the work were stopped, an additional half-year might be required on the average to recognize most of what has really been achieved on the job. For this,

$$DRAAT = 6 \text{ months}$$

The recognition of this error in the earlier progress estimate also tends to produce a revision in the previous estimate of job progress, with the attendant effects on the estimate of technological effectiveness (as discussed with reference to RCPEF, Equation 3-24 in the appendix to Chapter 3). The resulting modification relates to the degree (or percent) to which the earlier estimate is now felt to be in error. This percent error in the completion estimate believed by the firm is the ratio of the estimate error gap, Equation 6-14, to the believed completion itself, Equation 6-10.

$$\text{PECBF.K} = \frac{\text{GBPCF.K}}{\text{BPPCF.K}} \quad 6-18, A$$

PECBF--Percent Error in Completion Believed  
by the Firm (percent)

GBPCF--Gap in Believed Percent Completion by  
the Firm (percent)

BPPCF--Believed Percent of Project Complete by  
the Firm (percent)

Once the percentage completion has been found from Equation 6-10, the inverse can be used to designate what is left to be done. In our case, however, since a project can be overdone (more work completed than necessary), the unmodified inverse for such a case (i.e., less than no work to be done) would become ridiculous. Thus we shall speak of a job whose degree of incompletion ranges only from 100% down to 0%, and accomplish this reasonable limit in Equation 6-20. When this figure is known, we also know the estimated time remaining for completion of the project, if normal scheduling times are utilized. Because of technical requirements (division in one of our equations by a value of zero would stop the simulation computations), we shall restrict the estimated completion time to being no less than our computation solution interval. This has no effect on the simulation results.

TBPIF.K = 1 - BPPCF.K	6-19, A
BPPIF.K = MAX(TBPIF.K, 0)	6-20, A
TPCTF.K = (BPPIF.K)(NPD)	6-21, A
EPCTF.K = MAX(TPCTF.K, DT)	6-22, A

TBPIF--Trial, Believed Percent of project  
 Incomplete at the Firm (percent)  
 BPPCF--Believed Percent of Project Completed  
 at the Firm (percent)  
 BPPIF--Believed Percent Incomplete at the Firm  
 (percent)  
 TPCTF--Trial, Project Completion Time at the  
 Firm (months)  
 NPD--Normal Project Duration (months)  
 EPCTF--Estimated Project Completion Time at the  
 Firm (months)  
 DT--Delta Time, DYNAMO computation solution in-  
 terval (months)

For the most part the equations beginning from 6-10 above are also suitable to describe the customer's beliefs as to project progress. Equations 6-23 to 6-33 below are similar to the earlier defined Equations 6-10 to 6-20. We shall merely repeat them here for completeness of definition of our system model without any further comment.

BPPCC.K = BPPCC.J + (DT)(PRBC.JK + RCBPC.JK)	6-23, L
BPPCC = PPC	6-24, N
PRBC.KL = $\frac{(ENAWF.K)(MMEEM)}{EERC.K}$	6-25, R
RCBPC.KL = $\frac{GBPCC.K}{DRAAC.K}$	6-26, R
GBPCC.K = PPC.K - BPPCC.K	6-27, A
DRAAC.K = DMRAC + DVRAC.K	6-28, A
DVRAC.K = (DRAAT) $e^{-(40)}$ (FCGRC.K)(MGBCC.K)	6-29, A
MGBCC.K = MAX(GBPCC.K, - GBPCC.K)	6-30, A

BPPCC--Believed Percent of Project Complete  
 by Customer (percent)  
 PRBC--Progress Rate Believed by Customer  
 (percent of project/month)



RCBPC--Rate of Change of Believed Progress by  
the Customer (percent of project/month)  
PPC--Percent of Project Completed (percentage)  
ENAWF--Engineers Actually at Work at Firm (men)  
MMEEM--Man-Months of Effort per working-Engineer  
per Month (man-months/men-month)  
EERC--Estimate of Effort Required by Customer  
(man-months)  
GBPCC--Gap in Believed Percent Completion by  
Customer (percent)  
DRAAC--Delay in Recognizing Actual Achievements  
by Customer (months)  
DMRAC--Delay, Minimum, in Recognizing Achieve-  
ments by Customer (months)  
DVRAC--Delay, Variable, in Recognizing Achieve-  
ments by Customer (months)  
DRAAT--Delay in Recognizing Actual Achievements,  
Time-constant (months)  
FOGRC--Fraction of Gap Recognized by Customer  
(percent gap recognized/month)  
MGBCC--Magnitude of Gap in Believed Completion at  
Customer (percent)

The minimum delay in real achievement recognition is the same  
as the firm's, one month. DRAAT holds for both customer and firm, too.

DMRAC = 1 month

The customer's modification of his previous progress estimate  
(described by RCPEC, Equation 3-55) also follows the firm's description.

$$PECBC.K = \frac{GBPCC.K}{BPPCC.K} \quad 6-31, A$$

PECBC--Percent Error in Completion Believed by  
the Customer (percent)  
GBPCC--Gap in Believed Percent Completion by the  
Customer (percent)  
BPPCC--Believed Percent of Project Complete by  
the Customer (percent)

Finally we shall provide the equations for the customer's estimate  
of the percent of job yet undone, thus completing the R and D project  
model.

$$TBPIC.K = 1 - BPPCC.K \quad 6-32, A$$

$$BPPIC.K = \text{MAX}(TBPIC.K, 0) \quad 6-33, A$$

TBPIC--Trial, Believed Percent Incomplete by  
Customer (percent)  
BPPCC--Believed Percent of Project Complete by  
Customer (percent)  
BPPIC--Believed Percent of Project Incomplete  
by Customer (percent)

As extra information for use in studying the various simulation results we shall define a few equations which are not used internally in the project model. First, the profit rate to the firm is the percent of percent of profit allowed on the project billings times the expenditures covered by the customer. This cumulates in Equation 6-35 into the profit total to-date. Subtracting the firm's own investment (unreimbursed project expenses) produces the net profit before taxes as Equation 6-36. Finally the corporate tax rate factor produces the residual net after-tax profit on the project.

$PRF.K = (PPP)(ARECF.K)$	6-34, A
$PROF.K = PROF.J + (DT)(PRF.J)$	6-35, L
$PROF = 0$	6-36, N
$NPROF.K = PROF.K - TAIF.K$	6-37, A
$NATPF.K = (CTR)(NPROF.K)$	6-38, A

PRF--Profit Rate to the Firm (dollars/month)  
PPP--Percentage Profit on the Project (percent)  
ARECF--Auxiliary, Rate of Expenditure of Customer Funds (dollars/month)  
PROF--PROFit (dollars)  
NPROF--Net PROFit (dollars)  
TAIF--Total Actual Investment by the Firm (dollars)  
NATPF--Net After Tax Profit to the Firm (dollars)  
CTR--Corporate Tax Rate factor (percent)

As was mentioned earlier we shall use a profit percentage of ten percent, although this is on the high side of usual practice. The corporate tax rate will be assumed as a flat fifty percent. Either of these can readily be changed if felt desirable.

PPP = 0.10 (decimal percent)  
CTR = 0.50 (decimal percent)

## CHAPTER VII

### THE KEY DETERMINANTS OF THE PROJECT LIFE CYCLE

#### Introduction

Chapters 1 through 6 have attempted to describe thoroughly the cycle of continuing activities which make up the life of a research and development project. This process of tracing through the flows of resources and information in any type of problem situation is characteristic of the Industrial Dynamics methodology. Emphasis on such flow paths brings more clearly to light the specific decisions, policies, and constraining factors which control the flows and thus the behavioral outcomes of industrial and economic systems. The detailed developments of the last five chapters should therefore contain the relevant information as to the key determinants of the project life cycle. In reviewing this information, it is particularly important to note what it is about the research and development firm, its customer, and their product, which make one project different from another project. Why is it, for instance, that firm F working with customer C makes a success of project X while it fails in project Y? How would both of these projects have been different if firm G rather than F had undertaken the job? What distinctions would have occurred in the project life cycle if the government agency were customer D rather than customer C? The fact that in real life such differences in project behaviors do occur makes it important that we try to focus on the sources of these differences. This chapter, therefore, shall review the processes described in Chapters 2 through 6

with the view of identifying those factors relevant to the firm, the customer, and the product which might in fact cause the differences in project behaviors. These distinguishing characteristics will then be summed up at the end of the chapter.

#### The Perception of the Need for and Value of a Product

The first activity to be discussed was the process of perceiving the need for and value of a new product. It was pointed out in Chapter 2 that basic to this perception process is the existence of some underlying need for the product. This was related in the chapter to the unknown but nevertheless existing potential value of having and being able to utilize the product over a duration of possible product life. This characteristic was called the intrinsic product value.

However, since there is a difference between the intrinsic product value and the estimates of value made by the customer and the firm, it seemed important to point out that there is a significant delay in receiving and absorbing information pertaining to the potential value of a new product idea. This delay is principally dependent upon the managerial and technical knowledge of the firm or the customer and is the key in determining how long it takes before either the firm or the customer recognizes the need for a new product.

Finally, the perception of product that enters into the later decision-making and evaluation functions of both the firm and the customer relates to the future value of the product and not

its existing value. The forecast that the firm and the customer make of the future value of the product depends to a great extent upon their relative optimism, their willingness to take chances, and, in general, the extent to which they are willing to base decisions of consequence on risk-laden determinations of ultimate value.

#### The Estimation of Project Effort and Cost

The second process to be discussed was the continuing task of estimating the effort and cost requirements for the project. Here, too, the concept of some underlying determinant of the effort requirement was introduced. This underlying determinant is a two-fold notion which recognizes both the intrinsic size or complexity of the job and the changing level of technological effectiveness relating to the job. As in the value perception process, however, neither the firm nor the customer knows the intrinsic size of the job or the actual state of the art that is available to them. They do attempt to make continuing estimates of both of these factors.

In describing the way in which the firm or the customer attempts to estimate the size of the job initially, that is, before much work has been done on the project, Chapter 3 pointed out that here the previous job size experience of the organization, particularly as related to the basic underlying size of the contemplated job, is an important determinant of this initial estimate. The previous experiences of the firm and the customer tend to influence the way in which they both look at any currently con-

sidered task. In addition, it was pointed out that modifying the influence of this previous job size experience is an over-all tendency to underestimate all jobs. This tendency seems to be built into the institutional environment of governmental research and development management. Finally, modifying both the previous experience and this underlying tendency is the over-all managerial and technical ability of the firm or of the customer. The ability of the firm or the customer helps in correctly anticipating the effort and cost requirements on the job, regardless of either previous background or this tendency to minimize expected difficulties. These managerial and technical capabilities are obvious distinctions between one firm and another and one customer and another.

Initially, both the firm and the customer attempt also to estimate the technological effectiveness that they will have available to them in the engineering force of the firm. The first factor that influences this estimate is the real state of the art that is currently available to the engineers working for the company. Since, again, neither the firm nor the customer knows exactly this real effectiveness, they both try to estimate it. If, in fact, it is a new product area into which both firm and customer are moving, there is a tendency to underestimate the state of technology available for the project. Too often it is felt that a new product draws from a wholly new technology, whereas in reality there is a great deal of overlap between engineering methods and

technological developments in one area and the respective problem requirements in other areas. Modifying the skepticism, however, is the relative optimism of the firm as to the abilities of its own engineers or those which it expects to be able to acquire for the project. Similarly, the confidence which the customer places in the abilities of the firm's engineers can also serve to modify the customer's skepticism. Thus, the relative optimism or pessimism of the firm and the customer seems to play an important part in determining their estimates of the current technological effectiveness that the firm will be able to apply to the expected job requirements. Moreover, the estimate of the amount of effort required on the research and development task is dependent not solely upon the estimate of current state of the art, but also on a forecast of the future state of the art that will become available. This forecast is in part dependent upon the recent rate of change of technology, as well as on the degree of optimism, willingness to take chances, or risk-taking propensity of both the customer and the firm. The more the plans of both depend upon expectations of technological breakthroughs, the greater the risks that both are taking in committing themselves to such a project.

The way in which the firm and the customer make their initial estimates of the size of the job and the technological effectiveness was described above. But, as Chapter 3 pointed out, these estimates are undergoing continuous revision and reassessment through-

out the life cycle of the project. The revisions of the estimates are based largely upon the inputs to the initial estimation process, that is, on the experiences of both firm and customer, their abilities, underestimating tendencies, relative optimism, as well as on real environmental inputs. In addition, of course, revisions in these estimates are based upon the degree of responsiveness of the management of the firm and the customer to changes of all sorts. This responsiveness, that is, the time that it takes to recognize and react to changes in the technological and project progress situations, is probably dependent upon the managerial and technical ability of both the firm and the customer.

#### Funding the Research and Development Project

In Chapter 4 the problems of funding the research and development project were broken down into three areas: the firm's bidding phase, the customer's evaluation of the proposal, and the firm's decision to invest its own funds. The prime determinants of the firm's bidding activities with respect to its attempts to acquire funds from the customer are, first of all, its beliefs as to the expected value and expected cost of the research and development project. These estimates, however, are not underlying characteristics of the firm, but rather are results derived from those underlying characteristics which were discussed in Chapters 2 and 3. One characteristic, however, which does seem to be fundamental to the firm, and which was seen in Chapter 4 to influence the firm's bidding activities, is that set of criteria which determines for



the firm its desire to participate in a forthcoming project. These criteria were discussed as being relevant to the firm's objectives as to potential profitability, direction of technological development, size of job market in which the firm wishes to engage, and/or other particular characteristics. These things, in general, seem to relate to the over-all objectives of the firm, its goals, and its particular ways of manifesting these goals in its actions.

In addition to these objectives of the firm which determine on what projects and under what conditions it would be willing to submit a contract proposal to the customer, another important determinant of its bidding activities was pointed out to be the firm's integrity. This integrity factor particularly manifests itself in the way in which the firm presents an estimate of cost to the customer, which proposed cost in fact differs from the estimate which the firm internally holds. The characteristic of integrity in bidding seems to be a characteristic which is fundamentally different from one firm doing research and development to another, and thus ought to be included in this type of listing.

In examining the activities by the customer in evaluating the prospective job that he is to fund, we again account for the fact that those criteria which the customer uses in evaluating the suggested participation in project sponsorship seem to constitute an important characteristic of the research and development life cycle. These proposed evaluation criteria, as described above for the firm, also relate to the objectives of the customer, as well as to the project alternatives that the customer has available to

him. In addition, of course, the way in which the customer weighs the relative cost-value relationships is fundamentally related to the conservatism, or its opposite, the risk-taking propensity, that the customer is willing to manifest in its research and development sponsorship activities.

A second determinant of the customer's evaluation procedure that was mentioned is the customer's confidence in the ability of the firm's engineers and also in the opinions and information expressed by the firm. This shows up in the extent to which the customer takes into account the firm's bid cost estimate in determining its own anticipations as to the amount of money and effort that the job will require.

The third factor which determines the customer's participation in the job are the actual funds that the customer has available to him to allocate to different research and development projects. This is the first resource limitation that has been encountered in describing fundamental characteristics of the customer, the firm, or the product. But it, too, will distinguish one customer agency from another and so must be included in this itemization.

The final aspect of funding the research and development project that will be discussed here includes the activities of the firm in investing its own funds in the project. Here the firm's criteria for participating in a project, which characteristics were discussed above, are of course most important in influencing

the firm's investment decision on an R and D project. Secondly, it is important to recognize that the firm also is undertaking risks in investing its own money in such a project, and, therefore, the propensity of the firm to take such chances, its willingness to gamble with expected profits, its willingness to invest money without definitized project sponsorship, is an important characteristic of the firm that enters into these decisions. And, finally, just as in discussing the customer resource limitation above, it is important to recognize that the firm's available funds also limit the extent to which it can participate in its own sponsorship of research and development projects. Thus, the availability of company funds is a characteristic which might distinguish one company from another and which is a potential determinant of the life cycle of a research and development project.

#### The Acquisition and Utilization of Engineering Manpower

Once the funds have been provided through the process described above, the firm begins to engage in the activity of acquiring engineering manpower. One fact which influences the particular rate of acquisition is the extent of forward planning of the firm. If it begins hiring manpower in advance of receipt of funds, then recruitment activities are geared to the anticipated level of funding rather than to the existing level. The extent of forward planning by the firm is probably dependent upon the managerial ability of the firm and also, in part, upon the extent to which it is willing to take risks and commit itself to supporting a level

of manpower that is not yet adequately funded.

The second determinant of the rate of acquisition of engineering manpower for the firm is the firm's particular policy towards its training program for new recruits. The problem faced here is one of balancing the current project work need to avoid diverting fully-experienced engineers to helping out the new recruits, against the later project needs for more engineers which can only be met through an extensive training and development program. Here it seems that the ability of the firm to strike a balance between these two goals and these two problems will be the key determinant of the particular mode of acquisition of new engineering manpower.

The factors which contribute to engineering productivity in the research and development project were clearly outlined in the last portion of Chapter 5. The first of these factors, the changing level of external technological know-how, has already been related to the product and its technological environment. Thus this changing level of technological know-how is a basic determinant of the rate of engineering productivity, and it is also a characteristic of the product.

The first factor which modifies the actual effectiveness of engineers on the job that was cited in Chapter 5 was the on-the-project experience that had been accumulated by the manpower force. This on-the-job experience, however, is not a characteristic of the firm, the product, or the customer; rather it is something

which evolves as a variable element during the life cycle of the project. Thus it does not fit into our list of key characteristics which will make one job differ from another job. In a similar vein, though the existing split of the engineering work force among various worker categories is in fact an important determinant of the current rate of engineering productivity, this, too, is not a characteristic which would distinguish one firm from another firm. It is rather a phenomenon which is always encountered during the life cycle of any research and development project.

The final modifier of engineering productivity on a research and development project to be mentioned in Chapter 5 was the ability and skills of the engineering management. This is in fact a more intrinsic characteristic of the firm and was cited in Chapter 5 as being probably the key determinant of productivity of an engineering work force.

#### The Control of Research and Development Progress

The chapter which closed the loop on the cycle of research and development activities was broken basically into three parts: (1) the process of estimating task requirements; (2) obtaining progress measurements; and (3) responding to signals derived from these measurements. The key determinants of the first area, the estimation of task requirements for the R and D project, have been reviewed in an earlier section of this chapter which discussed the estimation of project effort and cost. The lengthy discussion

in Chapter 6 on the problems of obtaining progress measurements ended up with the conclusion that the ability to obtain intelligent measurements of real progress in a research and development project is dependent mostly upon the managerial and technical ability of the firm and also of the customer, to the extent that the customer attempts to assess this progress. The factor that was referred to as taste and judgment was listed here as being of vital consequence. This is of course one aspect of the more broadly defined capabilities of the firm or customer. In describing the responsiveness of the management of the firm and the customer to the changes that were indicated as a result of progress measurements, Chapter 6 pointed out the influence of integrity on whether or not engineers face up to the problems which they are encountering and admit these to their superiors and their customers. This seems to be an important determinant of the time that it takes to recognize the real progress on the job. This integrity also affects the extent to which the firm transmits its expectations of difficulties in the project to the customer. In addition, the time that it takes for the firm and the customer to fully recognize and respond to the changes that are more or less dictated by the indications they receive from the project is probably dependent upon the managerial ability of both the firm and the customer.

Thus we have now reviewed all of the phases of activity which constitute the life cycle of a research and development project. In each of these phases, we have attempted to point out those influences

upon the rates of flow of these activities which derive from characteristics of the firm, the customer, and the product, which may distinguish one firm from another, one customer from another, and thus one project from another. It seems reasonable, then, that we should attempt to summarize these influences into these very three categories.

### Characteristics of the Product

The review of the activities of research and development which constituted the first general section of this chapter pointed out three basic characteristics of the product and of the technical environment in which the product exists. The first of these was identified as the underlying need for the product, or as it was labeled, the intrinsic product value. The intrinsic product value has its main influence on determining the perception of the need for a product by both customer and firm, which perception influences the entire process of fund and effort allocation throughout the research and development project.

The second characteristic of the product which seems to be critical is the intrinsic size or complexity of the job. This measure of the inherent amount of effective manhours which would be required to complete the task is primarily influential in the estimations of project effort and cost, which activities were described in Chapter 3. Through this estimation process, the intrinsic size of the job makes its weight felt in the estimated manpower and dollar requirements which then, as did the value estimates,

permeate the entire process of the research and development cycle. In addition, of course, the intrinsic size of the job determined the basic measure against which effective manhours could be compared to determine the real progress in the research and development enterprise.

The final characteristic of the product which seems to be very important throughout research and development project life cycles is the changing level of technological effectiveness or, as it has been otherwise described, the state of the art. This characteristic was important in the process of estimating project effort and cost, but primarily the state of the art was regarded as the basic determinant of the actual engineering productivity described in Chapter 5.

#### Characteristics of the Firm

Several characteristics of the firm also seem at least potentially to be critical determinants of research and development life cycle behaviors. The characteristic of the firm which was mentioned most frequently in the first section of this chapter, and which seems to be most pervasive in its influences, was the firm's managerial and technical ability. This factor seemed to influence the time that it took to perceive the need and value of a new product. It influenced the degree to which the firm would correctly estimate both the size of the job and the technological effectiveness of the state of the art during its estimating of project effort and cost. It was also noted that the



managerial and technical ability of the firm probably influences to a great extent the responsiveness of the firm to changes in its requirement estimates. In the chapter on acquisition and utilization of engineering manpower, it was felt that the managerial ability of the firm determined the extent of forward planning that the firm did in attempting to acquire engineers. This ability also was cited as the major determinant of the wisdom of the particular training program policy adopted by the company. That chapter also showed that the managerial and technical capability of the firm influence to a great extent the actual productivity of the engineering work force that was being applied to the research and development task. To cap all this off, in the discussion on the control of research and development progress, the taste and judgment factor, that is, the basic managerial and technical ability of the firm, was said to determine to a great extent the accuracy of the measurements of progress on the job. In addition, this quality indicator determined the responsiveness of management in facing up to and taking action with respect to changes that were demanded by these progress measurements. Thus it seems that this characteristic of the firm, its managerial and technical ability, is indeed an important one.

A second characteristic of the firm seems also to have influenced many different aspects of a research and development project. In discussing the problem of perception of product need and value, it was felt that the forecasts of future value depend upon the firm's willingness to take chances. The next chapter pointed

up how the degree of optimism or confidence by the firm affects its estimates of technological effectiveness and also its expectations of further breakthroughs in technology. Chapter 4 pointed out how importantly the firm's investment decision was dependent upon its willingness to gamble or to accept risks in investing its funds in a project on which it had not received contractual assurance. All of these indicators relate to one over-all characteristic of the firm--the relative conservative or speculative nature of the company, the degree to which it is willing to undertake risks or, as we might readily sum these up, the risk-taking propensity of the firm. This propensity evidently affects a good number of the relationships and activities in which the firm engages in a typical research and development project.

Another characteristic of the firm which was thought to influence at least one aspect of research and development projects is the previous job size experience of the company. This previous job size experience of the firm in part determines the initial estimate made of the size of the job that the company was facing. Thus the previous job size experience of the firm provides a bias that will influence at least its initial decisions based on the relative cost-value relationships of the anticipated project. The bias from this previous job size experience is, however, modified by an over-all tendency towards underestimation of all jobs and towards uncertainty as to the state of technology. All of these have influence in the same general area, the estimation of project

effort and cost. All three influences should probably be recognized as approximating a single characteristic of the company.

Another basic characteristic of the firm was identified to be the integrity of the company. This strongly determines the request for funds which the firm makes of its customer, as described in Chapter 4. It is also felt to be of great influence in the process of measuring and reacting to progress on a research and development job. The integrity characteristic pervades an organization and creates an atmosphere which either encourages or makes it difficult for an engineer to face up to the difficulties which he is encountering in his task, and admitting them to his supervisor. Similarly, the lack of integrity in the organization discourages or prevents the firm from admitting its problems to the customer and perhaps making plans to solve these difficulties in advance. Thus the integrity of the firm seems an important determinant of research and development behavior.

Another basic characteristic of the firm relates to the criteria which help it to determine the nature of the projects in which it participates. The firm's policies might well be those of seeking any jobs which will be profitable to at least a minimal degree, or jobs that will satisfy the customer to a certain extent, or so forth. These criteria for project participation seem to be the most obvious manifestation of the goals and objectives of the firm. The goals and objectives of the firm certainly constitute a very important characteristic of the company. They in-

fluence the timing and the extent to which a firm will attempt to gain customer funding for a project, as well as the extent to which the firm will be willing to invest its own funds into some prospective project. Such goals and objectives did not explicitly fall into our discussion of the various research and development project activities.

The final characteristic of the firm which seems to have influence on controlling the flows of activity that have been described thus far is the availability of funds to the company. This is the constraining factor on the firm's ability to invest in a research and development project, and might for different firms allow one to enter competition in a new area and prevent the other from such an undertaking. Thus the extent to which a company possesses monetary resources may in fact strongly determine at least one aspect of its research and development project behavior.

#### Characteristics of the Customer

The factors that have been discussed above as characteristic of the firm do in fact most strongly influence the behavior of the company in its participation in a research and development project. These same factors, moreover, have great influence on the customer's behavior in an R and D project. The customer is swayed by the same general modes of influence in perceiving the need for and value of a product, estimating project effort and cost, evaluating the worth of a project for investment purposes,

and attempting to determine the relative progress on an R and D job. The customer does not usually engage to the same extent as does the firm in the acquisition and utilization of engineering manpower. However, on those jobs in which the customer staffs a management organization or an extensive project supervisory organization, he too is influenced by the same kinds of determinants as is the firm in acquiring and effectively using engineering manpower.

There seems to be only one additional characteristic of the customer which influences his decision-making. This characteristic is an interesting one to be singled out in this way because of the fact that it describes an interrelationship, the customer's confidence in the firm. The extent to which the customer has confidence in the firm will influence the degree to which it listens to and accepts the firm's estimate of the value and cost of the R and D project. It also affects the degree to which the customer will place faith in the technical capability of the firm's engineers to carry out the job at reasonable cost. Thus this characteristic of the customer, its confidence in the firm, seems to at least potentially be another added characteristic of importance in the research and development project.

#### Summary

Those factors itemized in the three sections above, the characteristics of the product, the firm, and the customer, seem to include those things which could possibly make important differ-

ences between one project life cycle and another. These potentially key determinants of research and development project life cycles are:

Characteristics of the Product

1. Intrinsic product value;
2. Intrinsic size of the job;
3. Rate of growth of related technology;

Characteristics of the Firm

4. Managerial and technical ability;
5. Willingness to accept risks;
6. Previous job-size experience;
7. Integrity;
8. Criteria for project selection;
9. Availability of funds;

Characteristics of the Customer

10. Confidence in the firm;

All the factors listed above as characteristics of the firm.

Although there are ten different characteristics listed above, these ten enable us to narrow the problem of understanding research and development into a far more compact grouping than the popular folklore of R and D would seem to allow. A one-sentence summary of the general theory of research and development project life cycles is that these ten characteristics of the project, the firm, and the customer are the factors which distinguish one job from another. The project case histories which will be developed

through simulation in the succeeding chapters will more specifically illuminate this point.

## PART II

## EXPLORATIONS INTO THE MANAGEMENT OF RESEARCH AND DEVELOPMENT

"If you have built castles in the air, your work need not be lost;  
that is where they should be. Now put the foundations under them."

Henry David Thoreau .  
Walden



## PART II

Part II of this work reports on a wide variety of studies of the general theory of research and development project dynamics that was presented in Part I. The studies were conducted by simulating the model developed in the appendices of Chapters 2 through 6 for a broad array of input and parameter modifications, concentrating mostly on the key determinants described in Chapter 7. The first chapter of Part II, Chapter 8, goes in detail through the life cycle of a typical R and D project, examining the causes of various project decisions and demonstrating the over-all plausibility of the general model of Part I. Chapter 9 reports on the effects of different changes in major product-related characteristics on the outcomes of research and development projects. Chapters 10 and 11, respectively, describe studies of the influences of the characteristics of the firm and the customer on project life cycles. Chapter 12 examines some characteristics, previously undiscussed, which were brought to light by the extensive computer simulation explorations. These factors relate to the general processes of performing research and development work, and seem of a different nature than the previously cited characteristics of the product, firm, and customer. These explorations into the management of research and development are finally summarized in Chapter 13, the concluding chapter of this volume, in which both conclusions of the undertaking and recommendations for future inquiries are outlined.

CHAPTER VIII  
THE LIFE CYCLE OF A TYPICAL  
RESEARCH AND DEVELOPMENT PROJECT

This chapter will present the simulated time history of the typical research and development project described in Part I. The equations and constants used in representing this project were those provided in the appendices of the chapters of Part I. This chapter's discussion will be based on the data produced by the computer simulation, much of which results are reproduced in the figures printed throughout this chapter. The input characteristics (and as we shall see, the resultant life cycle) of this project are probably similar to those of a large number of military (or, more broadly, governmental) research and development undertakings. The product inputs are such that the project requires something in the range from 500 to 2,500 man-years of engineering effort, depending on the state-of-the-art advances which can be utilized and the over-all ability of the developing firm's management and engineers. This effort requirement indicates project costs between \$15 million and \$75 million, a range covering many significant research and development activities, including, as examples, a new highly advanced computer system for the Atomic Energy Commission, a radar-control center for airport traffic control for the Federal Aeronautics Administration, a small jet engine for Navy helicopters, an air-to-ground missile for the Air Force, and a solid-fueled sounding rocket for the National Aeronautics and Space Administration. All of these examples, and the simulated project too, relate to areas where in the relevant technology

is in a state of rapid advance, the needs for the end product mentioned change as the times and circumstances change, and both the firms and the customers involved have a background of earlier experiences with each other and with at least somewhat similar types of undertakings.

### The Project History

With the above as background we shall immediately begin to relate the history of a typical research and development project, as revealed by the computer results of the project simulation. The project history begins with a single engineer working on company funds, doing work in an area technically related to our potential product. In general, he and his company management feel that it is worthwhile to allocate a small amount of funds and effort for such research, although at this initial time they as yet sense no particular value to the product area being investigated. As the engineer continues to work in this field, he gradually begins accumulating some technical know-how that will be relevant to the eventual direct product development efforts. Working on his own, with the usual available clerical, drafting, and shop assistance, the engineer can be relatively productive. He is personally experienced in related areas of work and is able to devote his full time to the research task at hand, not needing to spend any effort on recruiting, training, or supervising other engineers.

The company pays the costs incurred by the engineer out of its general funds, feeling that it ought to provide its traditional support of a one-man activity in this new technical area. As the costs pile up, the firm's investment in the area accumulates, and it charges this off to its general operations as a current expense. If the firm or the

engineer at work could conceive of the eventual project at this early time, they would estimate its cost to be extremely high. The excellent technical and managerial ability of this particular company would enable it to correctly estimate both the inherent scope of the job and the state of the related technology for performing the necessary research and development work. These factors would lead the company to an initial effort estimate of about 2,000 actual man-years of engineering, which amounts to a cost estimate of about 68 million dollars. This is based on figuring the job at an average cost of thirty-thousand dollars per engineering man-year and adding on the extras needed to cover the usual eleven and a half per cent engineering time spent away from the task. Such a cost estimate coupled with its current zero-value estimate of the product worth would give the firm no hope of getting any customer support as things now stand.

The customer organization has also had experience in related technological areas, as well as with the firm just under discussion. The customer's relationships with the firm have been reasonably normal for the military research and development field, and the customer has only slightly better-than-average confidence in the company's capabilities. The customer tries to keep fairly well informed as to the areas of current research of most companies working in his fields of interest. The companies of course cooperate because of their own attempts to determine customer thinking on various project ideas and also because of their interests in getting research support or major development contracts. In the specific product area under consideration the customer is aware of the company's efforts, but is also unimpressed as to any potential value

of the investigation. The customer has not at our initial time allotted any funds for the area being studied, and has not even been approached by the firm.

If the customer were made cognizant at this initial time of the potential product, he too would form a very high estimate of its research and development costs. This customer's ability, relatively speaking, is much lower than the firm's, and as a consequence his estimates would probably be in error by a wider margin. Given the customer's past experience with jobs somewhat smaller than the one currently under consideration, plus his own bias towards underestimating the complexity of a project, the customer would arrive at an estimate that the job ought to be able to be done under optimum conditions with about 300 man-years of effort. But then taking into account the undeveloped and apparently not changing state of the technological art in this field, and his own extra doubts as to this (or any other) firm's competence, the customer would raise the estimate by about a factor of ten. This would lead the customer to estimate R and D costs at about one hundred million dollars, almost fifty percent higher than what the firm would have believed. Under these existing conditions the customer is certainly unwilling to support any major program in the technical area under consideration.

The next few months pass with no noticeable change occurring in the situation. The single engineer keeps working on the task, developing some more understanding of the technical area; no changes take place in the real world affecting either the product development cost or the intrinsic value of the potential product; and neither the customer nor the firm perceives of a suitable undertaking in the area under study.

Then, at month six, something different begins to happen. Although neither the customer nor the firm recognizes this fact as yet, some things begin changing in the world situation which make our potential product have some underlying value to society. To be sure, its value at month seven is very small, very easy to ignore, and in fact the product value is overlooked. Yet, during the next few months, still unrecognized, the intrinsic value of this product begins to grow. The world situation is changing enough so that by month twelve, only six months after it began having any worth at all, the basic value of the product, if it were available to society, reaches one million dollars. In the meantime, product technology is still basically unchanged, although the company engineer's added experience is beginning to have slight, almost imperceptible positive effect on the overall productivity of his work. The potential research and development costs of the project thus remain about as they were initially, estimated at between sixty-eight and one hundred million dollars, depending on whether you think about the firm's or the customer's estimate. Thus, the potential project is still not attractive to either customer or firm, but the firm does continue supporting its engineer's efforts. In fact, the firm has decided by this time to try to entice the customer into sponsoring this work, and is currently requesting a small grant of thirty thousand dollars to provide for the next year's activities. The customer, seeing no value yet to the work area, and feeling that the firm ought to support such small costs out of its own funds, has so far rejected this request.

At about this time the firm and, soon afterwards, the customer begin to learn small bits of information which, when pieced together,

provide an inkling that there might be some value to the product area. Neither can yet pin down the exact need to be filled but both have a slight hunch that something worthwhile is going to turn up. Two continuing trends are helping along this perception of the potential value of the product. First, the underlying worth of the product area is itself increasing very rapidly. Due to changing world circumstances, this basic but unperceived value has moved from one million dollars at month twelve to ten million only six months later. Thus, the need for the product is steadily increasing and there is greater likelihood that the customer and/or the firm will be able to more clearly recognize this need. The second steadily increasing influence on the perception process is that the company is continuing its exploratory work in the potential product area, somewhat improving its know-how as each month goes by. This is gradually putting the firm into a better position for sensing opportunities and technical possibilities in the product area. And, to some extent, the customer receives information from the firm which assists his own ability to interpret the changing world circumstances into the need for specific products. For both of these reasons the perception of product value by customer and firm begins to increase, but not at all significantly. For example, the firm's perception of the current product worth does not pass the million dollar mark until month twenty-nine.

On the other hand, as the perceived value increases ever more rapidly, both firm and customer begin responding to the pace of change, looking forward to future increases in the need for the product. In fact, they begin thinking in terms of what the product might be worth

in the future, at a time by when it is possible that research and development on the product might be complete. Thus, at month twenty-nine, when perceived present value has just reached one million dollars the firm's estimate of the future value of the product is already up to three and one-half million dollars and rapidly growing. The steady advance of the perceived current value of the product influences both customer and firm to believe that such a trend as they detect will continue. In fact the "band-wagon effect" of this growth causes them to rely more and more on the projections of the value changes, rather than on the recognized product value itself. Gradually, the decision-making of both customer and firm moves toward depending on their estimates of future value, an even less reliable concept than their perceived present value of the product.

While all these changes are beginning to evolve on the value side of the fence, important events have also begun to occur in the product cost area. At about month nineteen some of the work being done outside of the company's activities begin to reach pay dirt. The gradual accumulation of technical knowledge in areas related to the potential product starts to pay off as new insights, techniques, and tools begin to appear in various scientific laboratories and engineering offices around the country (or world). For the first time since the beginning of our simulated project life, the optimum costs to do the job start decreasing. Using the new technical breakthroughs, a firm now can, at least theoretically, get the project completed for slightly less than before. Neither firm nor customer is yet aware of the initial discovery, or of the fact that new improvements now start showing up



with regularity, slowly advancing the state of the art and gradually cutting the necessary cost to develop the product.

But within a few months the customer, primarily through his industrial contacts, and the firm, in part through his conversations with the customer, begin to learn about these breakthroughs. Some signs show up in the trade literature and the professional meetings, and the firm's own activities are assisted by receipt of this additional knowledge. More importantly, both the customer and the firm start to factor the latest achievements into their thoughts about product possibilities and project costs. And again, just as the band-wagon began to grow in regard to value estimation, so too does the band-wagon phenomenon take effect in the cost estimating area. As the advances in technology are recognized, similar achievements begin to seem more feasible and, in fact, expected. The state of the art, once having begun a rapid advance, is expected to continue its headlong plunge into progress. Aided by their desires for optimism about product possibilities, both customer and firm rely more and more for their cost estimates on forecasts of a future technology.

To this basic underlying change in the real-world product environment is added a gradual shift in the customer's attitude towards the firm. Initially the customer's confidence, established from previous project experiences with the company, was about average and tended to bias the customer's estimate of the firm's ability to carry out a project efficiently. But as the customer builds up more of a contact with the firm in this new area, he gradually begins to shift his opinion. Several influences act to produce this shift. First, working without the

strains of a research and development contract between them, the customer tends to see the firm in a more favorable light generally. Secondly, the fact of the different technology (even if only slightly changed) can easily lead the customer to think that the firm's competences in the new area will be of a higher calibre than its earlier performances. Finally, the passage of time tends to cure all ills, and the customer can readily forget his earlier grievances with the company. This is particularly true because of a generally optimistic approach taken by both customer and firm to the new and the different area, with the catchiness of novelty helping dissuade everyone of his sometimes more rational hesitations.

These three forces---(1) the gradually rising perceived current value and similar future projections; (2) the apparently accelerating changes in technology and the future cost expectations induced by them; and (3) the customer's generally enhanced opinion of the firm's effectiveness, with attendant implications for project cost estimates--begin to improve the over-all appearance of suitability of the project. By month thirty the firm estimates that the future value of the project is about 8% of the expected total project costs, but this figure changes rapidly. Six months later this ratio is up to 32% and after only another three months, by month thirty-nine, the firm estimates future value of the product at 57% of cost expectations. This quick transformation is caused by the combined effects of rapidly rising future value estimates and rapidly falling estimates of the costs to develop the project under the expected future technology.

In turn, the more favorable project outlook begins to affect the

plans of the firm. The firm now begins to think that there is a slight but growing chance that the customer will in the relatively near future be willing to sponsor a major program in this area. This impression is based on the firm's own improving feelings about the product suitability, its understandings from contacts with the customer as to the customer's beliefs, the firm's knowledge as to the types of endeavors which have been pursued in the past, and on his awareness of the customer's allocation within the past month of his first few thousand dollars worth of funds for this technical area. The firm is therefore willing to take a chance and risk some of its internal funds in the project area, in the hope of speeding up a contract award and of putting itself in a better position to receive such an award.

The firm thus decides that it would like to hire several engineers to work on the project, but immediately runs into the restriction that the single engineer on the job cannot really handle more than a couple of new men. He has been doing exploratory studies up until now, had not really thought much about project work organization, and needs time to get things straightened out and smoothly rolling forward. During the next two months some engineers are found on other projects in the company who are freed part-time from their other tasks to begin working on this new area. The original engineer needs to spend more and more of his time explaining the area to the additional engineers, helping them get accustomed to the work, and supervising their efforts. This detracts from his own output on the job, and in fact, for a few months actually lowers the total group productivity to below that of the single engineer initially. But two new men are gradually added to the job and others

are sought.

This seems like an appropriate place to temporarily break this description of a project life cycle to see from whence we have come and where we now stand. Initially, we began with a situation of no really intrinsic or perceived need for our potential product and with a single engineer working on company funds in an area in which no technological change had recently occurred. The basic costs to do the job were very high, and therefore no suitable project appeared possible. Then, gradually, things began to happen. The engineer's work helped gain insights into product possibilities, basic changes began to occur in the world situation, which alterations produced increasing need for the product, and cumulative technological advances began reducing the expected research and development costs. As the situation bettered, the firm recognized the possible desirability of committing its own funds to the product area. It tried to add more staff to the project team but ran into the basic problem of being able to absorb them into the previous one-man effort. But after a few months, by about month forty-five, the group had at least gotten past initial growing pains, and though still quite inefficient in terms of their own productivity, are now trying to add more new engineers to the project. The intrinsic value of the product has grown to one hundred and sixty million dollars worth, but neither customer nor firm yet recognizes current worth of more than twenty million dollars. Estimated future value, as contrasted to the current value perception just mentioned, goes up to sixty-four million dollars presently, to compare very favorably with cost estimates ranging between forty-four and forty-seven million dollars. Both organi-

zations view the product area as one of high potential, but the customer's conservatism prevents him from leaping into the area so soon. He is still awaiting a more convincing product need-product cost relationship before committing much of his funds to a research and development project.

These factors are pictured in Figure 8-1, which consists of the computer output plots of the early part of the simulated project model. The entire period of time discussed to this point, almost four years, has involved activities usually ignored in any recorded manpower, cost, or contract histories of a project. These activities constitute the pre-formal-project stage of a research and development life cycle, an embryonic stage in which all the necessary precursors of the formal project get started. Within the project life cycle, foundations have now been laid for clear perception of the need for the product, for estimation of the required project effort and cost, for getting the process of customer funds allocation and the firm's risk-taking investments under way, for creating the core of a project engineering team and in fact, for actually accomplishing some small amount of research and development work on the project. Researchers or managers who ignore the existence of this phase of a life cycle forget the sources of the entire project concept and execution.

Returning now to the simulated project history, we find that the rapidly changing project situation reported above is still continuing. As the world problems evolve, the underlying value of the potential product to society holds to its increasing path. The perceived current value and the estimated future product value also are carried upward as



customer and firm receive and respond to new information about the world situation and as the firm continues to learn from its technical studies. Cost estimates for research and development of the product also continue their earlier steady decline as new technological know-how is recognized and further achievements anticipated. These influences keep pushing up the attitudes of both customer and firm as to the suitability of the potential product for large-scale development. As the firm employs more engineers on the job it requests more support from the customer. The customer soon begins to provide some token support of the work. By month forty-nine the customer is spending almost two thousand dollars a month on the project while the firm is adding more than seven thousand dollars a month out of its own funds. Both customer and firm now think that the future worth of the product is greater than what the product will cost to develop, but the customer is not yet quite satisfied that he should take the chance on supporting a major program in the area. The customer's funds are limited and he wants to invest in the most attractive opportunities (i.e., those with the largest value-cost ratios), so he is still slightly hesitant.

By month fifty the firm has decided that the customer will soon be willing to support the research and development project for the potential product and submits a full-scale proposal with an accompanying estimate of costs. The firm really believes that the project will cost about 41.5 million dollars, but cuts this by about 10% in its communication to the customer. The firm's integrity is fairly high, but it thinks that in anticipation of the customer's minor reluctance and in view of possible competition for the project, it should reduce its

initial funds request slightly. Under the Cost Plus Fixed Fee (CPPFF) type of contracting which pertains to most government research and development jobs, the worst that the firm might expect to happen as a result of this underestimation is that it will not receive its negotiated percent markup on the costs incurred beyond the amount bid. Actually, this too is not much of a problem since a large portion of the project cost overruns can usually be claimed as changes in the job specification and the fee also collected here. If all the project costs are legitimate, the firm does not have to worry about reimbursement of its actual expenses. The CPPFF system encourages the firm to be concerned only with the contract base for collecting fees, and not with the relationship of final actual costs to initial estimated costs. Thus, the company in our project model requests about 37.7 million dollars for a job it really expects will cost almost four million dollars more.

By this time the firm has four engineers on the job and is continuing to recruit, hire, and train more as fast as its existing project group can effectively absorb them. One more engineer is added in the next four months, another by three months afterwards, and so on.

The customer in the meantime has begun taking into account the firm's request for project funds. At the time of request the customer felt willing to commit as much as 45 million dollars to the project, and the firm's request added further encouragement. The customer's average confidence in the firm leads him now to gradually revise his earlier estimate of costs, taking into consideration the lowered figures submitted by the firm. The influence of the firm's bid combines with a continuing recognition of cost-saving technological advances as well as a continuing



perception of improving product worth. These convince the customer that the project should be supported adequately and he begins the process of allocating the needed funds to the project. One million dollars is obtained from other funds in a very short time, and during the next year the customer gradually builds up this allocation to about 30 million dollars. These monies are, of course, not immediately made available to the firm, but by month fifty-five, for example, the customer is willing to authorize spending at a rate of one million dollars per month. The firm's slow growth has kept its expenditures during that same month down to fourteen thousand dollars. Thus, the firm continues its attempts to expand its organization and is continuously restrained by the capacity of its current group to train and supervise more engineers.

By month sixty-two the project staff is still up to only nine engineers, with four more in the process of finishing negotiations to join the company. Not much real progress has been made on the research and development program, although no special technical difficulties have yet become apparent. The continuing recognition of technological advances leads the firm to think that the costs to do the project are much lower even than what it has indicated to the customer a year earlier. Thus, during the next few months the firm informs the customer that it believes costs will be lower, cutting its estimate by about five million dollars within the next year.

From month sixty something else has been hapening that augurs a different type of situation in the months ahead. The underlying intrinsic need for the product, which had steadily been increasing, slows its rate of growth and by month sixty has reached a plateau level of

real value at 200 million dollars. This results from changes in the world situation which diminish the importance of the initial source of need for the product, or which point to a more effective means of treating the underlying problem creating the need for the product. The intrinsic product value remains approximately constant for eighteen months and then begins to fall for the same two reasons mentioned. As before, neither the customer nor the firm have knowledge (nor is such possible) of this intrinsic value. However, they do gradually receive information about the world situation creating the underlying need, and they do gradually respond to modify their product value estimates. Particularly, as the rate of change of the world situation slows, the formerly steadily increasing urgency also slackens. Soon the firm and customer sense the fact that little more is going to happen to improve the ultimate values of the product. At month seventy-two the firm's estimate of the future value of the product, an estimate based on a four-years-ahead projection of the changing demand situation, peaks at 492 million dollars and from then on begins declining, somewhat slowly at first and then rapidly gaining momentum in its downward tumble. The customer's value estimates also go through a similar process.

The suitability of the project to both customer and firm still remains very firm. At about the time of the peak future value estimate, the customer, for instance, thinks that the project will be worth more than twelve times what it will cost to develop; i.e., the customer is then willing to develop the product even if the research and development costs were several times more than what they are expected to reach. Thus there is no slowing of project support and in fact, project activity

continues to steadily improve. The firm has managed to get twenty-one people at work on the project and has ten more near joining the firm's group. Despite the technological advantages which have accrued from the new breakthroughs outside of the firm's own work, its real project accomplishment is still small. There are two main reasons for this low progress: (1) the relative lack of effectiveness of the new engineers, most of whom are without much experience in general and particularly without experience in the technical area of the project; and (2) the need for utilizing most of the experienced project engineers to indoctrinate, train, organize, and supervise their newer colleagues on the job. But despite this slow pace the firm and customer both remain pleased with the project possibilities.

During the months that follow, up to month one hundred, real value keeps dropping, estimated future value also plummets, and estimated costs continue a slow decline as technological improvements are discovered, communicated, recognized, and interpreted with respect to their research and development cost significance. The engineering group is steadily built up to a level of 135 engineers plus supporting staff, by month one hundred with an anticipated increase of 50% within the next few months. Taking the project schedule into account the firm would actually like to have almost five times as many engineers but is unable to recruit and train that many in such a short period of time. Progress on the task has been accelerated greatly in the months prior to month one hundred but most of the job still remains to be engineered.

The significant change that has been taking place in these months, however, is in regard to the apparent over-all desirability of the project.

The customer, who earlier thought he would be willing to pay as much as twelve times what he then had estimated as the project costs, has gradually become far less enthusiastic about the job. By month one hundred, his perceived ratio of future value to estimated cost has fallen to 4.5, with an apparently continuing loss in the project's appeal. The firm, whose value estimate has fallen far more rapidly and who also internally holds to a higher cost estimate than does the customer, thinks the project is even more marginal a proposition and is beginning to worry about the prospects of the customer cutting off the funds. To worsen this situation in the firm's opinion is a slightly lowered efficiency which it begins to notice during month ninety-nine. This has a slightly boosting effect on the firm's estimate of what the project is going to cost to complete.

This seems like another good place to pause for perspective. From month forty-five the project life cycle has significantly evolved in terms of a more definitized cost-value structure, a broader span of activities, and a much greater number of engineers and dollars being utilized. During the period described the firm has requested major funding and the customer has responded with a large allocation to the program; the intrinsic value of the product to society has matured, stabilized, and gone far in its decline; and the expected future value of the product has similarly mushroomed upward, peaked, and sharply fallen. The attractiveness of the project has also boomed then staggered to the point where the firm, at least, is concerned about the completion prospects of the job. And yet despite all this activity, really not much money has been spent relative to total project cost

expectations, the engineering staff is still only a fraction of what seems needed to get the job done, and correspondingly only a small percentage of the task has yet been accomplished. All this sounds very similar to many other projects, particularly those which receive nationwide publicity, such as in the current conflict over the RS-70 3,000 m.p.h. bomber. Given our long lags in identifying worthwhile research and development undertakings and in being able to respond to such situations, our national research and development efforts seem to really get going in full swing either at a time when we feel it is no longer very much worth the effort anyway (as some now feel about the country's anti-missile missile program), or long after others have benefited by earlier achievement of the same product objectives (as was the case in our manned space flight efforts to date). So, too, our typical project simulation shows an emergence into the phase of major research activity at a time when the attractiveness of the entire project is beginning to dull.

The life history to date of the major project variables discussed is pictured in the simulation output graphs of Figure 8-2 on the next page. Here we see the same major variables that were shown in Figure 8-1 on page 356, but with the perspective of a longer time period and with two additions to the plots. The tremendous impact of technological advance during this period of more than eight years is clearly shown in the greatly reduced estimates of project cost. Also notice that the underlying value phenomenon, basic as a concept to the evolution of all product innovations, now appears as almost a full life span of embryonic existence, birth, and early growth, development to full maturity, gradual

PV=V, LRPVF=W, EFPVF=E, EVAUC=U, ETCPF=T, TECF=F, AAC=A, TCRFF=R, ENGRF=G, NPROF=N

0	50	100	150	200	G	
-400T	-200T	0	200T	400T	N	
0	10M	20M	30M	40M	RAF	
0	20M	40M	60M	80M	T	
0	200M	400M	600M	800M	UEWV	
0VG	-----	N	-----	T	-----	WVEUFAR
VG	.	N	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
VG	.	N.	.	T	.	WVEUFAR
10VG	-----	N	-----	T	-----	WVEUFAR
VG	.	N	.	T	.	WVEUFAR
VG	.	N	.	T	.	WVEUFAR
VG	.	N	.	T	.	WVEUFAR
WV	.	N	.	T	.	WVEUFAR,
WV	.	N	.	T	.	WVEUFAR,
WV	.	N	.	T	.	WVEUFAR,
WV	.	N	.	T	.	WVEUFAR,
WV	.	N	.	T	.	WVEUFAR,
WGV	.	N	.	T	.	WVEUFAR
20WGV	-----	N	-----	T	-----	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
WG V	.	N	.	T	.	WVEUFAR
30WE	-----	N	-----	T	-----	WVEUFAR, E
WE	V	N	.	T	.	EUG, WFA
WE	V	N	.	T	.	EUG, WFA
WE	V	N	.	T	.	EUG, WFA
WE	V	N	.	T	.	EUG, WFA
WUE	V	N	.	T	.	WFAR, UC
FWE	V	N	.	T	.	EU, FAR,
FWE	V	N	.	T	.	EU, FAR,
FWUE	V	N	.	T	.	FAR, WG
FW E	V	N	.	T	.	EU, FAR,
40FW-UE	-----	N	-----	T	-----	FAR, WG
FW UE	V	N	.	T	.	FAR, WG
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
FGW UE	V	N	.	T	.	FAR
50F G W	-----	N	-----	T	-----	FA
F GA W	U E	N	.	T	.	R
F G W A	U E	N	.	T	.	R
F G W	A U E	N	.	T	.	R
F G W	U EVA	N	.	T	.	R
F G W	U V E	N	.	T	.	R
F G W	U V E	N	.	T	.	R
F G W	U V E	N	.	T	.	R
F G W	U V E	N	.	T	.	R
60 F	-----	N	-----	T	-----	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
F	G W	N	.	T	.	UN
70 F	-----	N	-----	T	-----	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
F	G W	N	.	T	.	TN
80 F	-----	N	-----	T	-----	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
F	G W	N	.	T	.	VW
90 F	-----	N	-----	T	-----	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
F	G W	N	.	T	.	VF
100 F	-----	N	-----	T	-----	VF
F	G W	N	.	T	.	VF

obsoleting decline, and, not yet occurring, decay into nonexistence. The curve of value perceived by the firm shows up clearly the great time lag in the recognition of product possibilities during the entire emergence of the real worth of the product. Then comes the phase of product perception which is nurtured by its own history of growth, wherein the band-wagon effect of anticipated change overcomes the conservative influence of current achievement and knowledge. Examine the towering growth of the value estimates, relative to their real underlying counterpart. As the gap between expectations and reality widens, the danger increases that relatively small changes in the underlying world situation can precipitate radical revision of the whole previously established value-basis of the project. The estimated future value turns, begins to decline, and with it gradually erodes the suitability of the entire project.

Note also the customer's allocation of funds to the project. His favorable opinion of the product situation leads to relatively quick provision of funds to the project area, with gradual revision setting in as estimates of costs fall under the impact of continuing technological progress. Observe too the steady period of engineering work done by a single engineer in the firm, followed by the gradual expansion of the engineering group as more funds become available and then clearly growing in an exponential fashion in the second half of the simulated project graph. Finally, look at the history of the firm's profitability on this project. First one sees the long period of increasing financial loss on the project, as the company supports its small engineering effort out of its own funds. Then comes a stabilization

period as the customer support, including profits, just covers the current expenses of the project. And finally the rise in current profitability of the engineering activity takes place as the firm applies its fee to cancel out its previous investments, "breaking into the black" on the project at time 86, and rapidly increasing its accumulated profit on the more intensified spending rate.

Looking back at the latest year of the project life, one can readily see signs that people commonly associate with the formal beginnings of a research and development project. During the entire period of time a substantial and rapidly growing number of engineers are at work on the project. A formal and firm request for funds has been made and the customer has allocated a matching amount to the project. Expenditures are rising rapidly and the firm is starting to accumulate profits on the job. Thus we can consider the project to be formally well under way by month one hundred, from which time our project history now continues.

As the engineering organization grows in size, it increases its basis for further expansion both because of the number of people already in the organization and also because of their greatly increased average experience. Thus growth of the organization now takes place rapidly as the firm enters into large-scale development of the product. This rapid growth does, however, gradually affect the experience mix of the engineers and the firm soon starts recognizing slight slippage in its project performance. This reflects itself in the slow but steady rise, starting in month one hundred, that occurs in the firm's estimate of total project cost. After ten months of this rise the firm



finally decides to request more funds from the customer, and gradually begins to increase its pressure on the customer for more money for the project.

In the meantime, the customer's opinion of the desirability of the project has been slowly deteriorating. His estimate of the possible future worth of the product has dropped sharply, while his cost estimate has increased, helped along by the firm's requests for more funds. But even as late as month one hundred fourteen the customer thinks that his further investment in the project is justified. Comparing his estimate of the future value of the product to the estimated additional costs needed to finish the project and derive the value benefits, the company still thinks the project is worth twice the additional amount it will now cost. At month one hundred fourteen the customer thinks the project will require 19.5 million dollars more to achieve completion, whereas he feels that it will be worth 39.5 million dollars when completed. If the customer took account of the total expected cost 32.3 million dollars instead of the additional cost, the value-cost comparison would be less favorable. But the costs already put into the project should not enter into the customer's rational economic decisions. In addition, should they irrationally be considered, these sunk costs probably influence the customer to look for the project evaluation criterion which will tend to save those costs from being totally wasted. Thus the customer might well think: "I have already spent over twelve million dollars on this job. If I cancel now, I get no product benefits from this money. But the investment of an additional 19.5 million can pay off in a two to one ratio. Therefore, I should continue my support

of the project." Such behavior has been assumed in our typical simulation.

This customer evaluation policy is critical to the project behavior. It leads the customer to gradually increase his allocation to the project several months after the firm requests the additional funds. It leads him from month 117 on, for instance, to continue full support of a project whose total costs are now expected to exceed its total value derived. Though the customer no doubt feels disappointed in the project by this time, he still recognizes that he has more to gain by his additional investment than he will lose. It is with this set of attitudes that the customer fully finances the last phase of product development, continuing right up until he feels the job is done at month 128, after which the customer discontinues his funding activities.

The firm, during this entire final phase of the project, continues the growth of its engineering staff and advances the work on the research and development activities needed by the project. From about month 108 the firm has begun to feel the accomplishment slipping behind the project schedule. The firm revises its request for funds from the customer when the gap between the cost estimate and the allocated funds widens sufficiently that the firm thinks it necessary to go back to the customer for more money. In turn, the customer has also been led to revise his project cost estimates, but, as explained above, the customer gradually responds by providing the additional needed funds. With the large number of engineers at work on the project, 450 by month 117 and still growing, progress on the job begins to take place rapidly. By month 127 all the needed work on the job is completed in fact, and by the

next month both customer and firm are convinced that the research and development project is indeed finished. The momentum of the project causes a few extras to be done during that final month, such as additional product testing and more thorough final debugging.

But the work is now done, the customer stops reimbursing the costs of the firm, and the firm shifts its engineers as quickly as possible from what is now company-supported work in the technical area of the project just completed to other work within the company, or if absolutely necessary it lays off those engineers it cannot utilize. All of this is shown in the final part of the graphed project history, now pictured in entirety in Figure 8-3. The charts now clearly depict the project life cycle from many points of view. The total cycle of the product value phenomenon is now visible: intrinsic value growing, leveling, and falling into disappearance; perceived current value lagging in recognition all along; estimated value of both the firm and the customer lagging in growth, then accelerating and overshooting the real value counterpart, then falling rapidly for the firm and less quickly for the customer toward zero. This is one of the major life cycle characteristics of research and development projects.

Another is the perceived product cost curve. Starting very high relative to product worth at that time, estimated effort and cost on the project gradually fall under the influence of a rising technological state of the art. This decline in the cost estimate slackens as soon as the engineering work gets under way to any great extent, and the firm begins to form a more realistic impression of the effectiveness of the engineers. In fact, the cost estimate rises as a result of this same

IPV=V, LRPVF=W, EFPVF=E, EVAUC=U, ETCPF=T, TECF=F, AAC=A, TCRFF=R, ENGRF=G, PPC=P

	0	0.5	1	1.5	2	P
	0	200	400	600	800	G
	0	10M	20M	30M	40M	RAF
	0	20M	40M	60M	80M	T
	0	200M	400M	600M	800M	UEWV
0V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
10V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
V	.....	.....	.....	.....	.....	VWEUFAR
VW	.....	.....	.....	.....	.....	WEUFARG
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VW	.....	.....	.....	.....	.....	WEUFARG
20V	.....	.....	.....	.....	.....	WEUFARG
W	.....	.....	.....	.....	.....	WEUFARG
W	.....	.....	.....	.....	.....	WEUFARG
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W	.....	.....	.....	.....	.....	WEUFARG
30WE	.....	.....	.....	.....	.....	WUFARGP
WE	.....	.....	.....	.....	.....	EU,WFAR
WE	.....	.....	.....	.....	.....	EU,WFAR
WE	.....	.....	.....	.....	.....	EU,WFAR
WE	.....	.....	.....	.....	.....	EU,WFAR
WUE	.....	.....	.....	.....	.....	WFARGP
FWE	.....	.....	.....	.....	.....	EU,FARG
FWE	.....	.....	.....	.....	.....	EU,FARG
FWUL	.....	.....	.....	.....	.....	FARGP
FW E	.....	.....	.....	.....	.....	EU,FARG
40FW-UE	.....	.....	.....	.....	.....	FARGP
FW UE	.....	.....	.....	.....	.....	FARGP
F W UE	.....	.....	.....	.....	.....	FARGP
F W UE	.....	.....	.....	.....	.....	FARGP
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F W UE	.....	.....	.....	.....	.....	FARGP
F W UE	.....	.....	.....	.....	.....	FARGP
F W UE	.....	.....	.....	.....	.....	FARGP
50F	.....	.....	.....	.....	.....	FAGP
FG A W	.....	.....	.....	.....	.....	FP
FG W A	.....	.....	.....	.....	.....	FP
FG W A	.....	.....	.....	.....	.....	FP
PF W	.....	.....	.....	.....	.....	FG
PF W	.....	.....	.....	.....	.....	FG
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PF W	.....	.....	.....	.....	.....	FG
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PF W	.....	.....	.....	.....	.....	FG
PF W	.....	.....	.....	.....	.....	FG
60PF	.....	.....	.....	.....	.....	FG
PF	.....	.....	.....	.....	.....	FG
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PF	.....	.....	.....	.....	.....	FG
PF	.....	.....	.....	.....	.....	FG
PF	.....	.....	.....	.....	.....	FG
PF	.....	.....	.....	.....	.....	FG
70PFG	.....	.....	.....	.....	.....	FG
P F	.....	.....	.....	.....	.....	FG
P F	.....	.....	.....	.....	.....	FG
P F	.....	.....	.....	.....	.....	FG
P FG	.....	.....	.....	.....	.....	FG
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.PFG	.....	.....	.....	.....	.....	FG
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
80 P-FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
90 P-FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
.P FG	.....	.....	.....	.....	.....	VW
100 PE	.....	.....	.....	.....	.....	VW
EP	.....	.....	.....	.....	.....	VW
E P	.....	.....	.....	.....	.....	VW
E P	.....	.....	.....	.....	.....	VW
E P	.....	.....	.....	.....	.....	VW
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E P	.....	.....	.....	.....	.....	VW
E P	.....	.....	.....	.....	.....	VW
110 E	.....	.....	.....	.....	.....	VW
.E	.....	.....	.....	.....	.....	VW
.E	.....	.....	.....	.....	.....	VW
.E	.....	.....	.....	.....	.....	VW
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.E	.....	.....	.....	.....	.....	VW
.E	.....	.....	.....	.....	.....	VW
120E	.....	.....	.....	.....	.....	VW
E UVN	.....	.....	.....	.....	.....	VW
E V W	.....	.....	.....	.....	.....	VW
E V W	.....	.....	.....	.....	.....	VW
E V W	.....	.....	.....	.....	.....	VW
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E V W	.....	.....	.....	.....	.....	VW
E V W	.....	.....	.....	.....	.....	VW
E V W	.....	.....	.....	.....	.....	VW
130E	.....	.....	.....	.....	.....	VW
EVW	.....	.....	.....	.....	.....	VW
EVW	.....	.....	.....	.....	.....	VW
EVW	.....	.....	.....	.....	.....	VW
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EVW	.....	.....	.....	.....	.....	VW
EVW	.....	.....	.....	.....	.....	VW
140V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
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V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
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V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
V	.....	.....	.....	.....	.....	VW
150V	.....	.....	.....	.....	.....	VW

recognition, combined with the feeling that the basic scope and complexity of the project is bigger than anticipated.

The curve of engineering employment on the project also shows the rise and fall of the life cycle. For a long time only a single engineer is working in the product area within the firm. 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 force 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 quickly, tapering in its growth only as the project nears final completion. Then the last phase of the engineering curve shows the period of transfer of engineers out of the technical area of the project to other areas.

The last curve drawn on this graph shows the real percentage completion of work needed for the project. This curve is hardly visible for many, many months of the project life cycle. During what was referred to as the embryonic phase, up to month forty-five, the percent of project completion appears to have a zero value. Only during the latter part of the next period examined, the active birth and early growth of project activities from month 45 to month 100, does project accomplishment begin to appear on the graph. In part this is misleading. For although the engineering work output relative to that needed for project completion (this is the concept being shown on the graph) 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 a broad base for doing the project work; (2) cost estimation on the project had been firmed up; and (3) funds were allocated by the customer. These achievements were all vital to the project, but none of them can be related directly to the engineering tasks needed to be completed in order to finish the product development. In any event, from month 100 on the project engineering jobs do gradually get completed, with over 75% of the effective work being done in the last year and a half of the project life (from about month 110). The work was actually completed in month 127 and some extras added during the period of transferring the engineers from the project area.

#### Adding More Realism to the Project Model

The results pictured and discussed so far in this chapter do seem to portray the basic phenomena of research and development projects. But they appear to lack one element of realism. Most people who have examined research and development project data would observe that the manpower curves in projects tend to have many ups and downs, some sizable, in addition to the general growth and decline pictured in the simulation results. Some such observers offer explanations of these phenomena which relate to multi-phase scheduling of project activities or to other reasons which sound somewhat basic. In reviewing the project model used to develop the simulation results of this chapter, one can find two far simpler reasons for the lack of such fluctuations in the manpower chart. First, the problem of voluntary engineering turnover has been neglected. When engineers quit and leave the company (or are vitally needed on another job), their movements show up in the manpower

curve. Secondly, the curves plotted for most real projects are those of direct applied engineering effort. Such curves exclude engineers who are absent from work due to sickness, holidays, vacations, or other personal reasons.

To test the effects of such realistic causes of short-term fluctuations on the job a new project simulation was run in which a single change was made in the model. Previously a constant average figure of 11.5 percent was subtracted from the engineering force to determine those actually at work on the project. This took into account some of the results of a study made several years ago by the author in a General Electric Company engineering organization, in which for budgeting purposes various causes of engineering overhead expenses had to be examined.<sup>1</sup> In the new run the average monthly figures which made up this result were used instead. In each month of the new run the engineers actually at work were found by taking into account the expected average monthly absenteeism figure and selecting from a normal statistical distribution about this average.<sup>2</sup>

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<sup>1</sup>Edward B. Roberts, "The Digital Computer as an Element of a Financial Control System" (unpublished Master of Science thesis, Massachusetts Institute of Technology, June 1958), pp. A1-27, 28.

<sup>2</sup>To accomplish this, the equation for P<sub>WAW</sub>, Percent Workers Actually at Work, was changed from:

$$P_{WAW} = 1 - AVABS$$
 Equation 5-66, N  
where AVABS equalled the AVERAGE ABSenteeism of 11.5%. The new equations are:

$P_{WAW}.K = 1 - TABS.K$	8-1, A
$TABS.K = HABS*1.K + AABS.K$	8-2, A
$HABS = BOXCYC(12,1)$	8-3, B
$HABS* = 0.046/.046/0/.046/.046/0/.046/0/.046/.046/$ $.092/.046$	C
$AABS.K = NORMRN(AABS*1.K, STDEV.K)$	8-5, A
$STDEV.K = (0.25)(AABS*1.K)$	8.6, A

This sole change in procedure was used to produce the project history shown in Figure 8-4. Now in addition to the other variables shown earlier, there appears the curve of actual engineers working on the job. This in fact by itself does produce the kind of applied manpower fluctuations usually attributed to research and development projects, and thus satisfies our needed "realism". But the realism, or at least its appearance, is about the only thing that is changed. The basic phenomena of value, cost, and accomplishment are unaltered by the added random effects. This is as one should reasonably expect. The underlying concepts and mechanisms that bring about the life cycle of a research and development project do not respond to superficial changes that satisfy superficial observation of project behavior. Since these added fluctuations then serve only to slightly mask the basic changes taking place in the project,

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where:

PWAW--Percent Workers Actually at Work (percent)  
 TABS--Total Absenteeism (percent)  
 HABS--Holiday Absenteeism (percent)  
 AABSN--Additional Absenteeism, Normally (percent)  
 AABS--Additional Absenteeism (percent)  
 STDEV--Standard Deviation (percent)

These new equations say that the decimal percentage of workers actually working is 1 minus the percentage absent (Eq. 8-1). Those absent are the sum of absentees due to holidays and those due to other reasons (Eq. 8-2). The percent of a month's normal work days which are omitted due to a scheduled holiday is listed in the set of 12 DYNAMO locations, one for each month, designated by the HABS equation, with the values shown in the HABS\* table of constants. The HABS equation specifies to DYNAMO that the table values should be shifted around each month, so that the holiday absenteeism for the current month will always be in the computer location designated HABS\*1. The same type of thing is done for the normal absenteeism due to sickness, vacations, or any additional causes. Here, because such absenteeism is not deterministic, as are the holidays, but rather occur more randomly about some shifting monthly average, the additional absenteeism during any month (Eq. 8-5) is found by having DYNAMO select randomly from a normal distribution. This distribution has a mean shown by the average monthly additional absenteeism and a standard deviation (Eq. 8-6) that is 25 percent of the mean.





they have been omitted from the investigations discussed in Chapters 9 through 12, which reports can now be undertaken.

## CHAPTER IX

### EFFECTS OF PRODUCT DIFFERENCES ON PROJECT OUTCOMES

The product was described in the summary of Chapter 7 as having associated with it three characteristics which seemed of potential consequence in influencing the success or failure of research and development projects. These three factors were:

- (1) the basic amount of total effective work demanded by the product's size and complexity, to which we have referred as the size of the job;
- (2) society's inherent (but changing over time) need for the product, which we have called the intrinsic product value;
- and (3) the ever-changing potentiality for technical effectiveness of engineers on the project, which potential results from progress in the technology related to the product.

This chapter will report the results of experimental attempts to assess the extent of influence of each of these three characteristics. The experiments were carried out by using the high-speed electronic digital computer as a laboratory tool, operating upon the basic representation of general research and development project activities that was presented earlier. By making simple changes in the value of the particular characteristic under investigation and then producing new simulated project life cycles, we can readily isolate and identify the effects of each variable separately on the ultimate outcomes of research and development projects.

#### Job Size Variations

Variations in the basic size and complexity of a research and development job are found in all areas of technology where different

scopes of the same general need are encountered. For example, the development of a new rocket engine may be a more-or-less difficult job, depending on the state of technology, but the exact magnitude of the task will vary if the mission is to hurl a thirty-pound satellite into orbit instead of a three-ton spacecraft. Similarly, two computers could be developed to perform the same functions, but the research and development effort needed to house the computer in a one-cubic-foot box would differ greatly from the effort required to put the same product into room-size dimensions. Development of a new material that can withstand 3,000° Fahrenheit temperatures is an R and D project that is plausible, and it would require far less effective work than a project which sought a material which in addition could withstand temperatures approaching absolute zero. Thus in any area of current research and development activity, a given project can be increased or decreased in the needed amount of effort by merely shifting some of the end-product specifications.

Important questions to ask, then, are, "What is the effect on the project outcome of such specification changes? To what extent does a change in mission requirements that is bound to create a change in engineering man-months demanded really change the likelihood of project success or failure?" In order to get answers to this type of question, a series of computer studies were made, using the same model that produced the typical project life-cycle

discussed in Chapter 8.<sup>1</sup> In different runs the input parameter which designated the intrinsic job size (NLKP) was changed, with all other factors being left unchanged. The results then picture the over-all effects of this single aspect of an R and D project: the basic requirement for total effective effort on the job. Some of these results are pictured in Figure 9-1, in which three different curves have been plotted. In all three, we note a sizable variation in the resultant variables as the intrinsic job size changes.

The date of project completion, for example, occurred during month 81 of the simulation for the smallest job studied and was not reached until month 114 for the largest job actually completed. Perhaps more interesting is the fact that although simulation studies were made for projects with input effective effort requirements ranging up to 1,500 effective man-years of engineering work, no job that required more than 1,200 man-years reached completion. All jobs larger than that amount were cancelled by the customer after only part of the work had been done. Another interesting feature of the completion date curve is its nonlinearity. The smallest job shown had a simulation life span of more than six years, which takes into account the long embryonic phase described in Chapter 8. But this life span, and more significantly, the elapsed time of any concentration of engineering effort, did not increase in proportion to the size of the task. Doubling the

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<sup>1</sup>The only change in the model parameters was in the value for TEI, the Training Efficiency Index. Whereas this was defined initially equal to 1, it was set equal to 2.5 for all of the runs which investigated job size effects. The importance of changes in the TEI value itself will be described in Chapter 12.

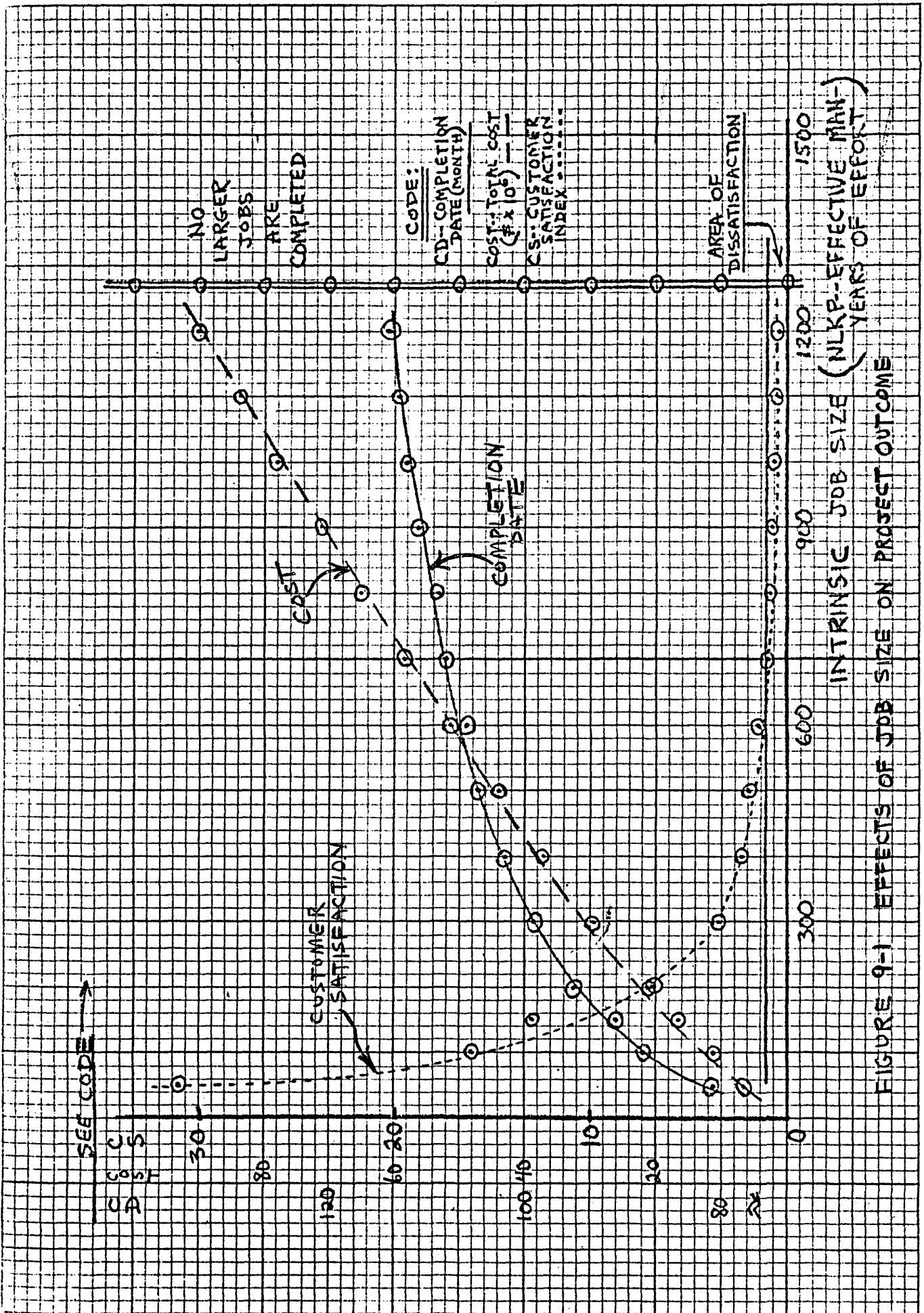


FIGURE 9-1 EFFECTS OF JOB SIZE ON PROJECT OUTCOME

basic job size from the smallest one considered of 50 man-years to the next simulated job size of 100 man-years added only about seven months to the project life cycle. Further size increases had still less than proportionate effects, and eventually a saturation effect seemed to dominate the time of completion, with the last four completed jobs all falling within three months of the same completion date. These figures emphasize the lengthy startup time encountered in research and development undertakings. This startup takes into account not only the obvious initial delays in processing funding requests and allocating support by the customer, or even the sometimes not so obvious delays needed to recruit, train, organize, and make productive the engineering team of the firm. It also includes the usually lengthy time from the first signs of a positive intrinsic product value to the time that R and D companies and customers begin to take note of these product possibilities and later to take their initial actions towards bringing the potential product into being.

Beyond the intrinsic size of 1,200 effective man-years, the completion date curve has a very sharp discontinuity (not pictured), at least conceptually, since larger jobs never reached completion. Such obvious departure from the asymptotic completion-date behavior cited above clearly indicates the influence of some factor other than job size. This factor must relate to the customer's willingness to allow (or rather his financial encouragement to achieve), project completion. Since the work is for the customer's use and is largely financed by his funds, the customer's decision to with-

draw support usually leads quickly to the halting of any further job progress. Remembering our discussion in earlier chapters of the customer's project evaluation practices, let us now look at the factors of direct consequence to this decision-maker.

Perhaps first among these factors is the cost of getting the project accomplished. This curve, too, has been drawn in Figure 9-1 for the range of jobs which were finished by the R and D firm. As the basic size of the job increased, the total cost of the project also increased. Despite some slight nonlinearities in the relative costs shown for the smaller jobs, by and large the total project costs increased in direct proportion to the basic size of the task undertaken. Although really comparative figures of this nature are currently impossible to obtain from industry, our intuition initially would very likely have led us to a different conclusion, leaning more towards costs which increase at a rate more rapid than the job size. A result of this nature leads to careful re-evaluation of the basic equations of the model, and in our particular case toward an attempt at increased realism in the formulation. However, as we shall see in Chapter 12, in which the formulation has been adjusted, the basic results pictured here (cost increases linearly related to job size changes) are not affected by the later model modifications.

The other influence on the customer's project evaluation that is of equal importance to the cost aspect is the perceived worth, value, or usefulness of the project results. In this series of runs,



the same input curve of intrinsic product value was used for all the simulated jobs of different sizes. Some may argue that there is an inherent correlation between the magnitude of an R and D project and the potential value to be derived from it. But this argument has only superficial validity and, coincidental relationships to the contrary, there is no causal or intrinsic mechanism that links the cost of a job to the utility of that job. To demonstrate, let us take the extreme of the Congressional "pork-barrel" project, defined as such since all observers feel the project to be just a waste of government funds to produce not a worthwhile end-product but merely the easing of politically-motivated pressures. Here the basic cost of the job might intrinsically be related to the significance of the politician, but certainly not to the societal value of the project. To be sure, it is often coincidentally true that a project inherently requiring greater effort also inherently has greater value. But these cost and value changes are seldom of the same magnitude. As example, the IBM 7090 computer has operating speeds about five times as fast as the predecessor IBM 709 computer. One reasonable measure of the computer's value might well be the number of computations that can be carried out per unit time, and in these terms the 7090 value is about five times as great as the 709. But the typical rental cost of the newer machine is only slightly, far less than twice, greater than that of the older version. Thus, while both the intrinsic value and production costs of these two pieces of equipment moved in the same general direction, there is no correlation

between their respective magnitudes. For our purposes, then, we have chosen to hold the product value curve the same for all project life cycles, while we have varied the inherent job size inputs. This allows us to temporarily segregate the effect of cost change on a project, and we can soon examine the alternative approach.

Now let us recognize the obvious outcome of increasing the total effective effort needed on a job, while the value of the results are unaffected by this increased effort. The larger job, as we discussed above, costs more money, but in our studies is worth no more to the customer. Thus, the cost-value relationships of the projects decrease as the cost rises. More significantly, the larger job takes longer to complete. But the basic nature of the intrinsic value curve, or of the perceived product value curve as discussed in the preceding chapter, is one of initial rise and later decline as the need for the product eventually diminishes. The job which is finished at a later date is perceived by its customer as being of decreased value. Thus, as projects increase in basic size and complexity, three tendencies exist: (1) increased cost; (2) later date of completion; and (3) decreased utility when finally available. These characteristics create the forces which lead to substantially decreased customer satisfaction and cancellation of the larger projects (in our case, requirements greater than 1,200 man-years of effective engineering effort).

As the third curve in Figure 9-1, we have plotted one such measure of customer satisfaction--the ratio of the customer's perception of product value (when he felt the job was finally complete)

to the customer's total project cost.<sup>2</sup> The customer satisfaction is obviously greatest for a project perceived to be still very worthwhile when it becomes available for the customer's use, particularly when the customer's cost to acquire the product is low. The customer is dissatisfied when he feels that the project "cost more than it was worth". This satisfaction measure is equivalent to an after-the-fact determination of return on the customer's investment. The strongly nonlinear curve of customer satisfaction realistically portrays the rapid decline in enthusiasm which takes place in any given project as costs climb and delivery date gets prolonged. Beyond a point (occurring in our typical project at input requirements of 700 man-years of effective effort) the customer feels strong dissatisfaction which results from his having spent more than he afterwards felt was justified by the benefits achieved.

For every one of these simulated projects the customer used the same initial investment criterion which sought a desired return on investment. The 500 man-year project was the largest to satisfy this initial goal at the time of completion. The 700 man-year job just broke even in the sense of returning to the customer benefits which he perceived (at zero rate of return) to equal his

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<sup>2</sup> The satisfaction value for each project simulation was found by computing the ratio,  $LRPVC.K/TECC.K$ , at the time that the customer recognized that the project had been completed. LRPVC represents the Level of Recognized current Product Value at the Customer (dollars) and TECC is the Total Engineering Costs to the Customer (dollars).

project costs. All larger jobs were less satisfactory, producing negative return on project investment. Obviously, we have no measure of value to the customer of the projects which were never completed and hence were never of significant use to him. The phenomena pictured in this satisfaction curve in part explain why so many large military R and D projects were deemed "obsolete" when finally completed, and never entered large-scale production and usage. The use value remaining in the product when it finally became available was so small, and the over-all disenchantment by the customer was so great (due to the poor value-cost outcome), that dissatisfaction with the project prevented the customer from, as he would probably justify it, throwing away more funds on the project.

#### Product Value Variations

During the preceding discussion of the effects of changes in basic size of a research and development project on the outcomes of the project, we had of course to recognize the interdependence of both cost and value changes on R and D decisions and results. We come now to examine more directly the effects of different intrinsic product value situations upon project life histories. In other words, we seek more information at this point regarding distinctions between projects of the same degree of technical difficulty but of differing degrees of worth to society. Differences in the real value of a product to society arise out of differences in the goals, needs, and problems of the society. For example,

in the absence of the constant potentiality for military conflict in the world, how would the real value of most of our military technology be changed?<sup>3</sup> Under various goal-need-problem environments, certainly some R and D projects would receive different treatment.

In trying to investigate this problem, we suddenly recognize the much greater degree of complexity involved in our concept of intrinsic product value than is present in the notion of intrinsic job size. The basic size of a job has but one dimension of variation--it is larger or smaller, more complex or less. Consequently, we were able to thoroughly explore the effects of job size variations on project behavior. But intrinsic product value is a concept describing the changes in real worth of a product as time evolves. This cannot only change up or down, but its life span can be expanded or contracted and its shape modified in a myriad of ways. In other words, we no longer have one dimension of change as we had with job size. We have the possible combination of this type of change for every one of the infinite number of points along our intrinsic product value curve. We shall therefore not even attempt a wide array of variations, in hopes of bounding this infini-

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<sup>3</sup> A good case could be made that our entire defense program can be justified solely on the basis of the economic and technological by-products of its existence, but this would be an argument as to the indirect value of the effort and not the direct value of the intended product resulting from the effort. Many see today in the goals and management of the N.A.S.A. space program a mixture of the direct with these formerly indirect results as part of the primary intended program purpose.

tude of possibilities, but rather shall examine only two possibilities: (1) the comparative effects of two input curves, one everywhere higher than the other by the same degree; and (2) the results of decreasing the time period of maximum worth of a potential product. Any other type of value curve variation can readily be examined by the curious reader through simple use of the simulation laboratory. For this particular study the additional effort required for these inquiries does not seem justified.

In the first set of runs, all modeled project characteristics were exactly the same as those used for testing the size of job variations, except that the intrinsic product value curve was reduced throughout by 50%. The figure below shows the initial product value input with its newer, halved-value, counterpart. These

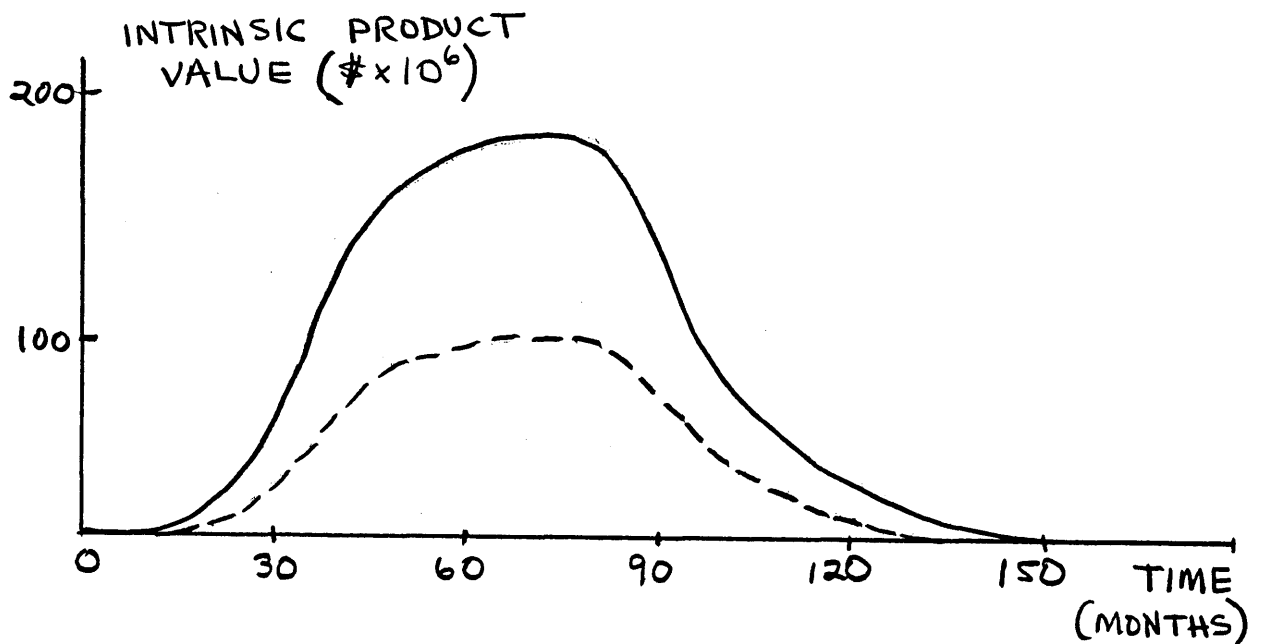


Figure 9-2 Original and Halved Product Value Inputs

runs will then demonstrate what would happen to a product development cycle if the outcome were just as hard to achieve but worth only half as much. On the next page, the completion date, cost, and customer satisfaction for this series are superimposed upon the corresponding segments from the original results (Figure 9-1). Some of the results are obviously expected ones. For example, given the lowered intrinsic value for the new project simulations, it is obvious that customer satisfaction for each completed project would be lowered. The difficulty of doing the job was unchanged but the resultant value decreased. Hence, the customer's perceived value return on his investment is diminished.

It is no doubt obvious that the cut-off point in the size of the projects which would be completed is also reduced as the value input is decreased. The customer can no longer justify some of the larger jobs on the basis of his given value-cost ratio investment criterion, and more jobs are cancelled sooner than before. The cut-off job size of 700 effective man-years is a small amount greater than half the previous cut-off size of 1,200 man-months, despite the halving of the product value input. This small nonlinearity is caused by the fact that in both series of projects a great margin exists between the perceived value-cost ratio and the customer's desired investment criterion ratio during the middle phases of the project life cycle. Thus a large number of projects are started. However, as the perceived value begins to decline, the value-cost ratio becomes more marginal. For the lowered value input simulations,

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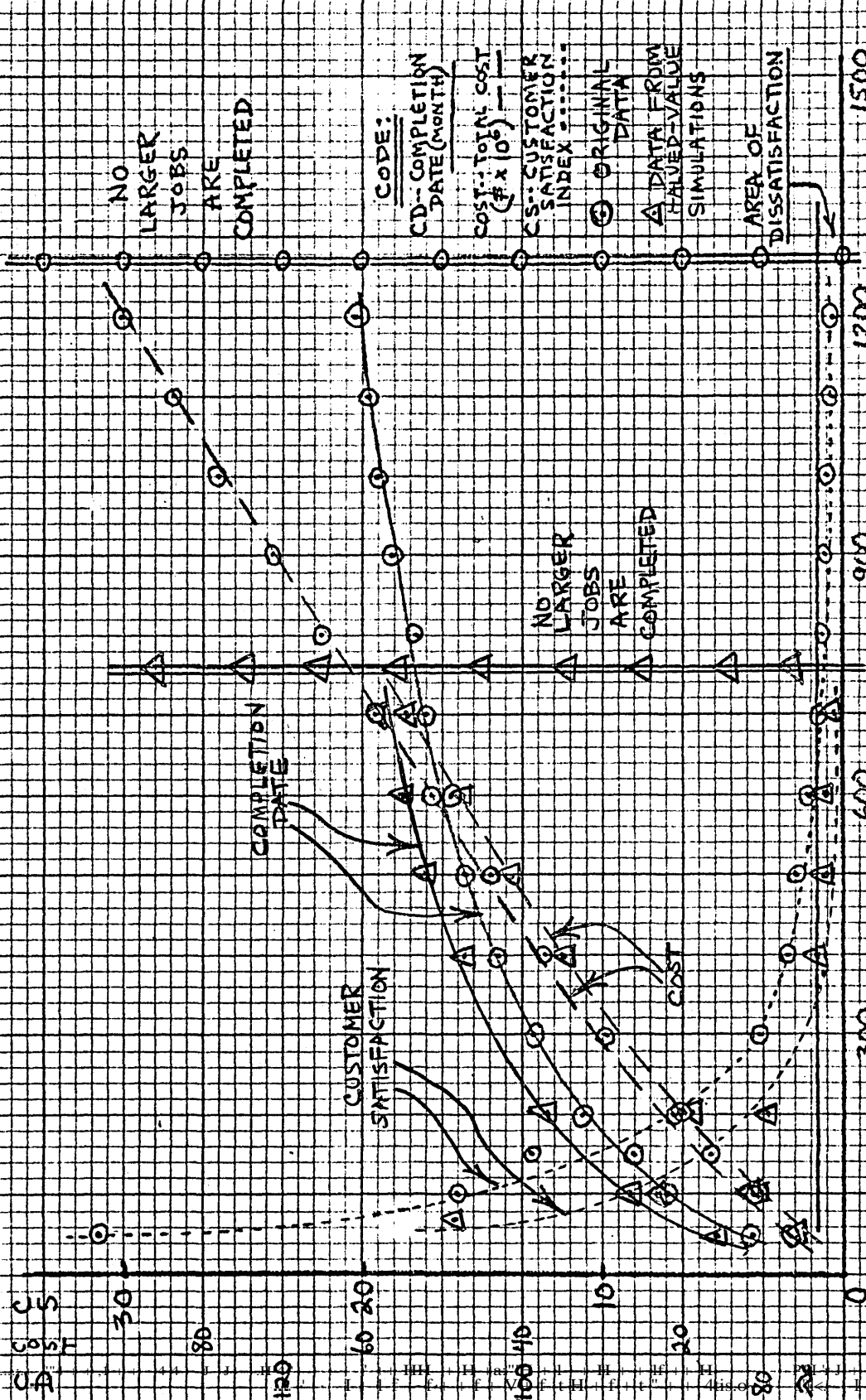


FIGURE 7-3 EFFECTS OF GENERAL LEVEL OF PRODUCT VALUE (INTRINSIC JOB SIZE (NLKP-EFFECTIVE MAN-YEARS OF EFFORT))



this value-cost factor becomes critical sooner than in the original studies; and hence several additional then incompletd jobs get cancelled. But the timing of this critical stage is not inherently tied to the completion-date curve and though more jobs are cut off, they do not quite constitute 50% more.

Some perhaps even less expected results are also found here, which results point up other facets of R and D management problems. On the new series of simulated projects, the date of completion always occurs at a later time than in the earlier runs, contributing to still lower final satisfaction by the customer. This results from the longer time needed initially before the firm and the customer become enthusiastic enough about the project possibilities that they are willing to provide funds for its support. Thus, the project which is inherently less valuable requires more time before it gets underway; and consequently is completed at a later stage of its declining value phase. Also somewhat different are the costs to develop the end products, being definitely but only slightly lower for the new product simulations. This is also caused by the decreased initial enthusiasm which slightly delays the R and D engineering schedule. Consequently, the engineers working on the project are able to take added advantage of the technological changes that are ever occurring in our simulated environment. This produces an increasing degree of engineering effectiveness and hence a decrease in project costs. To be sure this cost change is perhaps inconsequential in magnitude, but its presence

helps us to recognize the interdependency of various forces, changing over time, on project success or failure. The influence of technological progress on research and development results will be more specifically investigated in the last phase of this chapter.

Before going on to this exploration of the effects of changing state of the technological art, let us examine one more type of variation in the intrinsic product value input. Here we shall see the effects of changing the time shape of the product-value curve to reflect primarily a decreased period of maximum real value of the end product. Our initial value input and the changed curve are pictured in Figure 9-4. The change is really a small one. The new curve follows the original up to its peak value, but remains at that peak for one year less, and then follows the original curve's decline, but a year in advance of the original.

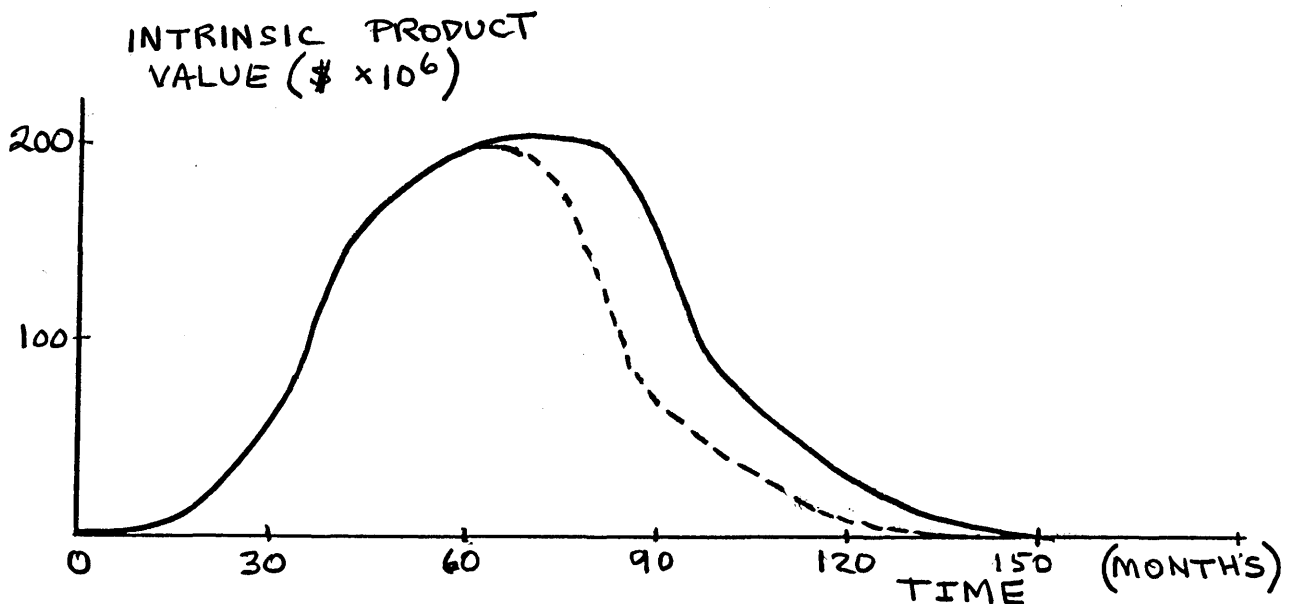


Figure 9-4 Original and Shorter-Duration Product Value Inputs

But its consequences are far more noticeable than the change itself. As shown in Figure 9-5 the shorter duration of maximum product value and the earlier decline of this value result in fewer of the large projects being completed. Here the cut-off job size has changed from the original 1,200 man-years of effective effort required to 800 man-years. In this case, the earlier decline of real value is, after the usual delay, felt by both customer and firm. This produces less time for a bandwagon-effect buildup in estimated future product value and the resulting earlier decay of product value expectations. As was mentioned in the discussion of the halved-value simulations, the customer's decision to cancel a project depends on the timing of the critical perceived value-cost ratio. If perceived value falls sooner, and from a lower height, then the project suitability for customer investment diminishes more rapidly in the customer's opinion. Project cancellation therefore occurs more often or sooner than in the original studies.

Since the initial phase of product-value growth was the same for the new runs as in the original investigation, the projects get started at about the same time and utilize the same basic available technology. Thus, the curves show no distinctions in date of completion or cost for those jobs which did get finished under these new conditions. The only exceptions are for the largest jobs to get done under both situations, since they become more questionable under the new value input and suffer some stretch-out of project scheduling prior to eventual completion. For all of these projects, however,

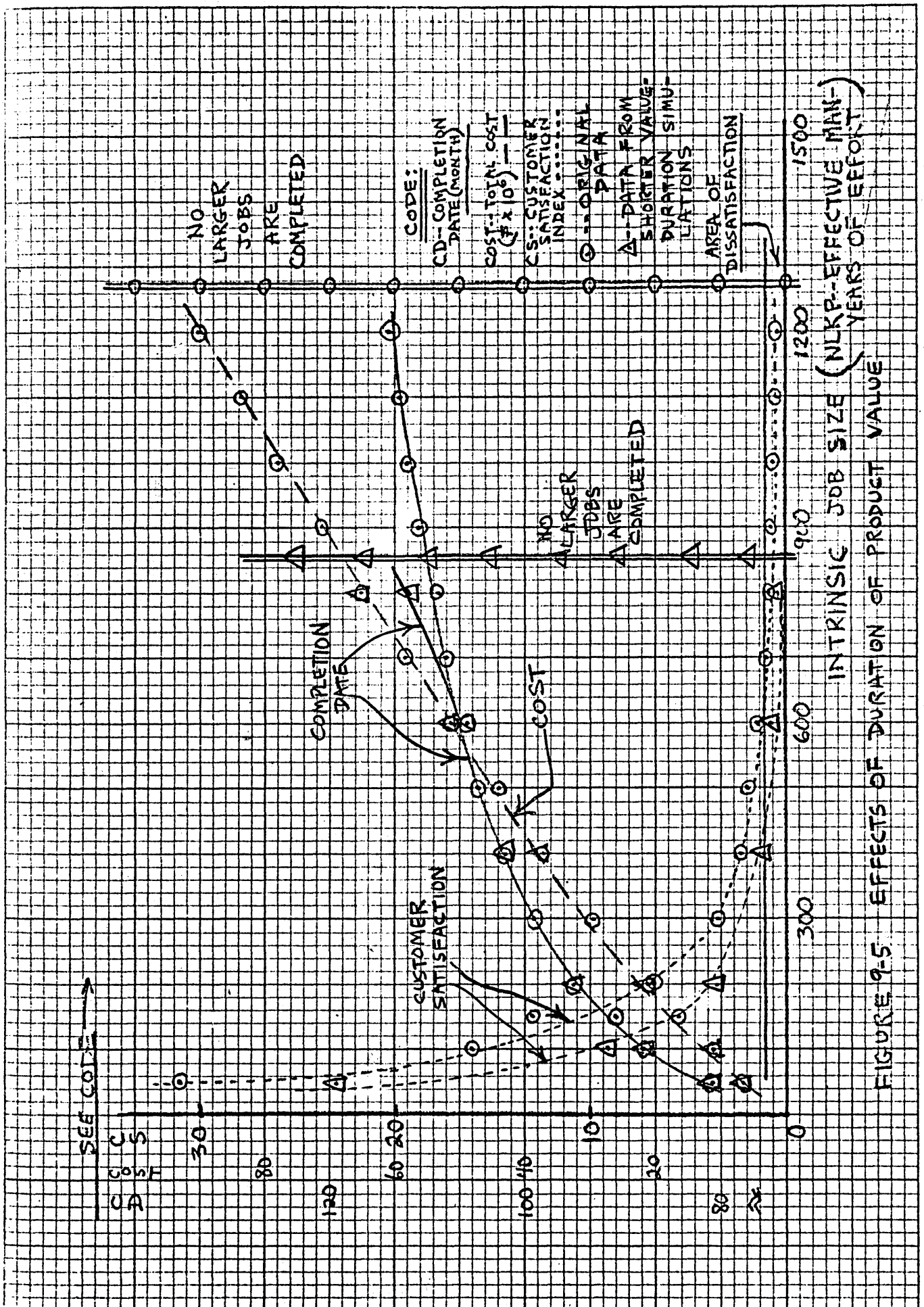


FIGURE 9-5 EFFECTS OF DURATION OF PRODUCT VALUE

the customer's satisfaction is lower than in the original case. This is due to the fact that the projects are all being completed during the declining value phase of the life cycle. Under the new test situation, the real value has declined further at these times of completion than in the original tests, and the customer's perceived value has decreased still further. Thus, the customer's satisfaction with the end product is also reduced for all the jobs completed.

Other types of value changes could be tested to demonstrate the significance of this factor on project outcomes. They would perhaps be of interest but could never be inclusive of all possible changes. Primarily, they would point out three factors, as these above experiments have already shown: (1) the consequences of changes in the intrinsic product value inputs are far more significant than the degree of change itself; (2) these results are largely dependent on the time changes of the perceived cost-value relationship, and not on either factor alone; and (3) changes in value input produce secondary effects in such things as completion dates and project costs due to direct influence of the value changes on overall project scheduling.

#### Product Technology Variations

Let us now go on to examine the effects of the third and final factor cited in Chapter 7 as a product-related key determinant of project behavior. This determinant is the technology related to the project undertaking, which we have identified in various places

as the state-of-the-art, the degree of technical effectiveness, or quite often as the extent of technological progress. In any project requiring several years from time of initial perception until the final job completion, changes in the basic technology available to the engineers can certainly have an effect on project outcome. The question of relevance is not the existence of the influence, but rather the degree of influence. How sensitive is the determination of a project's success to the particular rate of technological growth that is occurring during the project's life cycle? To provide some clues to this question, three runs were made on the same basic task for various technical progress curves. The job size used for all runs was 6,000 man-months of effective engineering effort.<sup>4</sup> The three input curves used to represent the changing state of the art are shown below.

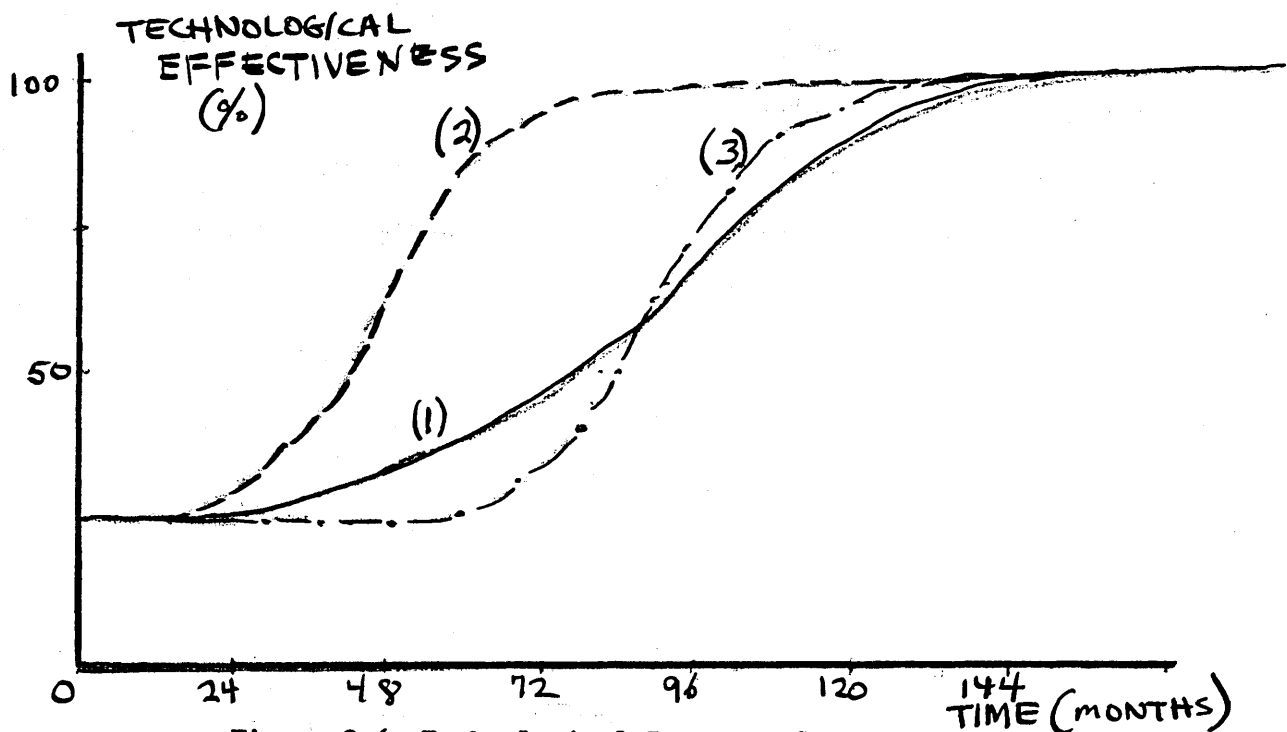


Figure 9-6 Technological Progress Curves

<sup>4</sup> The basic model parameters were all exactly the same as those used for the runs cited earlier in this chapter, except that TEI, the Training Efficiency Index, was restored to its original value of 1.

The curve numbered (1) was used in all of the simulation studies discussed earlier in this chapter. Number (2) shows a more sharply rising technological progress, while number (3) is delayed for a longer period before its technical growth begins.

The cost, date of completion, and customer satisfaction for each simulated project appears in the table below. Project 2 is clearly superior to the other two projects on all bases of comparison. Its completion occurs seven months prior to that of project 1 and ten months earlier than project 3. It costs 20% less

Input	Progress Characteristic	Completion Date (month)	Cost (\$x10 <sup>6</sup> )	Customer Satisfaction (%x100)
1	Original curve	130	28.9	0.7
2	More sharply rising	123	23.0	1.5
3	Delayed rise	133	27.5	0.5

TABLE 9-1 Effects of Various Technological Progress Curves

than project 1 and 16% less than project 3. Finally, and of probably greatest consequence, when we apply our previously defined measure of customer satisfaction, the ratio of the customer's perceived project value to his cost, project 2 is the only one which provides satisfaction, rather than dissatisfaction, to the customer. Both customer and firm quickly become aware of these major breakthroughs and their enthusiasm promotes an early project start. The technical advances soon become usable by the firm's engineers on the project,

greatly enhancing their effectiveness and reducing the total cost of getting the job done. With the job completed relatively early, the customer feels confident that he will be able to make worthwhile use of the end product. Thus, compared to projects 1 and 3, the customer finds in project 2 an available product of both greater worth and lower costs, and hence he is far more pleased with the project outcome.

Now turning to project 3, we find the prolonged period without technological change kept the customer and firm from moving into the project with any significant effort initially. The small and continuing effort over the longer duration did, however, produce some cost accumulation during this period of low engineering effectiveness. The technological change which then occurred produced a sufficient modification in the project cost estimates that full-scale project funding was provided and the remainder of the job was completed, taking some advantage of the more advanced state-of-the-art effectiveness. The earlier cost buildup, however, made this job more expensive than project 2. More significantly, the later scheduling of major engineering activities delayed project completion so much that its low value to the customer, when it became available, produced much customer dissatisfaction with the project.

In the original situation, project number 1, the early and steady growth of technological progress caused early entrance into the project effort. Funding was provided and engineers were employed



on the job during a period of steadily rising, but still relatively low, utilizable technical effectiveness. This lowered effectiveness produced the high total cost, while the earlier start pushed the completion date slightly ahead of that for project 3. The timing of completion was critical enough so that the resulting value-cost ratio for project 1 was somewhat better than for project 3, despite the increased cost of 1.4 million dollars.

To explore the effects of technological progress still further, four more simulated projects were studied under different sets of technical environments. For these computer runs, it was decided to hold the state of the art constant for the entire life cycle, thus disallowing any external improvement in potential engineering effectiveness. The runs were made holding the level of available technological effectiveness steady at 25, 50, 75, and 100 percent, respectively. Taking the first figure as an example, this means that each fully-experienced engineer will produce 0.25 effective man-months of effort for each man-month he actually works. The intrinsic job size for these simulated projects is the same as was used before, namely 500 effective man-years of effort. These two facts imply that 2,000 actual engineering man-years would be needed to complete the job if all the employees were fully experienced and fully employed on engineering work. Of course, most of the engineers would have to be brought into the project organization requiring training or indoctrination for their jobs, and would thus be less effective for the duration of this entry period. In addition,

other engineers would be unable to fully devote themselves to engineering tasks and thus their contributions, in terms of directly produced effective engineering output, would also be reduced. Even disregarding these added inefficiencies, the 2,000 man-years needed would cost (at about \$30,000 per man-year of engineering) about \$60 million.

Despite the fact that both the firm and the customer do eventually perceive the future value of the product as far greater than this base cost of \$60 million, the period of favorable perceived value-cost ratio is rather short. It is not surprising, therefore, for the project simulated with technical effectiveness at 25%, that it never really "got off the ground"; and the slight amount of effort was eventually stopped after only 2.5% of the job had been completed.

The same reasons could be ventured to explain the completion of only 17.5% of the project for the case of 50% technical effectiveness. However, with the base cost now at \$30 million, and the maximum value at \$200 million, it would seem that the perceived value-cost ratio should have been sufficiently encouraging to allow the project to be completed. Now we must recognize the significance of timing on whether a project gets completed or not. If very early in the product value life cycle, the cost is expected to be low enough to produce a favorable value-cost ratio (given the customer's investment criterion), then the project will be funded and it is likely to be completed. If the favorable value-cost relationship is not perceived until much later, then it is likely that

this relationship will become unfavorable before the project has a chance to be completed. For the project situation in which related technology is at a standstill, neither the customer nor the firm are apt to be moved towards early enthusiasm about the project prospects. This is what happened in the case now being explained. In the more usual situation of rising technological progress, the changes create influences upon the cost estimations of both customer and firm. They expect further progress and lowered costs, and enter a project based at least to some extent on expectations that a favorable value-cost relationship will occur in the near future. The possibility of such extrapolation is lacking in the case of no changes in the state of the art.

In the final two cases, technical effectiveness at 75 and 100 percent, respectively, the over-all lowered costs are sufficiently attractive that expected further lowering of costs is no longer necessary to produce a worthwhile investment opportunity. The former case would require an expenditure of \$20 million if every engineer could always work at the full available technical capacity of 75 percent effectiveness. The actual cost to complete the project was \$33.8 million, the additional 69% needed to pay for the training and supervisory costs. Thus, the cost to build and run a research and development organization is quite sizable, even when compared to the direct cost of performing the basic effort requirement of a project. This project was completed at month 121, and became available to the customer at exactly his

"break-even" satisfaction value of 1; the customer's perceived product value just equaled his total project expenditures. In the final project, the optimum cost would have been \$15 million, but the costs actually amounted to \$25.3 million, again approximately a 69% surcharge to pay for the lowered effectiveness due to manpower development and supervision. The job was completed at month 115, and the higher value then perceived combined with the lowered project costs to produce a customer satisfaction measure of 1.8, quite close to the desired value of 2, the customer's initial investment criterion level.

All of the results are summarized in the following table.

Technical Effectiveness (percent)	Cost (\$x10 <sup>6</sup> )	Completion Status	Customer Satisfaction Index
25	2.9	2.5%	-----
50	10.5	17.5%	-----
75	33.8	100% at month 121	1.0
100	25.3	100% at month 115	1.8

TABLE 9-2 Effects of Various Levels of Constant Technology

This series of runs has helped us recognize the important influence of technological progress, not only on the real effectiveness of engineers but also on the perceptions of expected project costs and on the investment decisions depending on those perceptions. Without progress occurring, the basis for a projected lowering of

of costs is missing. With it goes one of the important influences helping to get projects underway early enough to end in successful (and satisfactory) completion. Our simulated projects showed that for an unchanging state of the art only the most favorable value-cost situations will be successfully developed into a completed end product, satisfactory to the customer. These studies also helped separate the contributions to engineering effectiveness caused by enhanced technology from those caused by the engineer's own development and effort allocation. The cost in both completed projects to bring new engineers up to full competence level (this cost being divided between the higher dollars/effective-effort-output paid to new engineers and the needed supervisory costs) amount to 69% as an addition to what the project would optimally have cost. Any managerial activities that could increase the effectiveness of new engineers without expending too much effort by the fully-experienced staff can thus greatly reduce total project expenses.

## CHAPTER X

### THE FIRM'S INFLUENCE UPON PROJECT SUCCESS

The effects of product characteristics on the outcome of research and development projects, as described in Chapter IX, can certainly be recognized as significant. But R and D managers, both in government and industry, too often attempt to blame the problems of research and development upon product-related influences. In this chapter we shall demonstrate that factors and policies, related to or determined by research and development firms, are themselves significant in determining the success or failure of project undertakings.

#### The Quality of the Firm

The first company factor cited in the Chapter VII listing of key determinants of project behavior was the over-all quality or capability of the firm's management and engineers. The influence of this characteristic is all-pervasive in the typical project. The quality of the firm affects the accuracy of the estimates of project value and cost; it dominates engineering output rate through its influence upon the effective organization of work and on the technical decisions made in the project; it is a factor of consequence in every delay in recognizing and responding to changes in technology, funding requirements, project milestones, and engineering effectiveness; and finally, the quality of the firm's managerial and engineering personnel produces whatever effectiveness exists in the firm's policies for recruitment, training, and transfer of engineering personnel.

Does this characteristic appear to be so critical in our simulated projects? The first tests to be shown certainly lend evidence to this belief, as is illustrated in Figure 10-1. Using the basic model of a research and development project that evolved in the first seven chapters of this document, the parameter descriptive of the firm's general qualifications (QF) was changed in several simulations over the range from 30 to 100 percent effectiveness. (As a reminder, quality is used in the model in a multitude of ways: for example, 100 percent quality indicates that no harmful managerial effects exist on the basic engineering productivity; 100 percent quality also indicates that the natural initial error in the job size estimation is entirely wiped out. These examples demonstrate the kinds, and at least the direction, of effects of the quality factor.) The figure discloses that only with quality equal to or in excess of 90 percent was the project task actually completed. The other projects were halted woefully short of completing the product development. Not only does the lowered quality prevent the job accomplishment, it also increases the costs of the job by an enormous percentage. Although extrapolation of partial completion data provides a questionable basis for drawing any strong conclusions, examining the extrapolated total project costs is admittedly an interesting exercise. As an example, with a measure of 30 percent quality of the firm, 11 percent of the job cost 14.3 million dollars. The same cost rate produces an extrapolated total project cost of 130 million dollars, an amount four and one-half times as great as the actual project cost under maximum effectiveness.

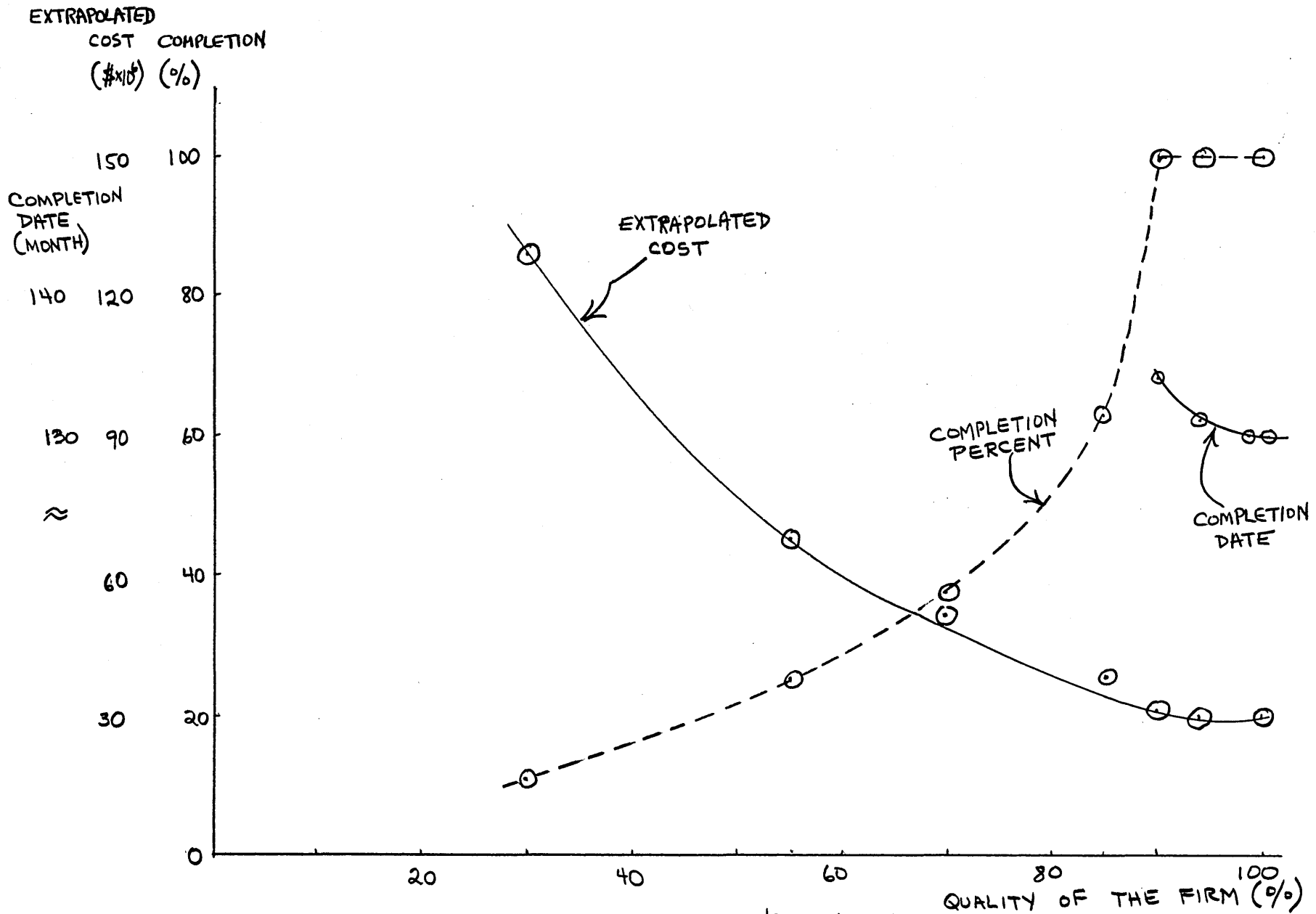


FIGURE 10-1 INFLUENCE OF THE FIRM'S QUALITY



Similarly, the 70 percent quality situation produces an extrapolated result of about 51 million dollars, about a 75 percent cost increase over the 29 million-dollar actual figure created by only a 30 percent decline in over-all ability.

These results attest to the unique sensitivity of project success to the basic capability of the R and D firm. Not only do relatively small changes (relative, that is, to the degree of change examined for other key determinants of project behavior) in the firm's quality produce drastically amplified effects, but in addition this amplification increases nonlinearly as the firm's ability declines.

But let us go on to more specific manifestations of the firm's general qualifications. The capability of the firm's management and engineers probably reflects itself very readily in the extent to which they are aware and can take advantage of new changes in the state-of-the-art. Management influences this by its relative wisdom in motivating the technical staff to keep abreast of new developments through conferences, professional activities, and university courses. The engineers' capability enters in their trying to read the numerous and complex technical journals, absorb the new information, recognize its applicability to their current problems, and actually apply the newer approaches and ideas to the project. The direct effects of an increased quality of the firm, in this regard, would then be in the role of decreasing the average delay in transforming the improved potential inherent in the state-of-the-art into engineering effectiveness actually utilized on the job.

This factor, too, shows up in the simulated studies as being of some importance. Table 10-1 documents the results for delays indicating

Delay in Acquiring and Absorbing New Technology (months)	Project Cost (\$x10 <sup>6</sup> )	Completion Status
96	22.8	only 43% completed
48	34.6	100% at month 147
24	27.7	100% at month 129
12	24.9	100% at month 127
6	23.6	100% at month 126

Table 10-1. Influence of the Delay in Utilizing  
the State-of-the-Art

a wide span of firm quality. Again, the lowest quality indicated, the delay of ninety-six months or eight years in finding out about and being able to use new technical advances, results in the highest potential project cost and the latest potential completion date, the potential indicating that that project was never completed.

For the other delay values, costs decline and completion date draws closer as this quality indicator (the shortness of the delay) improves. From the discussions of the preceding chapter, we can immediately recognize that the effect of these two facts in combination is to increase the customer's satisfaction with the project outcome as the company's ability increases.

It is certainly true that we could readily examine the effects of changes in many other aspects of our research and development activities, all of which might provide some additional insight into

the very consequential relationship between the over-all quality of the firm and project success. However, there are many other characteristics of the firm still remaining for our exploration, and continuation of the present line of inquiry could soon become marginal in terms both of our own interests and of the new information that would thereby be derived. Let us conclude this section by citing just one investigation in which we pushed to an extreme, impossible in practice but available to us through our simulation laboratory. In every information flow there is some delay, if only the time for an electromagnetic signal to cross a small but finite distance. Given this, we recognized the relevance of asking: "What would happen if all delays in receiving information--as to value, cost, technology, progress, etc.--were reduced to the minimum possible value?" This would represent one kind of maximum-maximorum of quality firms, and is of interest to examine. Several characteristics of this simulated project are listed below, with the corresponding results from our basic study presented for comparison. It may be surprising at first to see that all project measures presented

<u>Delays in Recognition</u>	<u>Peak Engineering Force (men)</u>	<u>Project Cost (\$x10<sup>6</sup>)</u>	<u>Completion Date (months)</u>	<u>Customer Satisfaction Index</u>
Normal	541	28.9	130	0.7
Reduced→0	702	33.6	112	1.25

Table 10-2. Comparison of Pseudo-Omniscient Firm to Basic Case

do not favor the pseudo-omniscient firm. Although its project was completed a full year and a half in advance of the normal case, the project cost 16 percent more. This perhaps is a reasonable trade-off of usage time versus the customer's money. However, the stability of the work force was substantially reduced in the quickened project, 30 percent more engineers being acquired at the peak of activity, therefore indicating 30 percent more engineers requiring eventual transfer from the project or possibly the firm. The advisability of this trade-off is not so clearly indicated by our comparative data. Finally, the customer was in fact, although barely, satisfied with the omniscient's project outcome, whereas he was dissatisfied, although only slightly, with the normal product result.

The key to this lack of impressiveness in the case of the special-delay project lies in three facts: (1) the quick recognition of the underlying value-cost relationship leads to a very early project start, at a time prior to the significant advance of the technological state-of-the-art; (2) despite the zero delays in recognition, the normal but substantial delays in recruiting, developing, and employing an engineering organization effectively caused project completion to occur at month 112 rather than near-instantaneously, as some might have expected; and (3) the assumption that the firm had almost immediate access to all information was accompanied by the equally plausible assumption that the customer too had product-value information readily available, and the customer's final comparison of real value to real costs turned out less striking than might have been the case if the normal value-perception delay were

utilized.

In summary, this last run shows that while increased quality of the firm can certainly have substantially amplified effects on project success, its exact influences are: (1) not very obvious; (2) limited by the constraints of getting things accomplished in a real world environment; and (3) dependent to a great extent on other factors, unrelated to the quality of the firm.

#### Willingness to Accept Risk

Let us now turn to another aspect of the firm's general characteristics which is not dependent on the over-all ability of the firm but which might also be significant in the determination of research and development project outcomes. The propensity to undertake risks, the willingness to gamble, to take a chance, to speculate, to deviate by some degree from total conservatism, are all shades of the same color. They appear in the presence of success just as they do with failure. The conservative investor in the stock market places his funds in an AT and T and sometimes is fortunate enough to find himself holding a substantial growth issue. In any event he seldom suffers much capital loss. The speculator, on the other hand, has much less of a chance of buying Litton Industries or Ramo-Wooldridge just before the boom than he does of latching on to a fly-by-night market sensation just before the bubble bursts. Of course, if the speculator can guess right often enough, he'll be a rich man.

What happens when both types of people, the conservative and the speculative, and the infinite varieties between, enter the world

of research and development as engineers, managers, or customers? Their intrinsic personality, as shown in their investment behavior, also tends to be projected onto the business. In this way a firm, and even a government agency, soon develops a reputation and a mode of action that is in one dimension a reflection of the willingness to accept risk of the people in the organization. Their attitudes toward new technologies, their basic optimism or pessimism, are all modes of expression of the same underlying phenomena. ("Which came first, the risk-propensity or the optimism?" is another chicken-or-egg question. The factors fundamentally relate, and in research and development projects they influence decisions of potential import.)

As embodied in the discussion above and in the representative project model, the firm's willingness to accept risks affects not only the relative optimism of his estimates of future product value, technological progress, and engineering effectiveness, but it also is a key determinant of how much of its funds the firm is willing to risk as an initial investment in an R and D project before it obtains substantial customer support. Let us examine some possible results of variations in this risk-taking characteristic upon a series of different size jobs, all ostensibly having the same input product-value characteristics. The chart on the next page indicates several measures of the effects of such policy variants.

Examination of this table shows up some very interesting characteristics. Both policies of risk-assumption, high and low (WARF=1 and 0.1, respectively), ended in project completion for the smallest

Intrinsic Size of Job (effective man- years of effort)	Project Outcome Measure	Risk-Taking Propensity of the Firm	
		High	Low
400	Cost (\$x10 <sup>6</sup> )	23.4	21.1
	Completion Status	100% at month 127	100% at month 138
	Profit to the Firm (\$x10 <sup>6</sup> )	2	0.7
	Customer Satisfaction Index	1.1	0.5
500	Cost (\$x10 <sup>6</sup> )	28.4	13.5
	Completion Status	100% at month 130	stopped at 38%
	Profit to the Firm (\$x10 <sup>6</sup> )	1	1
	Customer Satisfaction Index	0.7	---
600	Cost (\$x10 <sup>6</sup> )	22.4	10.7
	Completion Status	stopped at 53%	stopped at 24.3%
	Profit to the Firm (\$x10 <sup>6</sup> )	1.7	0.8
	Customer Satisfaction Index	---	---

Table 10-3. Effects of Risk-Taking Propensity of the Firm  
for Various Project Sizes

job size investigated. The more speculative firm invested more of its own funds initially, and got the project moving faster and completed much sooner. Since it worked with a slightly less effective level of technological art than did the more conservative firm, the former project cost about 10 percent more. But the former case was completed in time enough that the customer was satisfied that he had at least gotten his money's worth, and, relatively speaking, the customer was twice as pleased as with the more conservatively-managed undertaking. The conservative firm put very little of its own funds into the project initially, waiting instead until the customer provided financial support. This policy retarded project progress to the point that the customer became unhappy with the project as it neared completion and cut back on some of his support. This left the firm supporting an over-staffed engineering organization which did finally finish the job, but at a substantial cost to the firm's profits on the job.

In the case of the 500 man-year job, the contrast in ultimate effect of the two risk-propensities is much sharper. Here, the delays caused by the conservative management's unwillingness to build up its project effort in anticipation of funding produced not just customer dissatisfaction with the project results. This policy actually caused the failure to complete the job, and the complete waste of the 13.5 million dollars of customer funds already spent on the effort. Only through our simulation laboratory can such a result be pinpointed in a definite fashion, for we know that the only difference between the two simulated projects, the only possible cause of any differences in results, was the sharp distinction in the willingness to assume risk



by the two firms. This is not to say, however, that this effect exists only in simulated projects and not in the real world. To the contrary, company managements in numerous research and development project situations, both military and commercial, have often, as Monday morning quarterback, been forced to say, "If only we had started the work a little sooner, instead of stalling, we'd be sitting prettty now with two-thirds of the market (or that new large development contract)." In case readers need reminding, the aftermath of Sputnik I was a series of charges and countercharges as to who (which President or which Congress) had prevented the needed risks from being taken and the required funds from being allocated.

It is certainly not a cut-and-dried fact, however, that firms should undertake bold risks in every project contemplated. Obviously, the customer funding does not necessarily result just because the firm has advanced some of its own money into the project. The firm's own confidence in the project, as manifested by its investment, of course does actually encourage the customer's award of a project contract, but such a relationship does not uniformly hold nor could a firm feel guaranteed of customer support on any given project, just due to its own risk-taking. The non-discerning gambler, then, can go bankrupt in R and D as easily as he can in the stock market. But it is vital that all research and development management note that here is a policy area that can in some cases, through its own workings alone, change a venture from success to failure or vice versa.

From our simulation examples above, we have seen that as the projects become less cushioned in terms of their potential value-cost

relationship, the assumption of risk by the firm has greater influence on resulting project behavior. But the study in Chapter 9 of job size effects showed clearly that some projects are just too big and costly to ever be completed without a major upward revision in the value structure of the customer. The third set of projects indicated in Table 10-3 shows what happens in one of these too-large projects under both sets of extreme conditions of risk-assumption. Neither project gets completed, the conservatively-handled one going about 50 percent as far along as the other. The customer wastes more money under the high-risk project, and consequently the firm makes a higher profit due to this increased level of expenditures. It is now no longer obvious as to which risk-assumption policy is preferable. On this single project, the customer might not favor the high-risk policy which induced him to invest more in a fruitless effort. The firm, on the other hand, has to weigh the benefits of the current higher profits against the customer's perhaps increased dissatisfaction, considering the attendant future impact of such dissatisfaction on the firm's profitability. Instead of concerning ourselves with whether A or B was the better approach in this case, it suffices to recognize here that for some projects even the most speculative firm cannot by its policy alone-rescue the job from failure.

The discussion above presented evidence as to the effects of two extremes in the risk-taking of research and development companies on the results of jobs of varying degrees of intrinsic difficulty. It is of interest now to view briefly the continuum of results created by the full range of risk-taking propensities which lie between the

two earlier extremes. For the project of intrinsic job size equal to 400 effective man-years of work, with the quality of the firm set at the 75 percent level ( $QF = 0.75$ ; see discussion earlier in this chapter), the firm's willingness to assume risk was varied from the very conservative to the very speculative and the results plotted in Figure 10-2. Here we see indicated the final percentage completion of the project, and the time of completion for those which did reach fruition. Given the preceding discussion of the effects of risk-taking by the firm, the general nature of the results pictured is not surprising. As the firm assumes a higher degree of risk, a larger percentage of the job gets to be completed. Finally the point is reached (here, when the firm is willing to invest 70 percent of expected profits) where the job does get completed for all higher values of risk-propensity. It is also not strange, given the earlier discussion, that, for the completed jobs, the date the product is ready draws nearer as more risk is assumed by the firm.

What is noteworthy, perhaps, is the nonlinear rise in percent completion (particularly for  $WARF > 0.55$ ) and the nonlinear decline in the time of completion. These factors indicate that below some threshold value (different, to be sure, under various project situations) the relative effectiveness of risk-assumption is insignificant. But beyond that value, the increasingly greater undertaking of risk by the R and D firm makes much more likely the completion of the task, and at a timing which produces increased customer satisfaction. Past this threshold, the effects of the risk-policy seem highly nonlinear and can clearly spell out the difference between company success and failure,

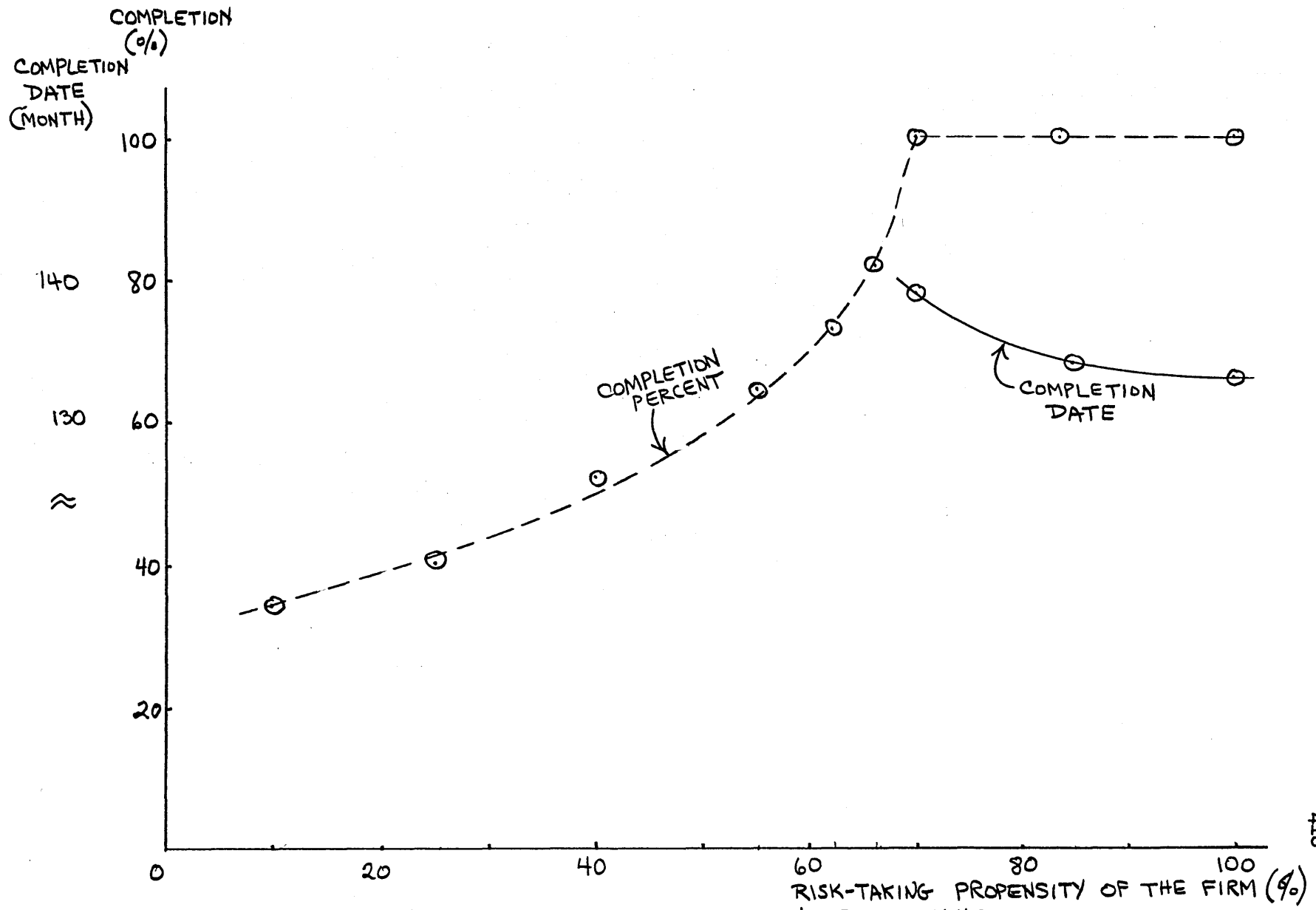


FIGURE 10-2 INFLUENCE OF THE FIRM'S RISK-TAKING

with respect to both the short-term profit situation and the longer-term business prospects that are based on satisfactory company-customer relations.

The aspects of conservatism of the firm studied thus far have been those which relate to the extent of the firm's investment in an R and D project. In considering the firm's investment criteria in the discussions in Chapters 4 and 7, we mentioned the likelihood of importance of the general rules that determined suitability of a project for investment by the firm. One such rule really relates to the conservatism of the firm. This aspect is the firm's basic optimism or pessimism regarding the customer's willingness to support the project. An over-optimistic management will expect the customer to be willing to contract for projects which even initially are marginal in their value-cost relationships, whereas the over-pessimistic firm will expect support on only those projects which have ultra-strong perceived value-cost ratios. This particular characteristic manifestation of the firm's risk-taking propensity has some, but as Table 10-4 below shows, only slight effect on the project outcome for those projects that are sufficiently cushioned in their underlying value-cost relations. The effect is more significant, potentially, for the more marginal projects also shown in Table 10-4.

In the first set of simulated jobs indicated, the project is completed in all three cases. The naive optimism of the firm (naive since the firm is incorrect) does produce a sufficient effect to get the job completed a few months earlier, whereas the pessimism has a similar delaying effect. Neither of these influences is great enough to alter either the firm's profits or the customer's cost or satisfaction by

Intrinsic Size of Job (effective man-years of effort)	Firm's Estimate of Customer's Investment Criterion (percent of correct value)	Project Cost (\$x10 <sup>6</sup> )	Firm's Profit (\$x10 <sup>6</sup> )	Customer Satisfaction Index	Completion Status
500	50	29.9	1.4	.83	100% at month 127
	100	29.0	1.3	.69	100% at month 130
	150	27.4	1.3	.70	100% at month 132
600	50	35	1.5	.43	100% at month 132
	100	23.1	1.8	---	only 55% completed
	150	20	1.7	----	only 46% completed

Table 10-4. Effects of the Firm's Risk-Taking Propensity As Manifested in its Investment Criterion

an important amount. The direction of effects, however, does follow our earlier established pattern-added hesitation prolongs the project duration and saves a small portion of the total project cost because of the newer technological advances utilized.

In the second set of projects shown above, where, because of larger intrinsic job size, the value-cost relationship has become more marginal, the naive optimism does have more effect. The firm incorrectly and optimistically underestimates the customer's return-on-investment demands, undertakes more self-sponsored activity initially and pushes the project to completion. The customer is not very satisfied with this job but might be more content than in the latter two cases

shown, in which only part of the job is completed. The firm, on the other hand, had better find satisfaction in the job completion or in the unknown longer-term effects of this project, since its profits are slightly reduced relative to the two latter cases. This was caused by the firm's increased support out of its own funds of the engineering costs on the project. Thus, in the case of projects which are basically marginal, naive optimism of the firm might change project outcome in the customer's favor, without necessarily benefitting the firm itself. In general, though, the results of the larger job simulations again follow the pattern that the more optimistic the firm the further along the project progresses prior to stoppage.

In the risk-propensity studies indicated above, we found that the firm's undertaking of risk can critically influence the success or failure of the job. Such influence comes about more through the size of the firm's dollar risk, in projects for which it expects customer funding, than through any overly optimistic or pessimistic attitudes as to which projects will eventually receive such funding. Thus, an optimistic attitude alone is not a crucial factor in determining the outcome of the project. But confidence, supported by the firm's funds, does have considerable bearing on research and development results. Such a conclusion helps to more clearly focus our attention on those ways in which the firm's key characteristics significantly operate.

#### Previous Job-Size Experience of the Firm

The testing of a dynamic model of a large system sometimes produces results which contradict the initial hypotheses of the model-

builder. When such a circumstance arises, it demands more careful analysis of the hypotheses to determine whether the theory was wrong or the model merely an inadequate representation of a correct theory. In our Chapter 9 studies, the resulting linear variation of project costs as job size changed led to a model reformulation which sustained these initial results as valid (as shall be demonstrated in Chapter 12). Now, in this chapter too, we encounter another example that causes this deep-seated re-evaluation of the theory and its model.

In earlier chapters we claimed that the previous experience of the firm, especially in terms of the size of projects it has undertaken in the past, would be of influence in the firm's management of a research and development project. Particularly, this previous experience was felt to modify the firm's ability to correctly comprehend the estimate of the size of a job which it is contemplating. The model equations in the Chapter 3 appendix incorporated this factor as a bias in the initial job size estimate of the firm.

Let us look at the simulated projects in which this experience factor was changed in order to test its effect on project behavior. Table 10-5 shows that over a wide variation in the previous job-size experience of the firm, relative to the current project being simulated, this experience has almost no effect. To be sure, the company with experience on larger jobs does apply slightly more engineering effort a little sooner, and consequently costs increase by a small amount. But in general, these results tend to deny our earlier hypothesis that the previous size of job experience of the firm is a key determinant of project behavior.



Average Size of Previous Jobs as Percentage of Current Job Size (percent)	Project Cost (\$x10 <sup>6</sup> )	Completion Date Month
5	27.9	133
30	28.1	133
50	28.2	133
75	28.4	133
100	28.6	133
150	29.8	132
175	30.7	132
200	31.7	133

Table 10-5. Effect of Previous Job Size Experience of the Firm

A re-examination of our model representation shows that the previous experience of the firm directly modified only the effort and cost estimation process of the firm. To be sure, the varying estimated magnitude of the job led to different timing and pacing of primarily the initial project efforts. But these initial flaws in the firm's programming are soon gradually corrected as the firm begins to gain "on-the-current-job experience". The real potential impact of the previous size of job experience of the firm is on the style or strategy of doing the job. The degree of preplanning, general information seeking, and laying of the groundwork might well differ between the firm experienced in handling big contracts and that which has handled the smaller jobs. But this degree of work detail has been

aggregated in our model representation into an indistinguishable part of the over-all company management and engineering effort. Thus, the effects of the previous size experience are not visible in our results. In fact, they would not be noticed except in a model of research and development projects of far greater complexity than that which we have ventured or thought worthwhile to develop.

#### Integrity of the Firm

The firm's integrity in presenting to the customer its own beliefs as to the expected cost and value of the R and D project was cited in Chapter 7 as a potential key determinant of project outcome. The firm's "hunger" to obtain a contract, produced perhaps by competitive bidding pressures but mainly supported by the inept CPFF contract regulations, very often leads the company to underestimate its expected project costs in the proposals submitted to the customer organization. Some firms are notorious in doing this and the huge cost estimation errors cited in Chapter 3 are in part due to this factor. Other firms regularly attempt to accurately anticipate the project costs and forewarn their potential customers of the full expectations. Still others manage to be "conveniently" optimistic, in varying degrees, at the time of proposal preparation.

The effects of these various shades of corporate integrity on the outcome of research and development projects were studied by means of our simulation laboratory. Using our typical project model, the factor denoting the firm's integrity characteristic (the Integrity Coefficient of the Firm, ICF) was changed from one project run to

another and the results recorded below. We first notice that the firm's integrity has relatively small effect on project completion status, cost, or the firm's profits. But as the integrity factor

Integrity Coefficient of the Firm	Project Cost (\$ x 10 <sup>6</sup> )	Firm's Profit (\$ x 10 <sup>6</sup> )	Completion Status
1.00	29.8	1.6	100% at month 130
0.90	29	1.3	100% at month 130
0.75	28	1.0	100% at month 132
0.50	28	2.2	only 91% completed
0.35	17	1.3	only 47% completed

Table 10-6. The Firm's Integrity versus Project Results

continues to be lowered, as the firm intentionally underestimates its expected costs by a higher degree, the results become more dramatically different. At the 50% level of integrity, at which point the firm initially bids only half of what it expects the project to cost, the project gets stopped shortly prior to completion, with the customer having spent as much money as was needed to get a finished project in the 75 percent integrity case. In the last case indicated in the table, the results are more severely changed, with the project getting less than halfway toward its objective before being cancelled by the customer.

How does such project behavior result from changes only in the firm's bidding influences? Let us look first at the 50 percent integrity case. Here the firm initially received customer support by

underestimating project costs by a factor of two. With this initially low cost estimate, the customer was persuaded to begin supporting the project a little sooner than in the Chapter 8 case study, but at a funding level commensurate with the firm's "halved" request. The firm, in turn, began to staff its organization and work on the project at the level provided for by its R and D contractual support. For a period of time, the firm continued at this project effort intensity without seriously revising its funds request. This is caused by three reasons: (1) given the recent low bid submitted by the firm, it would appear very suspicious and in general would be very awkward for the firm to immediately revise this cost estimate sharply upward; (2) during the early stages of the contract even the lower available funds are adequate to meet the firm's expenditures and little pressure exists on the firm to immediately obtain more funds; and (3) the firm often succeeds in convincing itself, after a few months of working under the contract, that what it requested is really not far out of line after all and there is no serious need for revising the funds request.

But as the project continues and the firm begins to more clearly recognize the amount of effort needed to complete the task, it also more clearly feels the need to acquire additional funds. A higher rate of effort is needed and the available funds are inadequate to support such a buildup. Thus, the firm begins gradually to request more funds, which action in turn forces the customer to revise his earlier project cost estimate now based largely on the contract bids. Not only does the customer require more time now to rebudget his funds

and allocate more to the project, but also the customer now has less confidence in the over-all suitability of the project. As time progresses the customer realizes the declining value of the potential product in contrast to the rising cost expectations. This project re-evaluation leads to a lessening enthusiasm of the customer for the project with an attendant stretchout of his project funding. As the customer "takes more time to think over" the project situation, his perceived value drops even further and results in project cancellation by the customer.

Thus, here is a case in which the lowered integrity of the firm caused the cancellation of the project prior to completion. The customer is certainly penalized by this policy of the firm, but the firm does not necessarily suffer equally. In terms of profits, Table 10-6 shows that this project, because of early funding and customer repayment of almost all the engineering costs of the firm, resulted in higher net profits than any other case presented. To be sure the eventual project failure may cause much greater losses in business at a later date, but these are neither shown nor certain.

In the final situation listed in the table, wherein the firm understates by approximately a factor of three, the project effort remains at such a low level relative to its needs for such a long duration that cancellation results before the job gets even half completed. From this example, and the preceding discussion, we can clearly see the significant impact that the firm's integrity can have on research and development project outcomes. Within a limited range, the simulated project histories showed variations in the firm's integrity

policy or behavioral characteristic can mean the difference between project success and failure. The firm itself does not necessarily suffer immediately from this policy. Therefore, the company management which seeks short-term profits under our existing contracting system may well be influenced to intentionally underestimate project cost requirements. Most government and industry people working in the research and development area recognize this practice to be dominant. To solve this problem, either industrial leaders must take a more long-range view of the determinants of corporate success (which may be naive hope), or major changes must be made in our system of R and D contracting to provide a structure of motivations and evaluation that will eliminate the wisdom of this industrial practice. New research programs are now beginning in this latter approach.

#### Resource Limitations of the Firm

The final characteristic of the firm to be examined in this chapter is the availability of resources to the firm. Principally, we think of financial resources in this regard, and we shall limit our investigation in the present chapter to this area. But limitations on the availability of skilled personnel are also potentially important, and shall be studied in Chapter 12. The amount of funds which the firm has available in general, or a specific dollar limit on investment in a single project, does certainly influence the activity level of any self-supported engineering program. Whether such a limitation is serious or not is illustrated in the next table. The variable factor in the three projects shown was the time at which

Timing of Funds Availability (month)	Project Cost (\$ x 10 <sup>6</sup> )	Firm's Profits (\$ x 10 <sup>6</sup> )	Completion Status
0	26.8	1.3	100% at month 135
40	27.5	0.9	100% at month 133
60	16.5	1.1	only 47% completed

Table 10-7. Effect of Financial Limitation of R and D Projects

adequate funds for project investment became available to the firm. The results show that if the firm is not financially able to support an early and steady engineering program in a new area of technology, then the later bettering of its financial situation may be insufficient to allow project success. Not only does the table demonstrate the potential importance of funds resource, but moreover it again emphasizes the need for the firm's undertaking of project risk by its own support of engineering activities. The lack of funds denies the possibility of such risk assumption by the firm and has its effect through this indirect channel. In addition, we observe that here too the short-term profitability of the various projects is not such as will of itself induce the firm to try to make funds available earlier. This therefore suggests a further needed change in contracting policies to give incentive to companies to provide early funding for research and development projects.

### Summary

This chapter inquired, through use of our typical research and development project model and the computer simulation laboratory approach, to uncover the extent to which the firm's various characteristics influence project success. The first characteristic studied, the over-all quality of the firm, was found to be quite consequential in its effects, and particularly noticeable as this ability declined. Both in its direct effects on estimate accuracy and engineering productivity and through its indirect effects on various organizational response delays, this quality factor was shown to be as dominant as the earlier discussions hypothesized. The willingness of the firm to accept risk and invest its own funds in prospective projects was also critical to project outcome, especially below some needed threshold value of risk-taking propensity. The same type of conclusion is justified in the case of the firm's contract bidding integrity. Here, too, variations in this characteristic of the firm could cause the difference between project success and failure. The need for the firm to have sufficient resources to undertake early project sponsorship was also developed in this chapter, as was the fact that the previous job-size experience of the firm has almost no effect on project outcome. The latter was a denial of our hypothetical claims and provoked the type of soul-searching that is itself a beneficial result of this mode of analysis.



## CHAPTER XI

### THE CUSTOMER'S INFLUENCE UPON PROJECT SUCCESS

In the preceding chapter the fact that the firm can strongly influence the outcome of research and development projects was clearly established. This chapter shall inquire into the same kind of question with respect to the customer and prime financial supporter of the R and D effort. Since, in general, the firm rather than the customer is the doer of the actual research and development work, we should expect that the influences of the customer will be less direct and perhaps also less critical except at extremes.

#### The Quality of the Customer

The first point which we can examine in regard to the above contention is the effect on project behavior of the customer's overall quality. In the model this characteristic influences only the accuracy of the customer's initial project, cost and value estimates. With just these factors active, the customer quality variation has almost zero effect on project outcome, as shown in Table 11-1 below.

Quality of the Customer (percent)	Project Cost (\$x10 <sup>6</sup> )	Completion Date (month)
30	29.1	130
60	29.0	130
100	28.6	130

Table 11-1. Direct Influence of the Customer's Quality

This table does not say, however, that factors certainly related to the quality of the customer are not important. One factor associated with the customer's quality that does seem to be important is the delay in the customer's response to the firm's request for funds. This delay influences both the customer's cost expectations which are based on funding requests and the customer's processing of the requested funding change. The higher the quality of customer organization, the more rapidly the customer will be able to achieve these things. This results from consideration of both: (1) the paper-processing time, which "red-tape period" is no doubt reduced as the customer's abilities are increased; and (2) the delay in getting approval from higher-ups, which is also probably reduced as the lower-level customer organization earns more of the confidence of its superiors. In any event, Figure 11-1 illustrates that this delay in the customer's response to requests for funds can significantly alter the outcome of R and D projects. Using the typical project model, the delay was changed from the six months figure used originally and the results recorded with respect to completion date, cost and customer satisfaction. This initial delay value of six months is about average for a wide range of projects but is definitely low for the larger R and D undertakings. From the graphs we see that the customer's delay in processing the funds requests has its greatest effect on the date of project completion, and upon the customer's satisfaction which largely derives from this timing. This effect is most noticeable in the range beyond the original six months delay, for which range the completion time shoots up from month 131 to month 150 (for DRRFC = 13.5 months) and beyond that to time = infinity, since none of the simulated

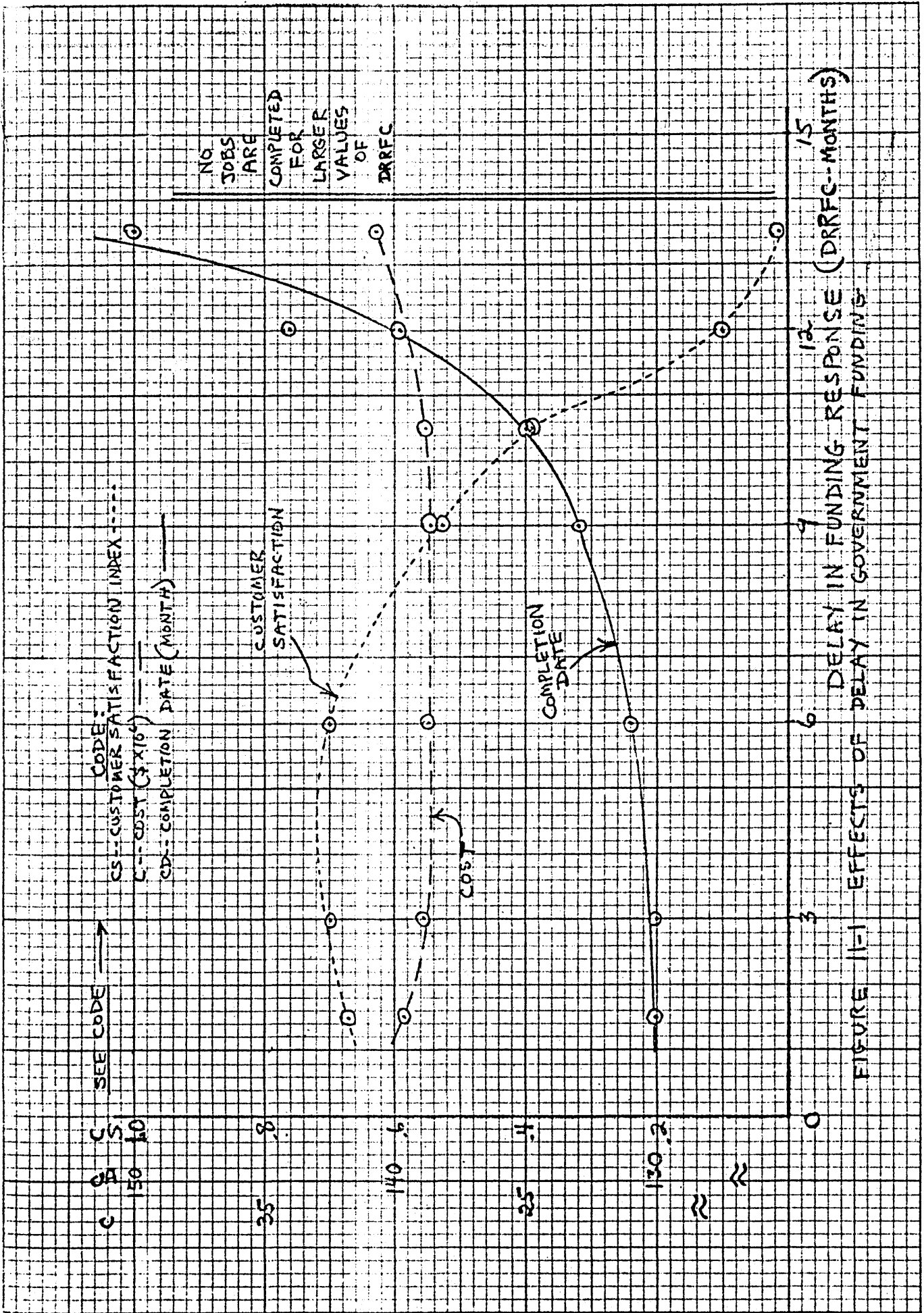


FIGURE 11-1 EFFECTS OF DELAY IN GOVERNMENT FUNDING

projects got completed for longer funding delay values. For smaller jobs, of course, the completion cut-off value of the funding delay would be much longer. Since the costs remain relatively unchanged (the highest cost is less than 10 percent more than the lowest cost), the customer's satisfaction drops almost continuously as the time of completion is postponed and the perceived product value declines.

Two features of these results are particularly noteworthy. First of all, the shape of the project cost curve demonstrates that some policies may appear to work well up to a point, but further extensions of them can be disastrous. For the range up to a delay value of nine months, the main effect of lengthening customer approval time is to postpone the major project engineering activities until further technological advances can be utilized. The completion date is delayed by a few months and the customer satisfaction index begins to decline, but neither change is very large and the satisfaction index is, of course, intangible. Thus the most obvious measurable result is that costs somewhat decline. But as the customer delay is further increased, the cost savings are quickly wiped out by the inefficiencies of the stretchout, the completion date jumps sharply, and the satisfaction index drops quickly toward zero. Now the measurable cost changes are more apparent and are disappointing to the customer, the delay in project completion becomes obvious, and the over-all customer disappointment with the project is sufficient to also become near-tangible. Among other things this illustrates the fact that the common process of evaluating project performance by the most readily attainable, traditional, and tangible measures may well mislead research and development managers, both in

industry and government, to institute or extend policies actually harmful.

The second feature of these results that bears noting is that here is an area of customer behavior, controllable at least to large degree by the customer himself, in which the customer's actions bring about project failures. Government, particularly, should therefore recognize that the slow-downs and postponements of project activities that are often caused by the delays in the customer's funding procedures can themselves be critically damaging to research and development project outcomes.

Another aspect of the customer's operations, which also reflects his over-all ability of planning and carrying out a new project activity, is the customer's scheduling of project programs. Whether the customer tries to get a project completed in one, two, three, or more years is an indication of how much he really understands about the scope of the job, and also shows his recognition of the timeliness of the project. For our typical project model, we have simulated the effects of the customer's attempts at scheduling the project duration. Table 11-2 shows the results of four simulated projects, in which the normal project duration (NPD) was varied from one to four years length.<sup>1</sup> The indicated results clearly show that the customer's intended scheduling has not been accomplished.

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<sup>1</sup>In our project model, NPD does not precisely represent the scheduled duration of the project. Instead it is the scheduled time-constant of the project, which is equivalent to the time required to complete approximately two-thirds of the project. This time-constant concept is analogous to the half-life concept used to describe the radioactive decay of an atomic particle.

Scheduled Project Duration (months)	Completion Status	Project Cost (\$x10 <sup>6</sup> )	Customer Satisfaction Index	Peak Engineering Employment (men)
12	100% at month 130	30.5	.67	823
24	100% at month 130	28.4	.7	477
36	100% at month 135	25.3	.6	335
48	only 82% completed	20.6	---	221

Table 11-2. Effects of Customer Scheduling of Project Duration

Halving the scheduled project time from our original value of two years to but twelve months made no improvement at all in the date of completion. Slowing the intended project schedule down by an additional twelve months only increased completion time by five months. These facts are true in this case because the factors really dominating the timing of completion exist apart from the schedule. Completion time is far more influenced by such factors as the company's risk-propensity and quality and the customer's funding delay, all of which have been discussed earlier, and by the ability of the firm to expand its organization more rapidly, which will be discussed in the next chapter. But the customer's scheduling decision does have distinct effect at the extreme, in that its prolonged extension, in this case to forty-eight months, is too long and the project suitability fades away before the job can get done, resulting finally in customer cancellation.

The most obvious effect of the scheduling period is on the stability of the firm's engineering organization, and secondly on the project costs which at least in part relate to the former. The crash

program suggested in the one-year schedule forces a very high build-up of the engineering organization, followed by a very rapid decay of engineering employment. This effect of the customer's schedule on the peak size of the project team is continuously observable in Table 11-2, with the stability of engineering activities increasing as the intended project duration is prolonged.

The effects shown in the above table are even more pronounced when the firm is able to respond more quickly to the customer's desires. In Figure 11-2 the results of variations similar to those described above are shown for a modified project situation in which the expansion ability of the firm's organization has been greatly enhanced.<sup>2</sup> The general shift in all the results, occurring because of the change in the firm's expansion ability, can be ignored until Chapter 12. It is sufficient here to note that the over-all conclusions of these runs are unchanged from those derived from the Table 11-2 results above, but indeed have been made more obvious. The major effect still lies in the stability of the size of the engineering organization, which stabilization takes place as the customer allows more time to get the job done. Secondly, deriving in part from the engineering stability, the project costs decline as scheduled project duration increases. The cost change is more pronounced in these projects than in the examples listed in Table 11-2 largely because of the wider variation in organizational size, and to some extent

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<sup>2</sup>The Training Efficiency Index, TEI, was changed from its normal value of 1 and set equal to 2.5, the same value that was used to produce the results for the "size of project" simulations that were illustrated in the first part of Chapter 9.

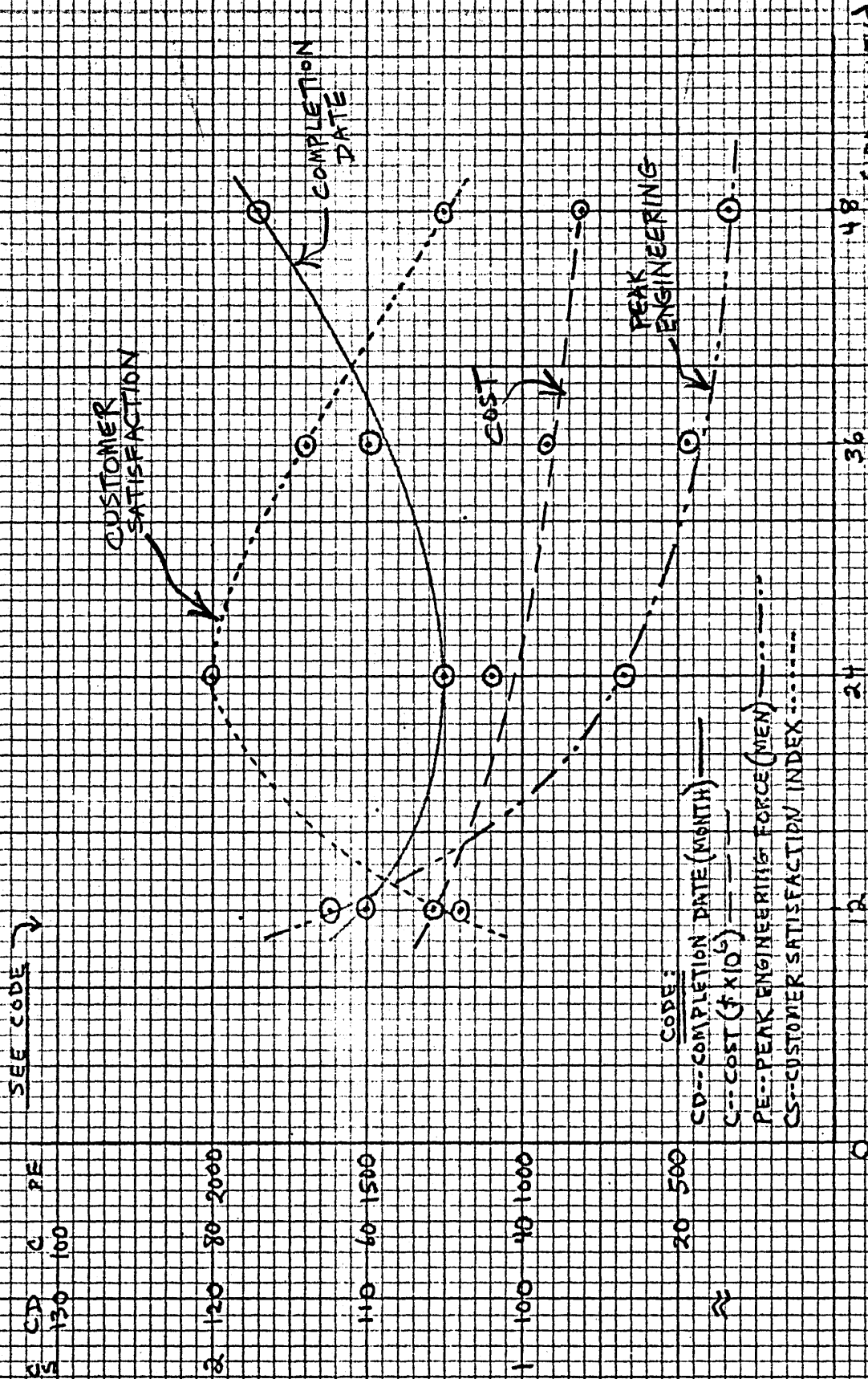


FIGURE 11-2 EFFECTS OF CUSTOMER'S SCHEDULED PROJECT DURATION

12 24 36 48  
NORMAL PROJECT DURATION (NPD) MONTHS



because of variation in the date of actual completion which permitted different degrees of utilization of the advancing state-of-the-art. Because of these factors, the customer satisfaction curve also shows a greater degree of variability.

For the particular set of project characteristics used here, referring especially to the combination of the project size, intrinsic value, and technological change inputs, these studies show that a maximum perceived return on the customer's investment, which we have defined as our measure of customer satisfaction, is achieved for the two-year project time-constant. This single resulting value could certainly be changed if a different set of inputs were used, although the characteristic nature of the resulting curves would remain substantially similar. This indicates that for any given set of project specifications, a particular scheduled project duration (or a narrow schedule range) produces maximum customer satisfaction. The customer, of course, might want to concern himself with a different satisfaction criterion than that represented in the graph. For instance, he might (or perhaps should) want to maintain a high degree of stability of engineering employment. To maximize this stability criterion alone, the customer would obviously have to provide eternal funding for a fixed number of employees. Such a policy would, for a low fixed number, result in no projects of consequence being completed while they are still of value, and for a high constant employment level, result in a phenomenally expensive set of end results. The varying demands resulting from different job characteristics would in addition make impossible the continued maintenance of any fixed-size engineering organization

without some such wastage. Thus, the customer could at best try to satisfy some reasonable degree of employment stability, while he also tries to satisfy some reasonable rate of return on investment. Most customer organizations tend by nature, or by the combination of political pressures and those created by research and development firms themselves, to try to meet some similar joint criteria of satisfaction. And as we can see from the results above, even those customers which did think solely in terms of maximizing a single criterion would be frustrated by the real world events.

#### Risk-Propensity of the Customer

The most significant embodiment of the customer's propensity to undertake risk is the ratio of perceived value to expected cost which the customer demands, before he will fully support a contemplated research and development project. The customer will not be satisfied after project completion unless the then-perceived value-cost ratio equals one or better, signifying at least that perceived value equals expended cost, thus producing the break-even on the customer's investment. Thus, if the customer is willing to start the project when this value-to-cost ratio equals one or less, he is staking his investment on hopes that neither cost will rise nor perceived value decline or that both will no worse than proportionately change by the time the project is completed. If the customer delays any major investment until the current value-cost ratio is greater than one, he is showing an increased degree of conservatism. The higher the value-cost

ratio demanded prior to major customer investment, the more conservative is the customer. The table below shows the results upon project outcome of this type of customer risk-taking propensity, for jobs of two different intrinsic sizes. In the job of smaller size, the job

Intrinsic Size of Job (effective man-years of effort)	Value-Cost Ratio Demanded by Customer	Project Cost (\$x10 <sup>6</sup> )	Completion Status
500	1	28	100% at month 131
	2	28.4	100% at month 130
	3	18	only 48% completed
600	1	34.1	100% at month 133
	2	23.1	only 55% completed
	3	16.5	only 35% completed

Table 11-3. Customer Risk-Taking Propensity

with more "cushion" in its built-in value-cost relationship, reducing the investment criterion from two to one has no significantly noticeable effect either on cost or completion status of that project. However, when the customer insists that perceived value be equal to three times expected cost before he will support the project, the customer delays the funding to the point where the project is doomed. For the larger job, in which the justifiability of the research and development project is more limited, the increased conservatism of the customer has its effect more quickly. Here, moving even to the investment criterion used as the "normal" above, a criterion which sought projects whose perceived

value equaled 200 percent of their expected cost, is sufficient to cause project cancellation. Thus, in all cases, the lower degree of customer risk-propensity makes less likely the successful completion of an R and D undertaking. In projects basically marginal in character, this characteristic is more quick to make itself evident in dooming the potential success of the projects. Thus, here is a policy of the customer which can well be self-defeating to the customer's own desires for project satisfaction.

#### Previous Experience of the Customer

In the preceding chapter the previous size-of job experience of the firm was found to have almost no influence on project outcome. Given this fact and the already-illustrated less direct effects of the customer on many aspects of research and development, we might perhaps expect the customer's previous experience to be similarly lacking in importance. This is true for a broad range of job-size experiences of the customer. However, as Table 11-4 on the following page demonstrates, when the customer's average previous job is large, relative to the current task, the effectiveness of this influence does become apparent.

The effect of customer conservatism described earlier in this chapter demonstrated that a more conservative attitude of the customer tended to delay his support of the project, retarding the rate of staff build-up and job progress. Under strong influence of this conservatism, the delay was sufficient to prolong the work on the job until the product no longer appeared worthwhile to the customer, and project cancellation took place. Here is another example of a customer characteristic which achieves its effect in much the same manner.

Average Size of Previous Jobs as Percentage of Current Job Size (percent)	Project Cost (\$x10 <sup>6</sup> )	Completion Status
5	29.1	100% at month 130
40	29	100% at month 130
82.5	28.9	100% at month 130
150	28.6	100% at month 131
175	29.2	100% at month 135
200	19.7	only 54% completed

Table 11-4. Previous Job-Size Experience of the Customer

The customer's experience with larger jobs in the past influences him to overestimate the magnitude and hence the cost of the simulated task. This increased cost estimate reduces the estimate of over-all suitability of the project for customer investment. As this discouraging (for the project) influence increases, the job progress begins to be delayed to the point that the date of completion comes later (at month 131 and 135 in the table). Finally, under sufficient constraint due to lack of early customer willingness to invest in the project, the work delay is long enough that the job enters into the time zone of a seriously reduced value-cost ratio and the job is finally cancelled.

The most important aspect of the customer's previous experience is the influence of the induced high customer cost estimates on the firm's actions. In the case of customer over-estimation of project cost,

the firm senses the fact that the likelihood of customer support of the project is lessened. Hence, the firm's willingness to invest its own funds in the project also declines. For these reasons, we have here the case in which the customer characteristic, at its extreme, has more effect on research and development behavior than the comparable characteristic of the firm. This results both from the strong influence of the customer's funding on the timing of the phase of major project effort and from the indirect discouragement provided to the firm's own risk acceptance.

#### Resource Limitations of the Customer

The financial resources of the customer provide the funds required to get the project accomplished. What happens, then, when the customer lacks such funds? As we did in the Chapter 10 exploration of the firm's resource limitations, so too have we in this chapter simulated a set of research and development projects in which the timing of the availability of funds to the customer has been varied. The results appear below. They show that the fact that the customer had no available money made no difference, as long as this problem was solved by

Timing of Funds Availability (month)	Project Cost (\$x10 <sup>6</sup> )	Completion Status
0	29	100% at month 130
40	29	100% at month 130
60	29	100% at month 130
80	16.6	only 50% completed
100	1.5	only 2% completed

Table 11-5. Effect of Customer Financial Limitation on Research and Development Projects

month 60 of the simulated situation. However, beyond this point lack of customer money resulted in overt failure of the project.

The results imply, in the first three cases entered in the table, that the firm's assumption of risk and undertaking of effort with its own money was sufficient to bring about project success, as long as the customer finally got its funds by month 60. In these cases when the customer did get his funds, he still felt the project worth supporting, did so, and the jobs got completed without change in final outcome. When the funds were further delayed in becoming available, the lack of financial support from the customer between months 60 and 80 was sufficient to retard project progress to the point that even though the customer finally did begin providing money at month 80, the job never got done. The work was slowed to the point that the decline in the customer's recognition of project value came about sooner than did the decline in expected additional costs to complete the project. Thus, stretch-out and later cancellation occurred.

In the final case shown in Table 11-5, the full 1.5 million dollars expended on the project was invested by the firm, with his self-supported engineering activities on the project increasing from one man up to twenty-two men at the peak, before gradually cutting back these activities. All of this engineering work took place prior to month 100, when the customer received his funding. By that time the firm had eliminated the project program, and the then apparent value-cost relationship made the project unattractive to the customer.

From these latter two cases we see that at its extreme the customer's resource limitations can affect research and development performance.

The effect took place somewhat sooner when it was the firm (and not the customer) which lacked these resources. This was due to the cruciality of the initial firm-supported staff build-up, which we have examined under several contexts earlier and which we shall again see in Chapter 12. However, the customer funding itself does not seem needed at early stages of a project life cycle, as long as the customer's attitude towards project potential is encouraging to the firm. This reinforces our finding in the previous section about the influence of the customer's previous job experiences. If the lack of customer funds is accompanied by the attitude that such funding availability is unlikely, even in the future (a situation not represented in our current project model), then the effect can be more serious over a broader range of variation.

#### Customer Confidence in the Firm

The final characteristic of the customer that was listed in Chapter 7 was the customer's confidence in the firm. This confidence basically determines the extent of influence that the firm's cost and value estimates will have on the figures which the customer uses for decision-making purposes. The customer's confidence in the firm also limits the customer's estimate of the technical effectiveness of the firm in carrying out the contemplated project. As we can see in Table 11-6, this customer characteristic, too, is important to over-all research and development results only at its lowest values. It acts in a way similar to the customer's risk-taking propensity. In fact, one could argue that to at least some extent any organization's confidence in another is a function of the former's willingness to accept risk.



Customer Confidence in the Firm (percent)	Project Cost (\$x10 <sup>6</sup> )	Completion Status
100	29	100% at month 130
80	29	100% at month 130
60	28.9	100% at month 130
50	28.8	100% at month 131
40	20.4	only 57% completed
30	16.3	only 42% completed

Table 11-6. Influence on Research and Development Results of the Customer's Confidence in the Firm

Regardless of such similarity (or lack thereof), the results clearly show that unless the customer's confidence is low, relative to the maximum possible confidence value, this characteristic of the customer will not be influential.

#### Summary

Of the customer characteristics studied in this chapter, only three factors, two of which were closely related to the customer's over-all ability, seem to have significant influence throughout their full range of operation. These factors are the customer's funding delay, his scheduled project duration, and his risk-taking propensity as manifested in his project selection criterion. All of the other potentially influential characteristics, including the customer's previous job-size experience, resource limitations, and confidence in the firm, did not have effectiveness over a broad range of situations. To be sure

many customers consistently operate within some one or more of these critical value ranges. Our discovery that close consideration of such customer factors is needed only under such limited cases, however, is itself an informative conclusion.

CHAPTER XII  
ORGANIZATIONAL REQUIREMENTS OF THE  
RESEARCH AND DEVELOPMENT PROCESS

The three preceding chapters have reported the results of explorations into the determinants of research and development project dynamics. These studies have focused, respectively, on the influence of characteristics related to the R and D product, the firm, and the customer. The course of conducting and analyzing such studies, however, has forced recognition of a different source of influences upon project outcomes--the organizational requirements deriving from the process of research and development itself.

Expansion of a Technical Organization

The process of research and development of new or significantly improved products or techniques requires the project organization to include sufficient number and breadth of technical manpower to carry out the task. In military R and D in particular, this demands growth of the project staff from the one or more engineers who initially undertake exploratory studies in the product area to the several hundred men oftentimes needed to successfully complete the job. In any area of new technology, or of significant departure from the firm's previous work specialties, the firm's ability to expand the technical organization is inherently limited by its existing capabilities. If, for instance, as often happens, only one man has pioneered the new endeavor in the firm, he is the only one in the firm with the necessary background upon which the organization can develop. Initially, much of his

time will be needed to recruit, train, and/or supervise others entering the project. This type of problem, the transfer of know-how from one person to another, the translation of individually-thought objectives and technical approaches into mutually understood goals and methods, is inherent to the process of research and development.

In our typical project model, we assumed that on the average every two fully experienced engineers, by devoting about 30 percent of their time, could help five new engineers reach the average effectiveness of their more experienced colleagues in a duration of eighteen months. Any of these figures are subject to debate, but there exists no reason or data that should lead to rejecting them as not plausible for many R and D projects. Moreover, on several occasions in the past three chapters, we found that the effects under study became more apparent when the firm's flexibility was enhanced by adjusting its ability to expand more quickly. Thus, it seemed that this expansion ability of the organization might be an important characteristic of research and development projects. The results below strongly confirm this belief.

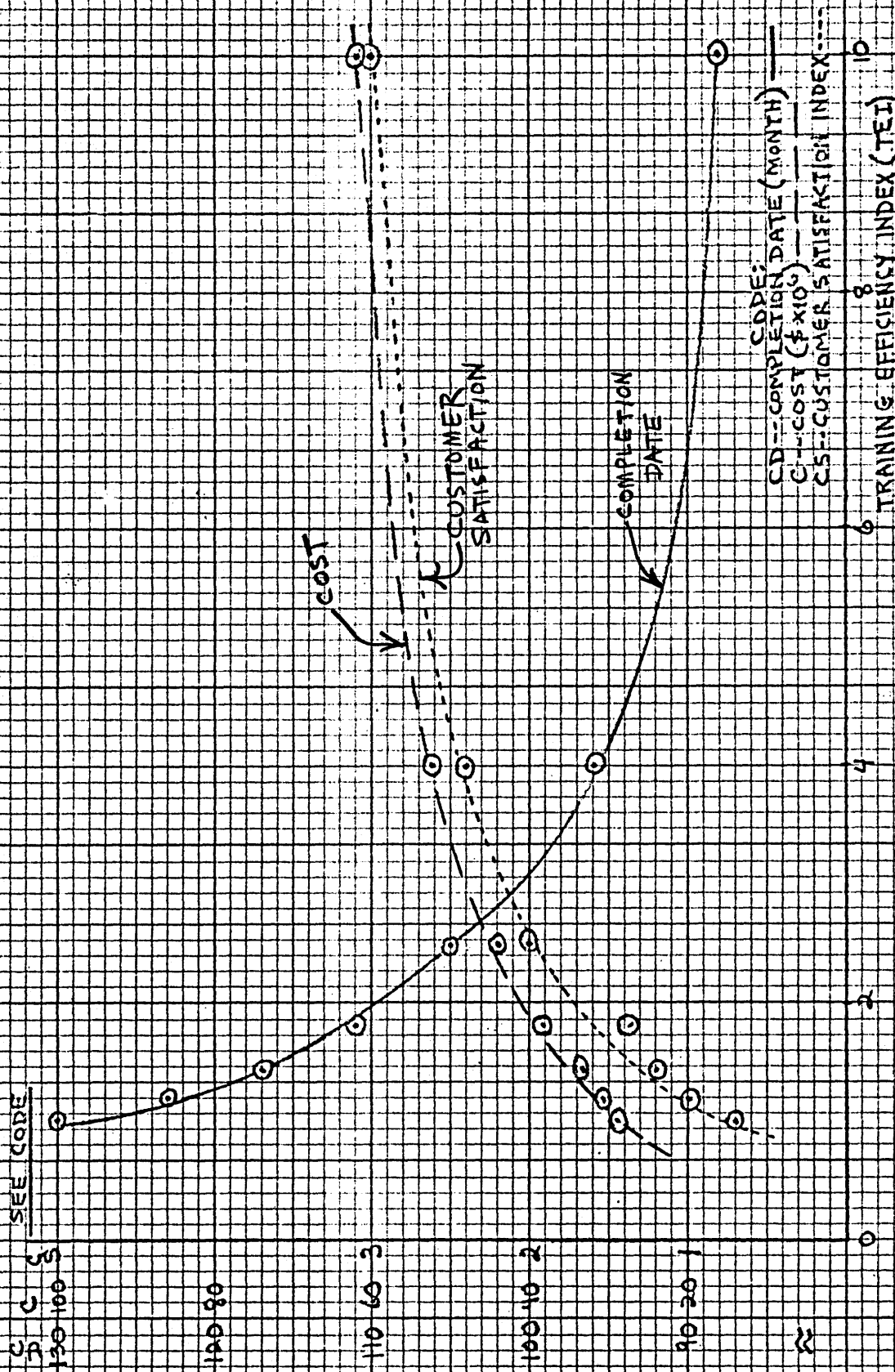
In the table are shown the outcomes of simulated project time histories for jobs of different basic sizes, using first the normal expansion ability of the firm and then increasing it by a factor of ten. This was done by changing the Training Efficiency Index (TEI) from one to ten, indicating that an experienced engineer, with the same basic effort and time requirement as before, could now assist the development of ten times as many new engineers. Such a test, while surely stretching the limits of plausibility, helps provide added

Intrinsic Size of the Job (effective man-years of engineering effort)	Training Efficiency Index	Project Cost (\$x10 <sup>6</sup> )	Completion Status	Customer Satisfaction Index
500	1	29	100% at month 130	0.7
	10	62	100% at month 88	3.0
600	1	16.3	only 26%	---
	10	76	100% at month 102	1.4
800	1	13.8	only 16%	---
	10	92.5	100% at month 106	0.8

Table 12-1 Effects of Expansion Ability of the Firm on Various Size Research and Development Projects

insights into the process under investigation. Under the greatly increased expansion ability, jobs previously left incomplete are now completed, jobs previously finished are now done much sooner. To be sure, there is a trade-off between time and money, and the first set of jobs indicated in the table shows a doubling of cost under the new conditions. Despite this, however, the much earlier job completion leads the customer to be far more satisfied with the new resultant.

This leap from a normal expansion effectiveness by a factor of ten is no mean feat to achieve, and is most likely a practical impossibility. It is of interest therefore to see what lesser and more feasible improvements might produce. In Figure 12-1 are displayed the results of a series of simulated typical projects, in which the training efficiency has been changed from one run to another. The unidirectional changes apparent in the graphs are impressive. As the expansion ability



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130-100 S

110-80

110-60 S

100-10 2

10-20 1

CODE:  
 CD--COMPLETION DATE (MONTH)  
 C--COST (\$ X100)  
 CS--CUSTOMER SATISFACTION INDEX

FIGURE 12-11 EFFECTS OF TRAINING EFFICIENCY ON PROJECT RESULTS

increases, the completion date continuously draws nearer, costs continuously rise as a partial offset, but customer satisfaction nevertheless also continues its upward advance, all in a nonlinear manner. These results clearly show the importance of the technical organization's ability to expand rapidly without suffering greatly from the pace of expansion. The sensitivity of project outcome to this process characteristic is at least as significant as the response to any other characteristic studied thus far.

However, it is unreal to think that by will alone a firm can greatly change its staff size without encountering at least transient loss of some of its engineering effectiveness. As but one kind of problem that is typically encountered, let us see what happens when the firm's increased expansion ability is accompanied by a decreased engineering effectiveness of the new recruits. Obviously, some temporary decline will also affect the more experienced engineers who will be needed more and more to double check the work of the new additions to the project or to assist in their over-all training and indoctrination. We can neglect this factor, however, and still gain a good idea of the general results of rapid expansion of an engineering team.

In Table 12-2 are pictured results that demonstrate the typical distinction between an orderly, smoothly growing project group and a crash project, expanding quickly and at least temporarily losing some effectiveness. The more rapid expansion approach still gets more of the job completed, or the entire project done sooner, but the cost increase is higher and the customer satisfaction only questionable improved. Compared to the entries of Table 12-1, these new figures show a far less

Intrinsic Size of the Job (effective man-years of engineering effort)	Program Type	Project Cost (\$x10 <sup>6</sup> )	Completion Status	Customer Satisfaction Index
400	Normal	26.8	100% at month 135	0.4
	Crash	69.5	100% at month 106	1.0
800	Normal	13.8	only 16%	---
	Crash	91	only 49%	---

Table 12-2 "Crash" versus "Normal" Project Management Approaches

favorable trade-off between time and money. This is due to the decreased engineering effectiveness of the new recruits which decrease accompanied their rapid absorption into the organization. This type of occurrence is what we expect and experience in any crash program--Atlas, Polaris, Mercury, and also in many lesser known R and D programs. The job gets done sooner--usually--but at the surrender of many added dollars. If the need for the project results is urgent, the more timely completion is sometimes well worth the effort. But in some situations the lowered efficiency and the resulting mushrooming costs can make the crash program less justifiable. At times this haste is even self-defeating, producing great customer (and Congressional) dissatisfaction and even project cancellation.

Management Policies to Effect Needed Expansion

The studies outlined above have demonstrated that one characteristic of the process of doing research and development work, the need for



efficient absorption of new people into the R and D organization, is of critical importance to project behavior. What beside wishing can R and D firms and their customers do to handle this problem area? Two approaches seem feasible within the existing organizational framework of most research and development companies: (1) the firm can attempt to reduce the training time of the new engineers on the project, making them able sooner to undertake full productive responsibilities, including giving assistance to other new personnel; (2) initial project study groups can be staffed in larger numbers, thus providing a broader base for project growth. A third alternative might require rather sweeping changes in corporate organization to increase mobility and rapidity of adjustment to a new work configuration. A proposal along the latter lines has been presented by Jay W. Forrester in his recent book.<sup>1</sup>

#### Decreasing the Training Time

Let us examine the first alternative in more depth. We have assumed that in about eighteen months the average new engineer coming into a project can be developed to the point of nearly equal effectiveness with the other engineers in the organization. Some studies to which we earlier referred suggested that this period lasted only six months, whereas others have argued for as much as three years. Certainly the different experiences of different organizations working in different technological environments can readily explain such

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<sup>1</sup>Jay W. Forrester, Industrial Dynamics (Cambridge: The M.I.T. Press, and New York: John Wiley and Sons, Inc., 1961), pp. 329-335.

variation in the estimates. For our purposes, it is not important to settle upon a single agreeable training period for the simulation model. Rather, we should seek to find out what differences in outcome might result from the various assumptions, and further to suggest what procedures might lead to the more desirable results.

In Figure 12-2 are shown the results on the typical project model of various training time requirements. The curves show that the project outcome is extremely sensitive to the delay in developing new engineers in the organization, with the completion date and customer satisfaction being particularly responsive. Additional simulated projects not shown on the graph establish that with the given set of project characteristics, a training time longer than eighteen results in project cancellation prior to job completion. For a delay of 22.5 months, 44 percent of the job is done; training time of 27 months results in only 26 percent completion; and a 36-month training period produces but 13 percent job progress. These figures, too, emphasize the nonlinear sensitivity of the project outcome to this training time period. Furthermore, although a different initial set of project characteristics would have led to other specific values of the measured results, the curves and the conclusions would have appeared similar in nature, thus emphasizing the generality of the observed phenomena.

Thus, in research and development work the many months needed to develop new professional talents constitute a vital influence upon R and D project behavior. Companies working in this field should obviously strive to reduce this time period. The new project which can

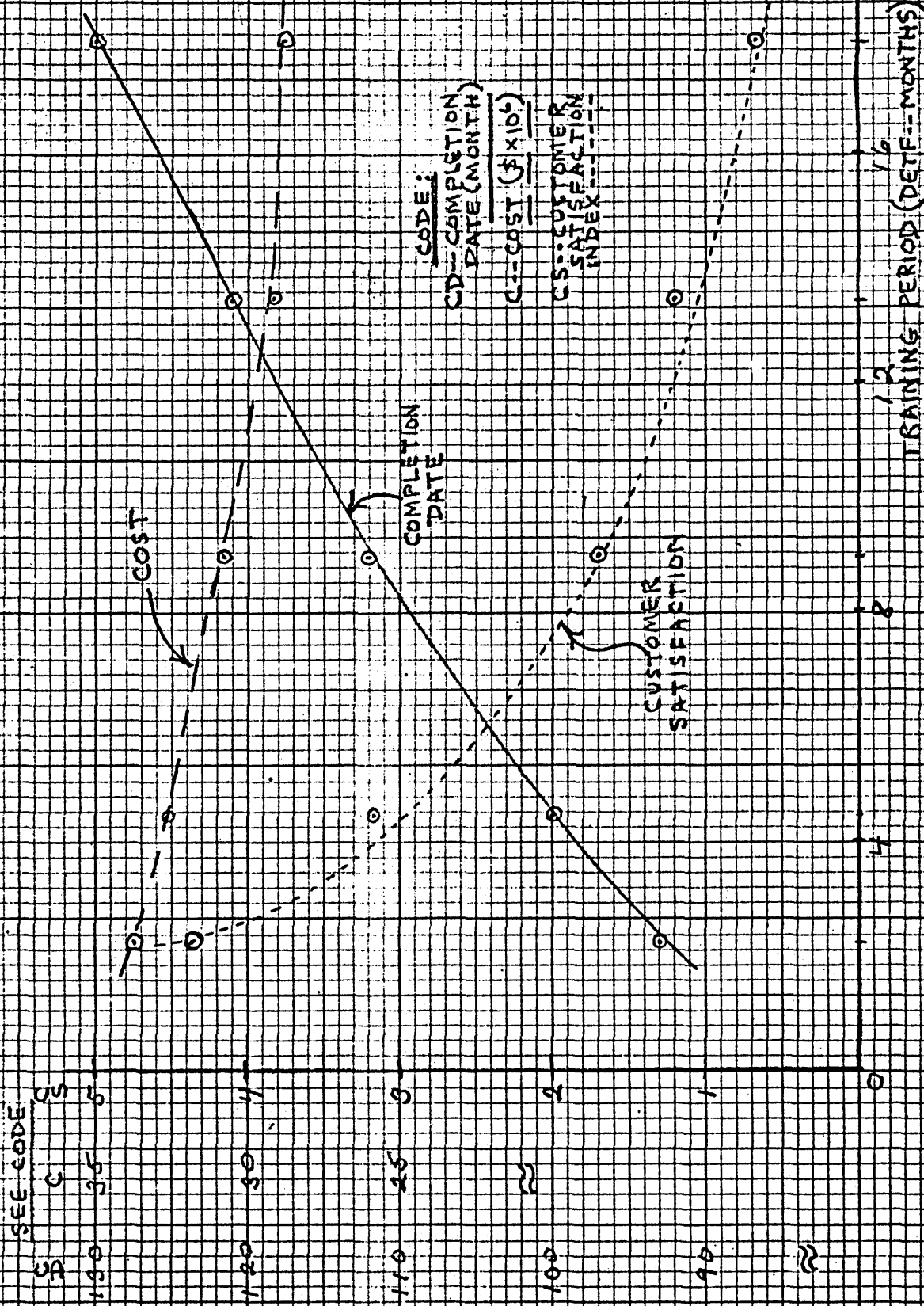


FIGURE 12-2 EFFECTS ON PROJECT OF VARIOUS TRAINING REQUIREMENTS

draw on engineers available elsewhere within the firm is greatly aided. A similar advantage accrues to the firm which locates itself in a strongly technically-populated geographic area. Whenever skilled individuals who require less break-in time are accessible, a decreased period of indoctrination and personnel development is needed, and beneficial results accrue to the project.

In the technological development which is radically different from its predecessors, very few experienced engineers are likely to have skills or knowledge significantly transferrable to the new area. From what we have observed above, it becomes obvious that in such a situation the project growth will take place very slowly, with both a low rate of absorption of new people and a long time period to develop their skills. Such has been the experience of many R and D-type projects, including our own Industrial Dynamics Research Group at M.I.T.

One obvious danger of jumping to conclusions about the implications of the above simulation results is that one is liable to attempt reducing the formal or informal indoctrination time, without making extra effort to accomplish the same effectiveness of the training. If the reduced training time is accompanied by a diminished productivity of even the trainees, the results may be disappointing. This is demonstrated in Table 12-3 below. As was mentioned before, for our chosen project specifications the 22.5-month training period results in only partial completion. If, however, the firm could reduce the training period to eighteen months, for example, without lowering the effectiveness of the program, the project would be successfully completed. On the other hand, as is also shown in the table, a decrease in

Training Time (months)	Effectiveness of Trainees	Project Cost (\$ x 10 <sup>6</sup> )	Completion Status
22.5	Normal	16	only 44%
18	Normal	28.9	100% at month 130
18	Lowered	20	only 37%
9	Normal	30.8	100% at month 112
9	Lowered	33	100% at month 114

Table 12-3. Changed Training Time and Trainee Effectiveness

effectiveness which accompanies the decrease in the training period might do more harm than good, resulting in the expenditure of more money and the accomplishment of even less progress on the job. If lowered effectiveness of the new engineers necessarily goes along with a shortening of their time of training, obviously a more substantial reduction in the training time must take place for any given decline in effectiveness before the change can reap a desirable outcome for the project.

#### Increasing the Initial Staff Size

The second alternative suggested above as a means to cope with the need for organizational expansion in all R and D projects was for the firm to staff initial study groups with more engineers. This would provide a larger base of people exploring the problem area of interest, developing a mutual understanding of the difficulties involved and of the means to accomplish project objectives. It should, therefore, allow for more rapid project expansion. But, to what extent can this be effective?

The curves of Figure 12-3 show that, to perhaps even a surprising degree, a higher initial staff size can have excellent effects upon research and development project results. The ability to get the job done sooner is greatly enhanced by the bigger "push" initially and, despite higher costs accruing from use of a less-developed technology, the customer satisfaction with the project is still much strengthened. In the typical project model that was used in Chapter 8 and as the basis of all the exploratory studies reported in the other chapters of Part II of this work, each project's beginnings were assumed to stem from

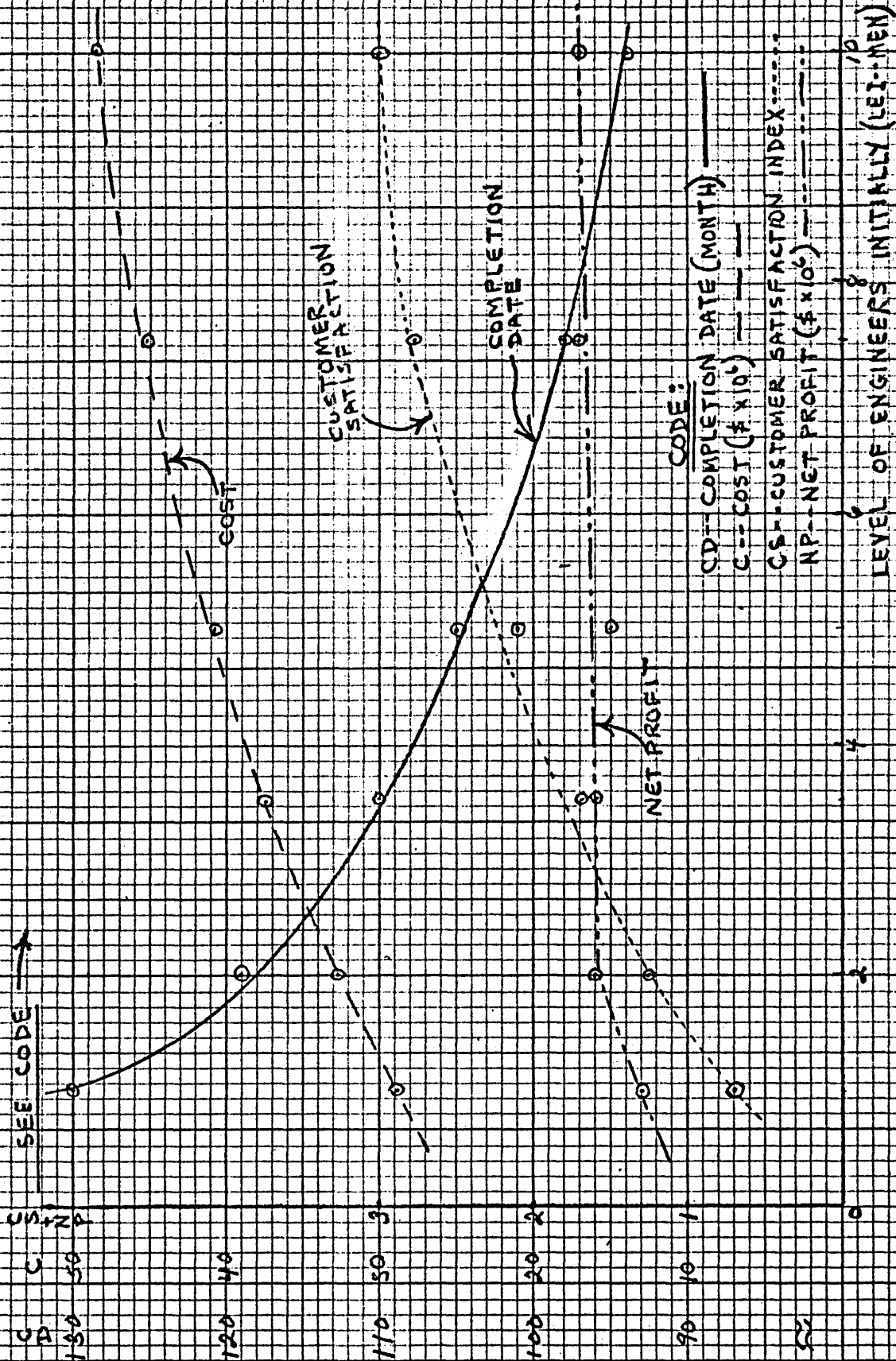


FIGURE 12-3 EFFECTS OF INITIAL STAFF SIZE

one engineer. His initial work, combined with other knowledge and beliefs of his company management, led to the gradual increasing of staff on the project and eventually to the major activity phase of the research and development project life cycle. For the simulated runs used in Figure 12-3, however, the initial "research" staff was set in different projects at a level of as many as ten people, producing the graphed results. The greatest effects take place for the first few increments in staffing. Moving from the situation of one man working only half-time (not shown on the curves) to one man full-time changes the job from only partial completion to one which is fully completed but with some accompanying customer dissatisfaction. Adding one more man to the initial staff brings up the customer's perceived value received to beyond the "satisfaction break-even point" and also reduces the completion time by eleven months. These results perhaps demonstrate the "critical mass effect" of an initial threshold level of engineering effort concentration that is needed to "get the ball adequately rolling". Beyond this number, the still further increases in initial staff size do cause more benefits, but at a gradually decreasing rate of change.

Especially when viewed from a practical light, the outcome of these tests of initial staff size effects seem encouraging. For example, staffing an initial project study group with three men instead of one man produces results comparable (in terms of completion date, cost, and customer satisfaction) with cutting the over-all engineering training time down to nine months while avoiding any decreased effectiveness. The higher staffing, however, can reasonably be accomplished,



given the availability of somewhat more money and manpower initially, whereas the severely decreased training period is highly unlikely, particularly without serious counterbalancing effects on engineering productivity. Again, from a practical viewpoint, the results bear upon management decisions as to how many men to put on a preliminary study contract, or as to how many different projects a limited engineering staff should try to keep active.

Since the implication of these results is that research and development firms should be induced to accept higher risk on any project through larger initial manpower and monetary commitments, the curve of net profit to the firm, also shown on the preceding figure, is of interest. It demonstrates the existence of very little short-term financial incentive for the firm to adopt policies beneficial to the customer's derived utility from his research and development support. It seems reasonable that the customer's policies, therefore, with respect to his criteria for awarding contracts and/or for setting the rate of compensation for research and development projects, ought to reflect an attempt to encourage these apparently desirable staffing practices. To an indefinite, relatively insignificant, and grossly inconsistent extent, such a policy does get followed by government contracting agencies today. This practice needs great strengthening before its potential effectiveness can become realizable.

One way of summarizing the results of the two policy approaches suggested here is to examine the relative effectiveness of the two in meeting the same objective. Figures 12-2 and 12-3 show, respectively, the effects of training period and initial staff size on project cost

and completion time, and the satisfaction of the customer with the project outcome. Since, at least theoretically, a research and development project is sponsored by a customer to satisfy the needs he recognizes, the customer satisfaction criterion seems a good one for analysis of the effectiveness of the two approaches. To achieve this resultant each of the curves was examined to find which value of training time (or initial staff size) produced customer satisfaction indices 1, 1.5, 2, 2.5, and 3. The training time and staff size values for each index number then served as the horizontal and vertical axis coordinates of the new Figure 12-4. These points were joined to form a tradeoff curve which shows, at each point, the alternate policy parameters which can achieve the same customer satisfaction result. The curve shows, for example, that in our typical project simulation either a training time of about seven and one-half months or an initial staff size of about four and one-half engineers can achieve a customer satisfaction measure of 2, which indicates a perceived 100 percent rate of return on the project investment.

The tradeoff curve emphasizes not only that "there is more than one way to string a cat", but also that the relative desirability of the two alternatives can be subjected to analysis. If it is equally difficult to shorten training time by one month (while maintaining training effectiveness) as it is to increase the initial staff by one man, then the slope of the tradeoff curve indicates the more effective policy approach. When operating in the region to the left of point A on Figure 12-4, decreasing training time would produce better results, while increasing staff size would be more effective to the right of

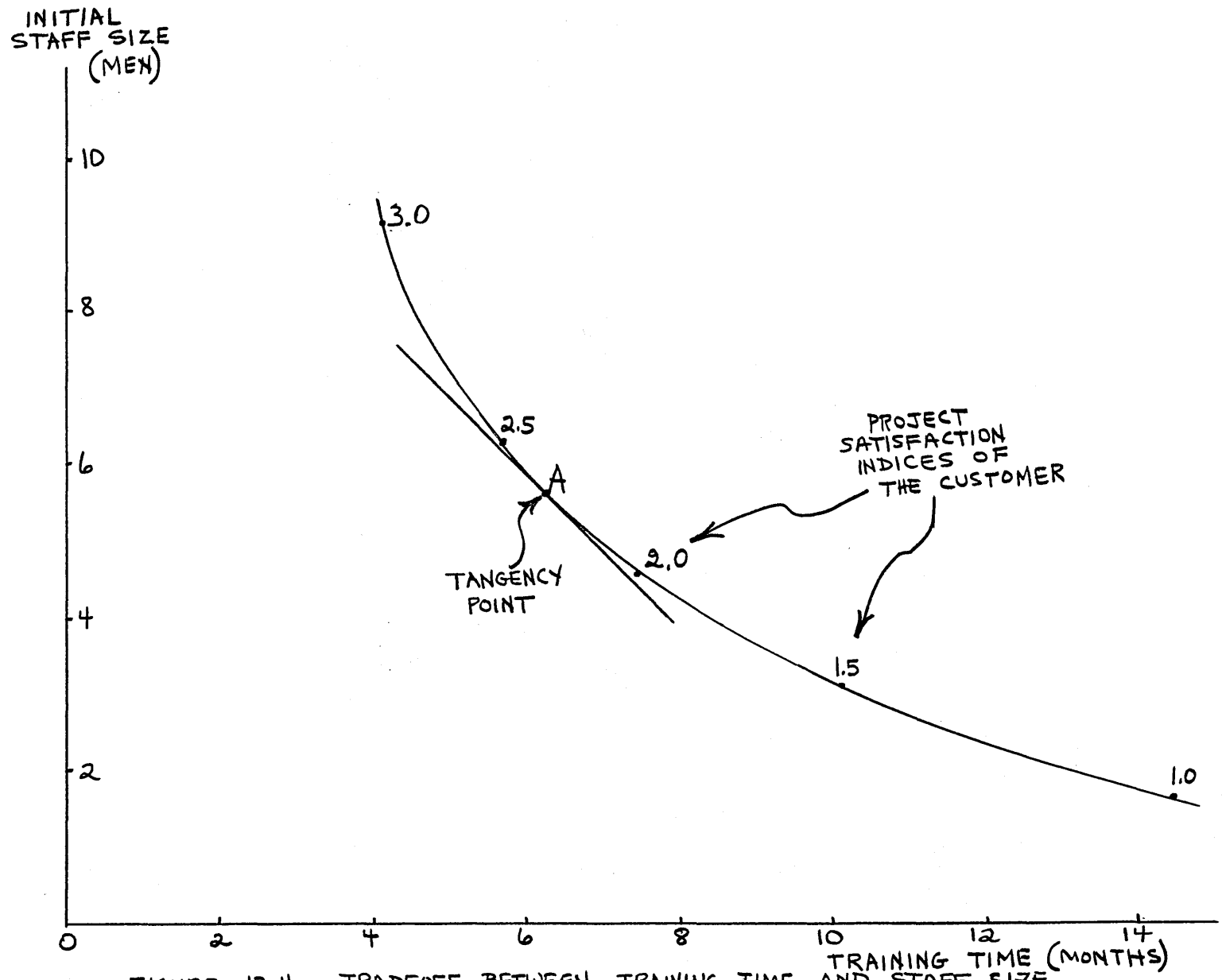


FIGURE 12-4 TRADEOFF BETWEEN TRAINING TIME AND STAFF SIZE

point A. This particular analysis, however, is not correct, since it is extraordinarily more difficult to cut the training period by a month than it is to add another engineer initially. But the general methodology outlined is meaningful and with a much greater input of effort than seems appropriate here could be extended and applied to tradeoffs between other policies, using perhaps other objective criteria, as well as to the example demonstrated.

#### Effects of Organization Size

In our Chapter 5 discussion of engineering productivity, the size of the engineering work force was cited as influencing the organization's effectiveness, pointing out the inefficiencies which arise as the organization grows.<sup>2</sup> Problems of poor communication, organizational inertia, strangling red tape, and low motivation of engineers all plague the typical large project group. To be sure, some exceptional organizations avoid these size effect problems. More usually firms suffer from the size inefficiency effects. The typical project model studied to this point, however, did not directly include any size influence on the productive effectiveness of the engineering team. Now, to see if this factor really matters, inefficiency due to the size of the engineering manpower force shall be introduced and studied.

Previously, the engineering output of the firm depended upon the number of engineers, distributed according to experience and project utilization, the relative productivity of each engineering category, the percent of engineers not at work due to holidays or sickness, etc.,

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<sup>2</sup>R. B. Kershner, "The Size of Research and Engineering Teams", IRE Transactions on Engineering Management, Vol. EM-5, No.2 (June 1958); p. 35.

the available state of the technological art, the managerial ability of the firm, and the engineers' experiences on the current project. To this, we now add consideration of an over-all inefficiency due to sheer size of the organization.<sup>3</sup> The figure below pictures our assumption as to the size effect on organizational efficiency. As the size of the organization grows, its work efficiency decreases, slowly at

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<sup>3</sup> The initial engineering productivity formulation is pictured in Figure 5-7 and developed in Equations 5-59 through 5-66. The engineering output rate itself was written as:

$$\text{ENPRF.KL} = (\text{UTEF.K})(\text{MEPIK.K})(\text{RPEWF.K}) \quad 5-66, R$$

We now write instead:

$$\text{ENPRF.KL} = (\text{UTEF.K})(\text{MEPIK.K})(\text{RPEWF.K})(\text{SEEF.K}) \quad 12-1, R$$

$$\text{SEEF.K} = \text{TABHL}(\text{TSEEF}, \text{ENGRF.K}, 0, 750, 50) \quad 12-2, A$$

$$\text{TSEEF*} = 1/1/.95/.875/.8/.7/.625/.575/.55/.54/.53/ \\ .52/.51/.50/.5/.5$$

ENPRF--Engineering Productivity rate of Firm  
(effective man-months/month)  
UTEF--Utilized Technological Effectiveness at  
Firm (percent)  
MEPIK--Multiplier to Engineering Productivity  
due to Increased Knowhow (percent)  
RPEWF--Relative Productivity of Engineers actually  
Working at the Firm (effective man-months/month)  
SEEF--Size Effect on Efficiency of the Firm (percent)  
TSEEF--Table of Size Effect on Efficiency of the Firm  
(percent)  
ENGRF--ENGINEERS at the Firm (men)

The table values of TSEEF are taken from the curve of Figure 12-5. The values correspond to engineering organizations whose sizes range up to 750 men. This limit is incorporated in the SEEF equation through use of the DYNAMO TABHL function which treats all input values as if they lie in a permissible table range.

first, then diminishing more rapidly as the size gets still larger, and finally tapering off to an over-all effectiveness equal to half the normal amount. No evidence exists to either substantiate or refute this or any other curve of efficiency versus size of organization. The existing curve will serve adequately for our exploratory studies.

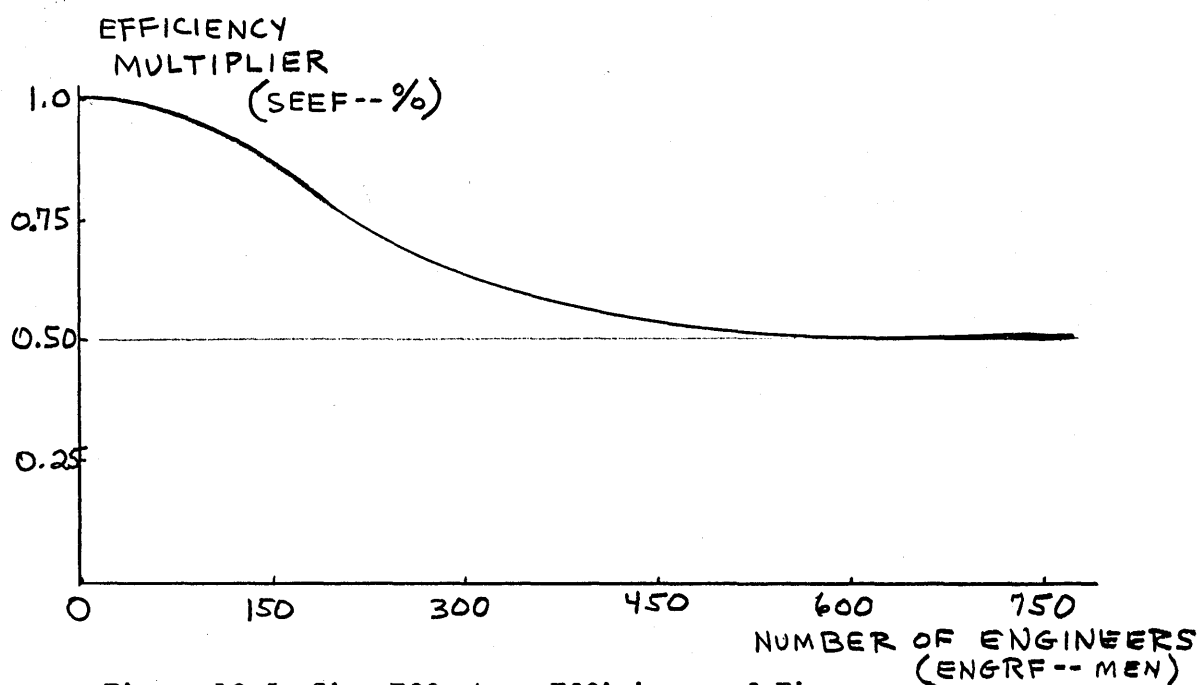


Figure 12-5 Size Effect on Efficiency of Firm

Three sets of analyses were made of the project model with the size effect included. The first of these examined the size effect's influence upon project results, when the basic scope of project is varied in magnitude. In Figure 12-6 the outputs of this set of simulations is compared to Figure 9-1, in which extensive variations of job magnitude sans size effect were reported. Many of the obvious expectations can be observed here. First, due to decreased efficiency as the organization grows, every job costs more to get done. Secondly, for reason of the same lessened efficiency, every job is completed at a

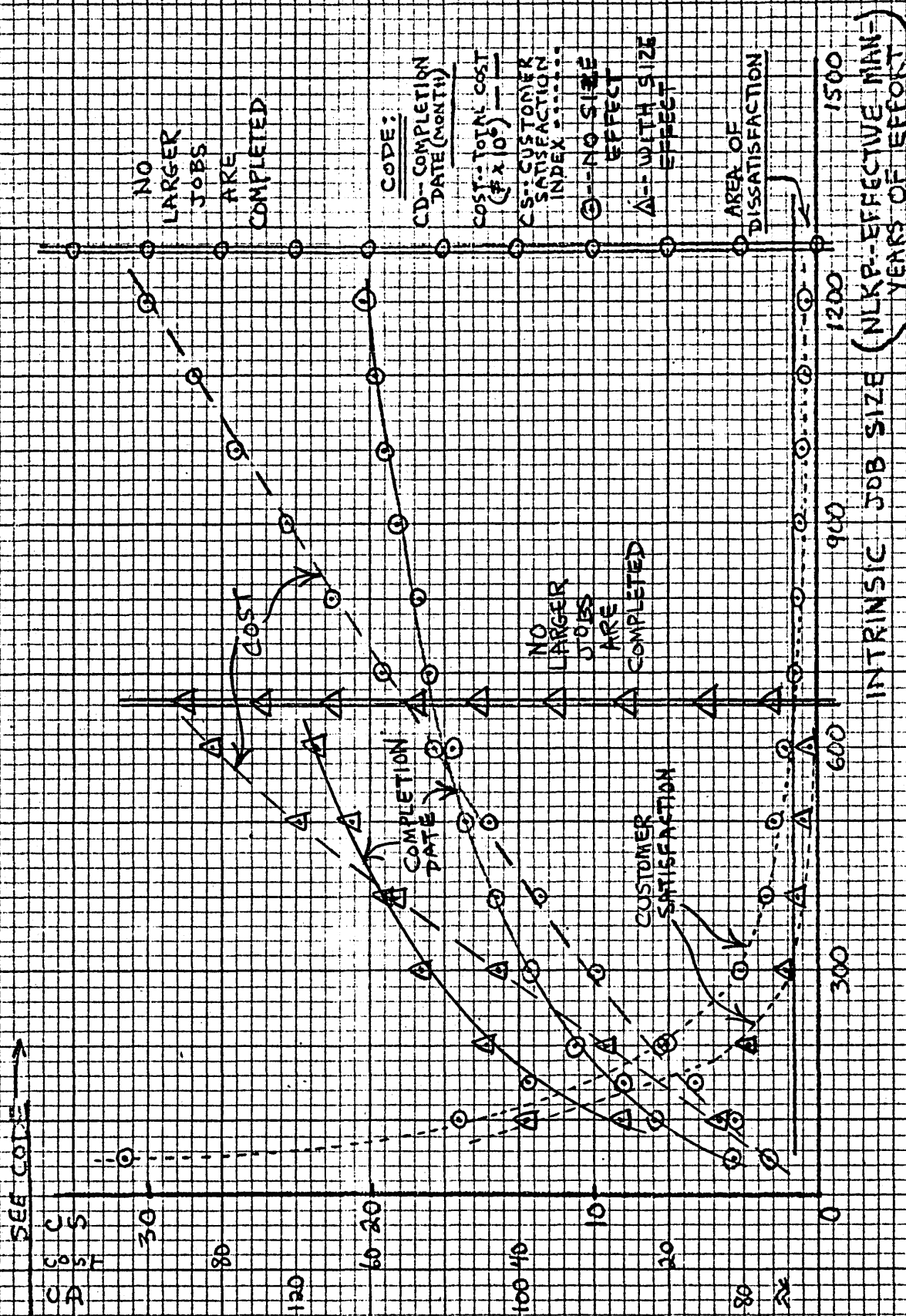


FIGURE 2-6 EFFECTS OF JOB SIZE ON PROJECT OUTCOME

later date. Third, customer satisfaction is accordingly reduced on all jobs, for reasons both of the higher costs and the delayed completion, hence lowered finished product-value perceived. Finally, the lowered satisfaction of the customer causes him to cancel a greater number of the projects, some of which did get completed under our earlier considerations. What perhaps was not expected is the fact of the great similarity in the nature of the new resultant curves with the earlier outcomes. Costs, for example, do not rise nonlinearly upward due to the decreasing effectiveness, as might have been assumed. Nor does completion time soar as jobs get bigger and organization size larger. In the cases illustrated here the non-"organization-size" influences on the project seem to determine the characteristic nature of the results, with the size efficiency factor affecting only the magnitude of the results.

The second type of effect examined under the added pressure of engineering size inefficiency was that of the expansion ability of the firm, shown earlier in this chapter in Figure 12-1. Again, as can readily be seen from the next diagram, Figure 12-7, the size inefficiency of the firm causes increased cost, delayed completion, and decreased project satisfaction by the customer. But again, although the scales may be shifted, the basic character of the research and development results is unchanged.

The final variation attempted, using the organizational size effect on efficiency of engineers, was to test the response to changes in customer scheduling of project. This again causes higher costs and later completions, with attendant lower satisfaction. Again this



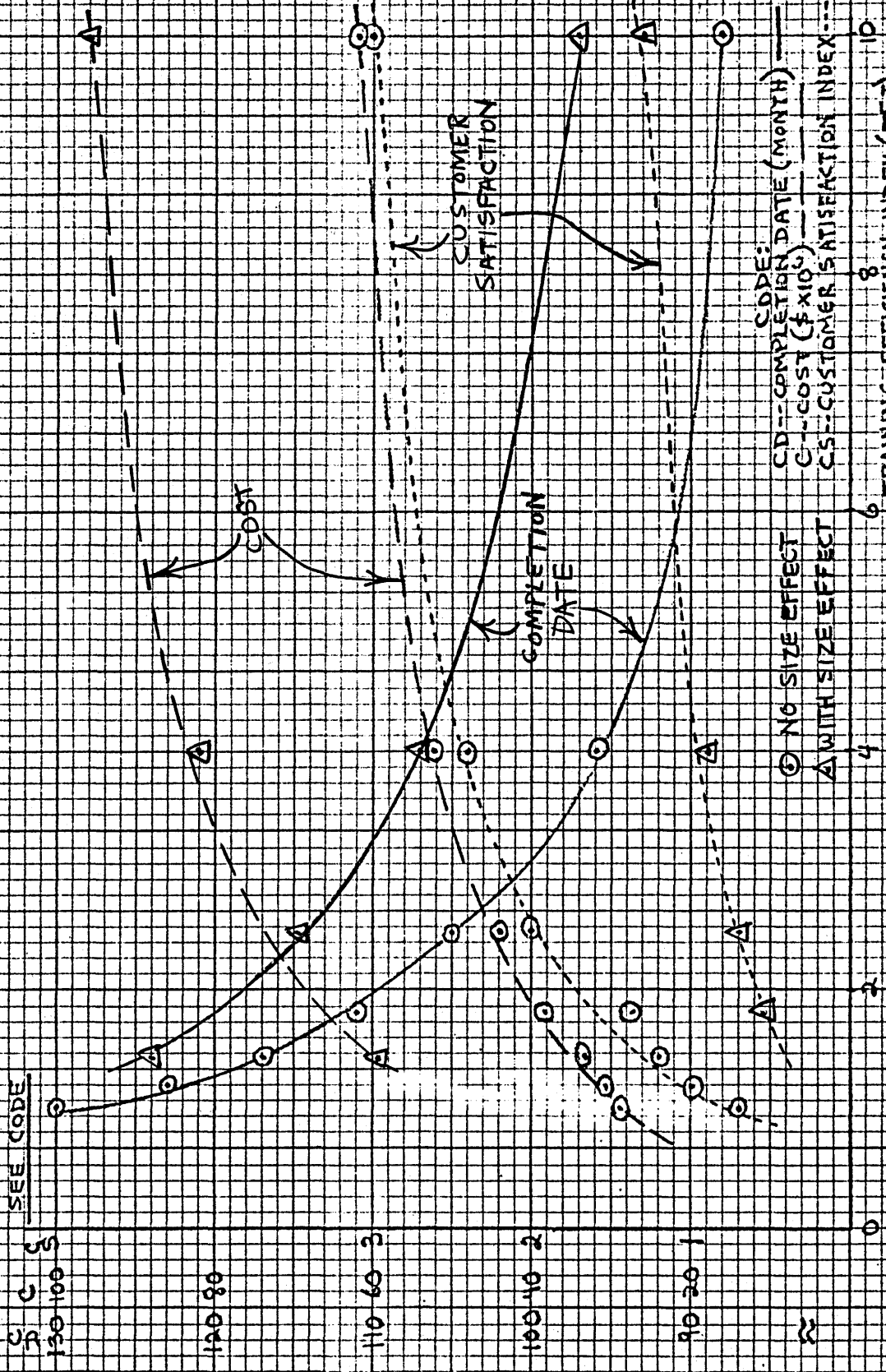


FIGURE 12-7 EFFECTS OF TRAINING EFFICIENCY, WITH AND WITHOUT SIZE INFLUENCES

takes place without disturbing the basic nature of the earlier results that were produced with no size inefficiencies. Here in Figure 12-8, we have also shown the peak engineering work force utilized with and without size effect on engineering efficiency. The lower efficiency results show that many more engineers are employed on the project, causing greater disturbance to the job market than in the full efficiency cases. Once more, however, this change appears more as a shifting of the curves rather than a real modification of their character.

From these experiments, one can conclude that the effect of increased organization size on project results, even when one directly assumes decreased effectiveness accompanying increases in size, is of a scaling nature only. The basic character of all the output curves drawn, and the conclusions drawn in earlier chapters, are not at all affected by explicit recognition of organizational size inefficiencies. This factor was thus appropriately left out of the typical project model and should not concern research and development managers, except to the extent they believe that they can limit the size of their project teams to below several hundred people. In the larger projects such a demand will require a new organizational approach, a different project schedule, or a very lengthy absorption process that will maintain engineering effectiveness despite organizational size. Further consideration of all of these alternatives is beyond the scope of our current efforts.

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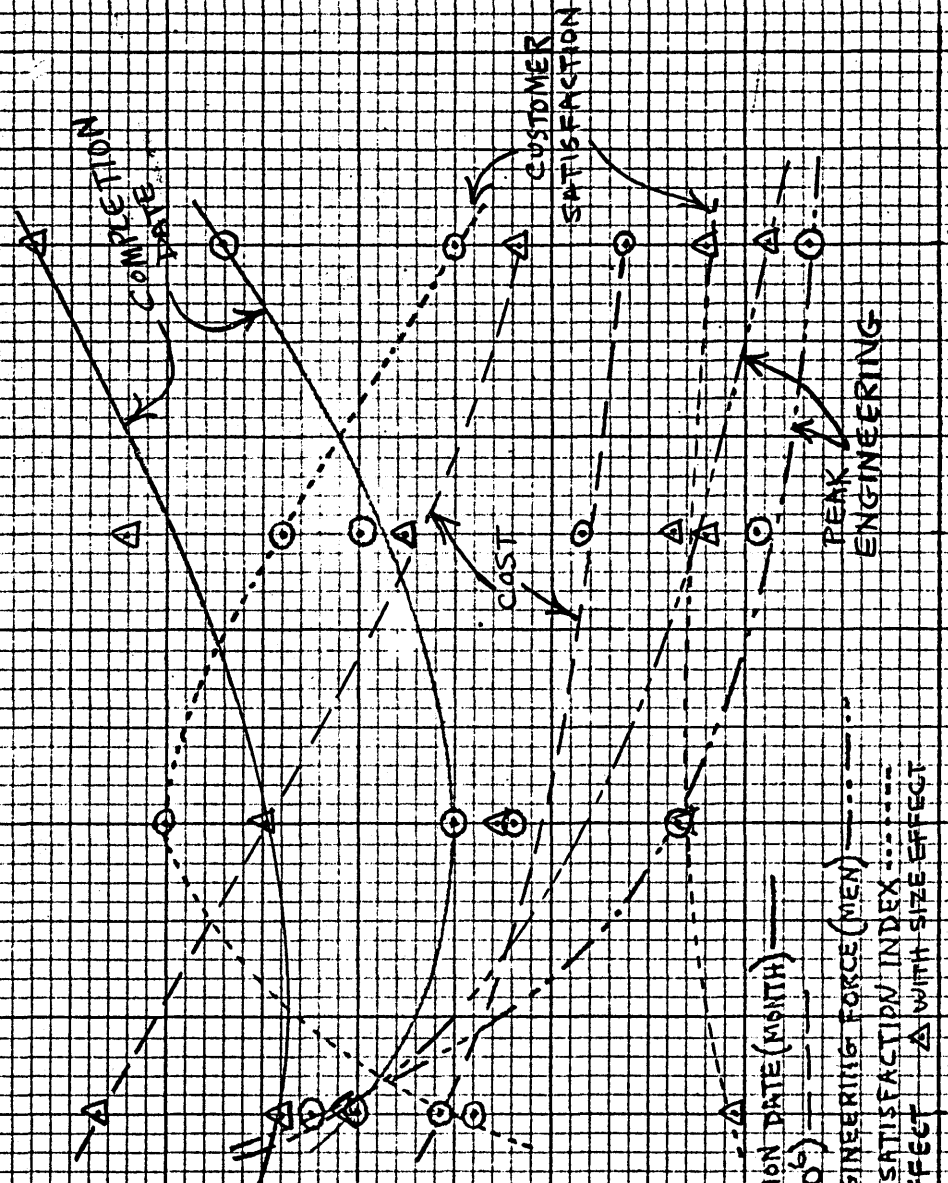
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 C--COST (\$ X 10<sup>6</sup>) ———  
 PE--PEAK ENGINEERING FORCE (MEN) -·-·-·-  
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21

12

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FIGURE 12-8 EFFECTS OF CUSTOMER'S SCHEDULED PROJECT DURATION

## CHAPTER XIII

### SUMMING UP AND LOOKING AHEAD

This chapter will perform two functions, providing a summary of the major conclusions of the preceding work and a designation of that further study and research which now seem needed as a result of this investigation. The summary is divided into four sections: (1) a restatement of the dynamic systems theory of research and development projects which formed the basis of this study; (2) a brief review of those factors relating to the research and development product, customer, firm, and process which emerge from the simulation studies as vital in their consequences to project behavior; (3) a discussion of the additional findings of this research effort which appear important to those both in government and industry who formulate and administer the policies of research and development; and (4) an analysis of the general applicability of this study approach and results to all types of research and development undertakings. The additional studies recommended in the latter part of this chapter are themselves divided into two parts: (1) suggested extensions of the model-building and simulation approach utilized here, to add more depth or breadth to investigation of research and development management problems; and (2) data gathering and analysis undertakings which seem necessary to pinpoint more exactly the sensitive parameters and critical policy variables of research and development.

A Dynamic Systems Theory of Research and Development

The chapters of Part I described and the results of Part II verified the validity of a dynamic system theory of research and development project behavior. This system encompasses interactions between the manifested characteristics of the research and development product, the firm, the customer, and the processes relating to the nature of the work itself. These interactions take place continuously in the context of the life cycle of research and development projects. This life cycle was pictured in the following form:

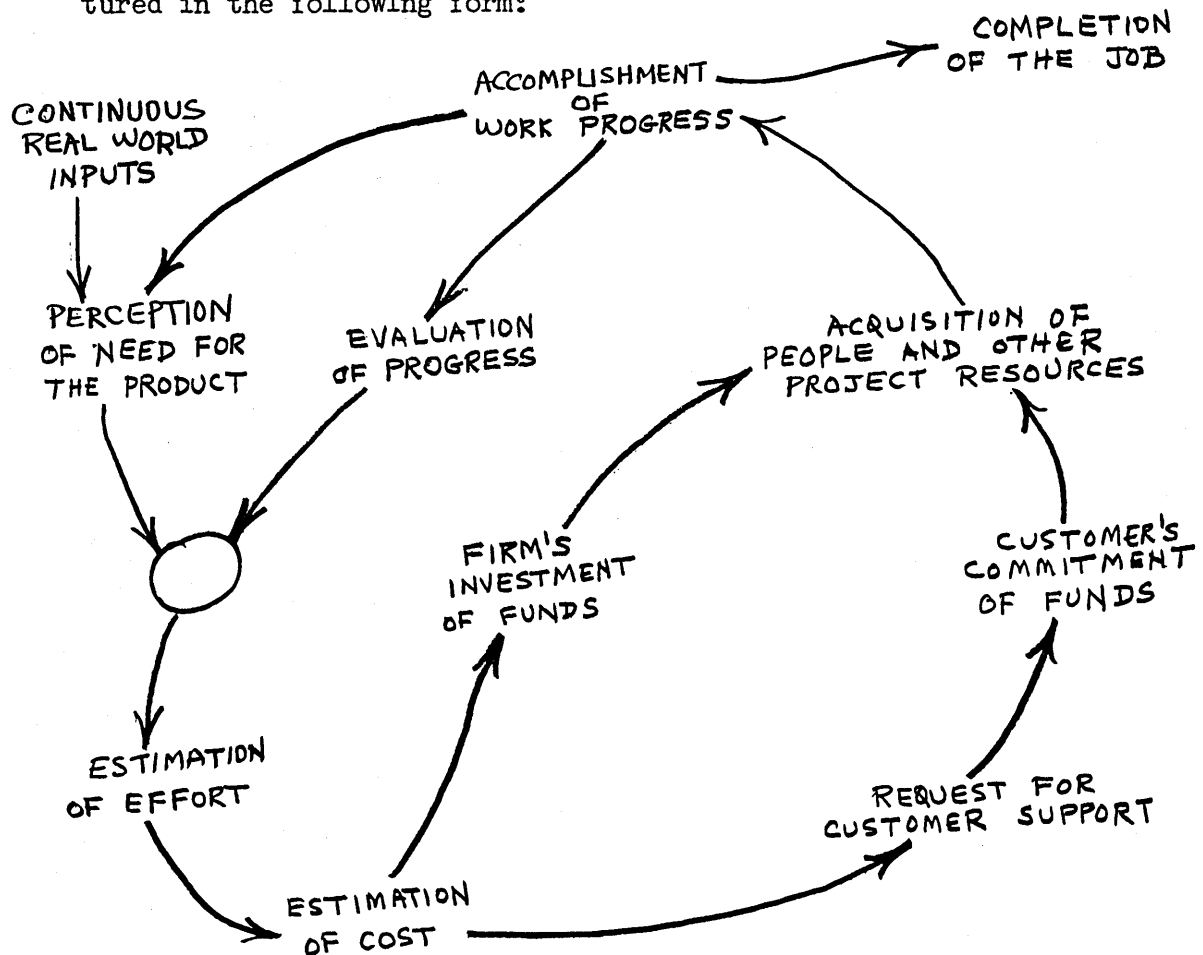


Figure 13-1 Dynamic System Underlying Project Life Cycles

Its closed-loop activities include several stages, initially sequentially phased in time but becoming a continuously ongoing set of activities once the project has gotten underway.

These activities include:

1. the perception of the need for a new product by the customer and/or the firm;
2. the estimation by customer and/or firm of the amount of manpower effort required to develop the product;
3. the estimation of costs corresponding to the expected effort requirements;
4. the firm's request for financial support by the customer; followed by,
5. the customer's evaluation of the funds request with respect to the expected cost-value character of the proposed project, leading to the commitment of customer funds in those projects which continue to further stages of development: or,
6. instead of, or in addition to, the request for funds from the customer, the firm may initiate the investment of its own funds in the project;
7. the undertaking of project-oriented effort, including the hiring of an engineering staff;
8. the employment of the technical staff and the consequential accomplishment of job progress;
9. the attempt at assessing the degree of project progress;

10. the reformulation of project effort estimates and value estimates, based on the newly achieved project know-how, producing re-evaluation of the suitability of the project for continued customer and/or firm investment; and finally,
11. the continuation of the ten activities indicated above until the desired results are achieved and the job is completed, or until the project is cancelled at some stage prior to job completion.

Since these general activities contain within them the elements of research and development life cycles for projects both large and small, the representation of research and development requires detailed description of only those ten phases. This general representation was accomplished in the chapters and appendices of Part I.

#### Factors of Consequence in Research and Development

By means of the simulation experiments described in Part II the key influences upon research and development success and failure were isolated and studied in depth. The factors of consequence emerging from these studies can conveniently be grouped into four categories: (1) those characteristics relating to the product under development; (2) the critical factors involving the research and development firm; (3) the customer's determinant aspects; and (4) the influences resulting from the very process of doing research and development work.

Turning first to the product itself, research determined that

three basic factors were important influences on the outcomes of research and development projects. These characteristics were: (1) the intrinsic job size of the product, measured in terms of the amount of effective engineering effort demanded by the size and complexity of the task; (2) the intrinsic product value, measured by the amount of money an all-knowing society should be willing to pay to receive the product benefits at any given time; and (3) the state of the product technology, also called the state-of-the-art or the technological progress, which factor contributes to the changing potential effectiveness of engineers who are working on the project. All three of these factors were thoroughly explored by use of simulation investigation methods and all were found highly consequential to project behavior.

Five characteristics of the firm were then studied to determine their importance to research and development. Of these, three were found to have major significance over a wide range of variations: (1) the over-all quality of the firm, which directly influenced the firm's estimation ability and engineering productivity, and indirectly affected most of the time delays in perception **and action**; (2) the firm's willingness to accept risk, or the firm's risk-taking propensity, as measured by the percentage of expected profits a company would invest in a project prior to contract receipt; and (3) the integrity of the firm, which indicates the extent to which a firm would admit its internally-held project cost estimates to the customer during the bidding acti-



vities. A fourth factor, the financial resources of the firm, was found to be important only under conditions of extremely prolonged financial limitations, which had effect by preventing the firm's exercise of its normal risk-assumption function. Finally, a fifth characteristic of the firm, the average size of the firm's previous jobs, was shown in the simulations to have no effectiveness except for slight cost influence. The earlier theoretical assertion that this factor is important can be borne up only to the extent (possibly considerable) that the previous job-size experience affects the style or strategy of doing the job, which variables were omitted from the model representation. These results do not question the importance of the previous experience of the firm with respect to the areas of technical activity. Such experience largely determines at least the initial technical effectiveness of the engineering organization and is no doubt significant to research and development results.

The customer characteristics were also investigated in the simulation phase of this Industrial Dynamics study of research and development management. The results, as reported in Chapter 11, showed that project results are sensitive over a wide range of variation to but very few aspects related to the customer. For example, while the direct effects of customer quality on job outcome seem almost nil, the indirect effects, as manifested in the length of the customer's funding delay, are consequential to project results. In particular, the project completion date responds

in a sensitive manner to changes in the customer's funding delay. Furthermore, the risk-taking propensity of the customer can have substantial effect on research and development behavior, with conservatism by the customer being particularly able to doom a project to failure. The other customer factors studied are important only at their extremes: a very large average size for the customer's previous jobs can harm project results; an extreme (more so than for the firm) lack of funds by the customer can doom a project; and extremely low customer confidence in the firm can affect project results.

Finally, two problems which seem to relate to the process of doing research and development work were also investigated. The first area, that of achieving rapid-enough expansion of a technical organization was found to be of critical importance. Two possibilities for achieving the required expansion ability, namely, (1) decreasing the training time period for new engineers, and (2) increasing the initial size of the engineering organization, were explored and found to be able to strongly influence the project results. The second problem, that of decreased effectiveness due to the size of the project organization, was also studied. This added source of inefficiency was found to contribute only a scaling effect to the previous project results, without significantly altering any of the characteristic behavior produced in the projects.

Findings of Importance to Research and Development Policy-Makers

This study of the dynamics of research and development has been no doubt both long and involved for the people reading. It seems especially vital, therefore, before concluding, that those findings of particular import to managers of research and development firms and to their customers be brought into focus here. These findings are of two types: (1) some general observations about research and development projects; and (2) specific conclusions which pertain to the factors of consequence to project results, which conclusions may recommend specific policy moves.

A first general observation, discussed earlier in this chapter but repeated here for emphasis, is the apparent importance of the project life cycle concept used as a basis for our inquiry. This orientation to the ongoing interconnected circular flows of activities in a research and development undertaking provides some handles for getting a better grasp, an improved insight, into research and development operation. In looking more closely at these entire cycles, one can make another observation of interest regarding the perhaps surprising length of the typical time-duration of the complete life. This length results from the necessary inclusion in the life cycle of that preparatory portion wherein little activity or even thought may be obvious to the random observer. But project life cycles do include a very lengthy startup time, usually not recognized, during which period customers and firms begin to recognize the potential value of a product, begin the actions leading towards the product's development,

begin to process the initial funding requirements, and finally begin recruiting, training, organizing, and making productive an engineering team. All of these ought to be recognized as integral parts of the project process.

A second general conclusion is that timing considerations seem very consequential to research and development decisions. In particular, whether a project gets completed or instead gets cancelled by the customer seems to depend upon the timing of a critical perceived value-cost ratio by the customer. Furthermore, if, very early in the product value life cycle, the cost is expected to become low enough to produce a favorable value-cost ratio (given the customer's investment criterion), then the project will be funded and probably ultimately completed. If, however, the favorable value-cost relationship is not perceived until much later, then it is likely that this relationship will become unfavorable before the project has a chance to be completed, then inducing customer cancellation of the project.

Another observation of a general nature relates to the denied similarity between one factor's label and its implications. Specifically, the scheduled project duration had very little influence upon determining the observed project duration. This is particularly noteworthy since the most widely acclaimed current management fad is P.E.R.T. (Program Evaluation Review Technique) and the closely related critical path scheduling methods. Here, the whole concern is with continuous project schedule redetermination with speci-

fication of expected project bottlenecks. This whole approach, with apparently no proven merit to research and development has received wholesale approval, with attendant incorporation into contract specifications, of the government customers of research and development. It is significant to note then that our investigation showed that the factors which really dominate the timing of project completion exist apart from the intended schedule. Project completion time is far more seriously influenced by such factors as the company's risk-taking propensity and general quality, the customer's funding delay, and the ability of the firm to expand its organization rapidly while maintaining its effectiveness.

With respect to the latter reference to the importance of efficient growing capability of a research and development firm, the observed costs of this growth process deserve mention. In typical projects simulated the costs due to needed growth of the organization added about 70% to what the project might optimally have cost. These costs are divided between the direct supervisory and training costs for the new personnel and the indirect costs attributable to the lowered effectiveness per new engineer. These growth-dependent extras thus constitute about 40% of the total actual project cost. Such an observation commends the advisability of both managerial attention to and corporate investment in the process of engineering training and development and in fact in the entire approach to project organization.

One final general problem seems worthy of comment. It seems likely that the common process of evaluating project performance (in fact, most corporate activity) by the most readily attainable, traditional, and tangible measures may well mislead research and development managers into instituting or extending policies that are actually harmful. This is illustrated by the experiments on the effects of the customer funding delay. Stretching this delay out somewhat did in fact reduce costs slightly; i.e., by not rushing into the project the customer delayed major activity until a more advanced technology helped produce a small savings in effort and cost. If the customer realized that the lengthened delay produced the lowered costs he would likely continue or even further extend this policy. Moreover, because costs are tangible and easily accounted, it is likely that the customer would in fact become cognizant of the policy results. The diminished countervailing factor, the perceived product value, could possibly escape notice because of its lack of solid measure. Thus, by relying on the available and traditional cost measure of performance, the customer is liable to be misled into believing that a lengthened funding delay is effective. Should he further this policy, as was shown in the simulation studies, the customer would eventually discover that this policy wipes out the previous cost savings and, more importantly, significantly delays project completion and produces heightened customer dissatisfaction.

In concluding these general comments it seems appropriate to comment on the model-building and computer simulation approach used

in this study. This inquiry demonstrates the feasibility and effectiveness of such an approach even to those areas of socio-economic activity which are laden with intangible but consequential influences. This applies not only to the management of research and development but also to other top-level corporate areas. The model-building sharpens the precision of ideas relevant to the area under investigation, while the simulation brings out clearly the dynamic interrelationships of the system and allows immediate determination of the implications of changed hypotheses.

The specific conclusions derived from the study are organized to coincide with the corresponding factors of consequence to research and development that were listed earlier in this chapter. The first set of these conclusions relate to the intrinsic product size. The investigation pointed out that as projects increase in their basic size (and complexity) three tendencies exist: (1) total project costs increase; (2) completion is achieved at a later date; (3) decreased product utility remains when it does become available. These characteristics tend to produce decreased customer satisfaction on larger projects, leading to gross disappointment on some jobs, a feeling that the final product is "obsolete" on still other tasks, and actual cancellation on some other projects. The feeling of obsolescence really indicates that the customer perceives the product value as being very low compared to earlier beliefs as to what this product would be worth when ready, or, even more likely, compared to what the

project actually cost.

The costs in research and development projects of the same general type seem to proportionally change as the intrinsic magnitude of the task changes. This phenomenon was observed in the simulation studies even when inefficiencies due to organizational size were added to the picture. But whereas cost shows this linear cause-effect relationship to job size, both the project completion time and the customer satisfaction measures display nonlinear saturation-type effects as projects grow in basic job size. This shows, at least beyond some point of research and development project size, that completion time and customer satisfaction are relatively independent of the size of task.

Three major conclusions can also be drawn from the experimental variations in the intrinsic product value: (1) the consequence of a change in the intrinsic product value inputs are far more significant than the degree of change itself; (2) these results are largely dependent on the time-variation of the perceived value-cost relationship, more than on either cost or value alone; and (3) changes in the value input produce important indirect effects on such things as completion dates and project costs due to the direct influence of the value changes on the over-all project scheduling. The initial conclusion here shows the extent of amplification which exists in the research and development system, making small shifts in society's underlying need for a product have large effects on project outcomes. The second observation



points up the fact that intrinsic product value has no necessary relationship to the intrinsic magnitude of the job. Hence, product value has no necessary relationship to the cost of achieving the product. Thus, it is important to note that while value and cost are independent of each other, it is their effect in combination that is the critical influence on evaluation and funding decisions, and on ultimate customer satisfaction. To add more clarity to the observed third effect of value on the system, let us review the result of an assumed lowering of the input value curve. With lower initial growth of perceived product value accompanying this lowered input, enthusiasm for the project is slower in building up and is lessened at any point in time. This retards funding and hence effort on the project, thus causing later job completion. In this manner perceived value at the time of completion is lowered by two factors: first, the initial assumed lower input; and second, the lowered value resulting from completion at a later point on the declining value curve. Thus, perceived value at completion time is doubly damaged, and customer satisfaction falls correspondingly.

The final product-related characteristic that was found significant was the technological progress. It has an important influence not only on the effectiveness of the engineering effort, but also on the perception of expected project cost and on the investment decisions which depend on that perception. For the project situation in which related technology appears to be at a standstill, neither the customer nor the firm is apt to be moved toward early

enthusiasm about the project prospects. In the more usual case of rising technological progress, the changes in technology create influences upon the cost estimates of both customer and firm. These participant organizations expect further technological progress and lowered costs, and they enter a project, to at least some extent, on the basis of expectations that a favorable value-cost relationship will occur in the near future. Without such progress occurring, the rationale for a projected lowering of costs is missing. With technological progress goes one of the important influences helping to get projects under way early enough to end in successful (and satisfactory) completions.

The second source of the system characteristics of importance to these conclusions is the firm doing the research and development work. Its most vital character is its basic capability which permeates the firm's operations. Relatively small changes in the over-all ability of the firm produce far more significant results on projects, the extent of this amplification factor increasing nonlinearly as the firm's ability declines. Thus small improvements in the existing capability of research and development firms can produce very important successes before diminishing returns to such improvement efforts begin to become important considerations.

The next characteristic or perhaps policy of the firm that is very important is risk-taking. By risk-assumption alone, a firm can in some cases change a venture from failure to success.

Some projects, of course, are just inherently too big and costly to ever be completed, regardless of the degree of risk-assumption by the firm, unless a major upward revision should first occur in the value structure of the customer. But in those projects in which the dangers of loss to the firm are greatest, i.e., those which are least cushioned in terms of their potential value-cost relationship, the influence of the firm's risk-assumption on resulting project behavior is also greatest. Increased risk-taking by the firm gets jobs finished sooner for those which do reach completion, and pushes progress to a further point even for those projects which get cancelled before completion. This effect of risk-assumption on project completion is a nonlinear one, with some minimum threshold level of risk-taking needed before significant changes in results begin to occur. Added hesitation due to more conservatism (i.e., less willingness to accept risks) does somewhat lessen project costs, since project timing is delayed and the firm uses a slightly advanced technology on the job. The cost savings due to conservatism do not compensate for the loss in product utility caused by its later availability. One difficulty in all this is that a dire lack of funds may prevent the firm from following the risk-assumption policies needed for project success.

From a policy-maker's viewpoint it is interesting to note that whereas risk-taking by the firm does definitely advance the customer's interests, the firm's profitability on the particular project is not similarly aided, and in fact seems lessened.

There is then a conflict between the customer's project satisfaction objectives and the firm's profitability objectives. The customer must therefore modify his policies so that it is also beneficial to the firm to undertake needed risk. Some change in contracting policies is desired that will provide incentives to companies to make available early funding for research and development projects. One way of doing this is to offer a higher percentage fee to a company which has invested its own monies in the project. Or, the customer could adopt a more generous attitude towards repayment of certain risked expenditures of the firm. Other changes might include the suggestion of a broadly-based reorganization of the entire customer-firm relationships in research and development. This latter idea is beyond the scope of this discussion.

Another characteristic of the firm which has vital bearing on policy-making is the firm's integrity. A low integrity, resulting in significant underestimates of project cost, can produce job failure. It does this by inducing a reduced initial rate of funding and engineering effort, and a slower initial rate of job accomplishment, thus delaying recognition of real expected costs until a time when these costs are more likely to appear unfavorable relative to the perceived product value. This phenomenon causes project stretchout by the customer and cancellation. It is interesting to again call attention to the simulation results which showed that the firm does not suffer in its profits from low integrity

in the short-run, whereas the customer's desired project satisfaction is decreased by low integrity of the firm. Thus, the company management which seeks short-term profits under the existing government contracting system may well be influenced to intentionally underestimate project cost requirements. Here, too, the goals of the firm and those of customer seem in conflict, given the rest of the contracting system relationships. To solve this problem, either industrial leaders must take a more long-range view of their self-interest (which may be a naive hope), or major changes must be made in our system of research and development contracting. Such changes should provide a structure of motivation and evaluation that will encourage industry adoption of a high-integrity policy. This action would, of course, have effects on general business ethics, which effects, of themselves, seem worthwhile.

The customer's effects on the project results offer other areas for policy formation. An initial problem arises out of consideration of but one manifestation of the customer's ability, i.e., his delay in approving funding requests. If this delay is too long, it can cause project failure. Government, in particular, is guilty of acting to induce slow-downs, postponements, and the general uncertainty which results from the tangles of red tape. One approach towards solution might include shifting the center of customer project responsibility and decision-making down closer to the work-interface between customer and firm. It may also be wise to shift these customer activities to the part of the organ-

ization intended to use the product.

Another customer ability relates to the customer's project scheduling. Project scheduling time particularly affects the stability of an engineering organization, and also affects the total project cost. Too short a project duration results in tremendous cost and manpower utilization inefficiencies that historically seem to accompany a crash project. However, dragging a project out over too long a period can result in its never getting accomplished. Too long a scheduled duration delays achievement until the product value has almost vanished, and sometimes even to the point of producing project cancellation. Thus, it seems that customer satisfaction would best be served if some middle range of project duration is utilized. For any given project size, such a desirable time scheduling is at least in theory determinable.

Another policy of the customer which can serve to defeat his own ends is a low risk-taking propensity. This policy makes less likely the successful completion of a research and development undertaking.

The simulation studies also pointed up the fact that if the customer's past experience with large jobs leads him to initially overestimate the cost of the project under consideration, the firm is influenced into believing that little likelihood exists for customer support of the project. This induces a lessened willingness by the firm to invest its own funds in the project, causing the same problems which arise from a low risk-taking propensity of the firm. This example again highlights the system of inter-

relationships between customer and firm through which the customer's beliefs and practices, operating upon the firm's attempts to meet its own objectives, affects the decisions and actions taken by the firm. This same phenomenon is confirmed by the finding that customer funding itself is not needed during the early stages of a project life cycle, as long as the customer's attitude toward project potential is encouraging enough for the firm to undertake risk-assumption.

The final source of information important to research and development policy-makers is the series of studies of the research and development process which emphasized two aspects, the process of organizational growth and the effects of organization size. The most obvious conclusion of these studies is that the over-all expansion ability of the firm very sensitively influences project outcomes; the more rapidly the effective growth can take place, the more satisfactory the project results are to the customer. The problem exists in trying to grow while maintaining engineering effectiveness, since if even the effectiveness of the trainees is decreased because of the increased rate of expansion, as obviously occurs in most crash programs, then the project results are no longer obviously desirable.

Two possibilities for achieving a more rapid growth process were studied through model simulation. These investigations demonstrated that reductions in the time required for engineering training and development would meet the needs for more rapid organizational expansion. Particularly the project completion date and customer

satisfaction are extremely sensitive to changes in the engineering training delay. Thus, in research and development work the many months needed to develop new professional talents constitute a vital influence upon project behavior. Companies doing work in the research and development projects can strive to reduce this time period by locating in strong technically-populated geographic areas, by developing competence within the firm which can be drawn off to nurture new projects, or by attempting new organizational approaches to the whole problem.<sup>1</sup> It is not an easy task, however, to reduce the engineering absorption time without suffering some loss of engineering effectiveness. The simulations clearly showed that under such conditions of diminished effectiveness of the training program a decrease in its length may well do more harm than good. In addition, the curves were used to produce a tradeoff curve, showing comparative effectiveness of the two policy approaches (shortened training time and increased initial staff size) on the customer satisfaction criterion.

An alternate way of achieving more rapid project growth was also tested. The alternative used, a higher initial staff size, was found to have excellent effects on research and development results. The greatest effects take place for the first few increments in staffing. This demonstrates the "critical mass effect",

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<sup>1</sup> As one example of an organizational framework different from what is usually encountered, see Forrester's Industrial Dynamics, pp. 329-335.



namely that an initial threshold level of engineering effort concentration seems necessary to "get the ball adequately rolling". These results are important to management policies regarding the number of men to assign to a preliminary study effort, and with respect to the number of different projects a limited engineering staff should try to maintain. The very interesting fact about these findings is that whereas the reductions in training time mentioned above might be near-impossible to effectively attain, the increased staff size is clearly dependent only on the availability of the necessary support funds and personnel, both easily within the realm of implementation.

A final observation with respect to this latter policy for accomplishing organization growth is that the higher risk required of the firm by the increased initial staffing is not rewarded by higher project profits to the firm. Therefore, again, the customer's objectives of project success are in conflict with the firm's profit objectives. The government customer must eliminate this conflict by changing existing policies for awarding contracts and/or for setting the rate of compensation on projects to encourage research and development firms to adopt these apparently desirable-to-the-customer staffing practices. The firm with a longer-range view of its self-interest might well see the wisdom of adopting such staffing policies even without encouragement by the customer, since the increased likelihood of customer satisfaction with the project results will no doubt eventually benefit the firm's own success through improved reputation and increased business oppor-

tunities with the customer. The customer, however, should still seek to alleviate this source of conflict with its own objectives. In addition, the curves were used to produce a tradeoff curve, showing comparative effectiveness of the two policy alternatives (shortened training time and increased staff size) on the customer satisfaction criterion.

#### General Applicability of the Results

This study of the dynamics of research and development has emphasized projects performed by a company for a government customer on a military or quasi-military product. This approach seems to have value for such a situation. But what of other kinds of research and development projects? To what degree can the methods used and conclusions established here be extended to other research and development environments? The answer is that almost all research and development projects can be treated by the broad systems framework and the basic life cycle descriptions adopted. Even the conclusions as to factors of consequence and most of the policy-oriented observations and recommendations have general applicability.

To argue this claim let us examine, very briefly, other classes of research and development activities. First we can take the case of the project performed by a commercial product development company for another firm, as sponsor and customer of the development effort on an industrial or consumer product. Here we encounter exactly the same system as before. The customer and

the firm are two distinctly separate organizations from all formal considerations, each with the same class of characteristics described earlier in the military research and development case. The product, be it for government, industry, or consumers, can be described by the same characteristics used before. To be sure, the product might not be as technologically complex as the usual military product. On the other hand, if we think about some commercial computer systems or industrial precision equipment or any one of our nationally-used communications networks, we find products more complex than many military products. We might suppose that less uncertainty as to product value would be featured in a non-military market. Indeed, this is probably true, but yet who in 1950, even after successful operation of prototypes of modern data processing equipment, forecast the present market value of such equipment? Or, who knew or could regard with much certainty the demand for hula-hoops or Edsel cars? Thus, while some of the parameters might be different in this case from those in our more intensely-investigated research and development example (and we cannot be very certain that they are in fact different), the basic variables, their interrelations, and the conclusions dependent upon these might well be very similar.

Let us take a different kind of organizational situation, one in which the project is performed by the product development division of a company under the sponsorship and financing of a manufacturing division of the same company. This, too, might be a different basic system but in fact it seems like the same

one heretofore considered. The decentralized manufacturing division might feel more friendly towards the company research and development group than in the comparable military customer-private firm case, but certainly many corporate research and development executives would testify to other kinds of feelings for company compatriots in the product divisions. No doubt many manufacturing officers could raise questions as to their confidence in the research and development group that would be very similar to those a government customer might ask of a contracting company. The decentralized product division might be under more pressure to sponsor projects or more pressure to refrain from cancelling such projects than the government customer. Even if this were true (which is doubtful), this difference would be one of degree and not one of basic underlying substance. Thus, it seems that this class of research and development projects fits the same mold as the earlier research and development projects studied. A similar situation also exists when manufacturing and research and development are simply separate functional organizations within the same company or product division. To the extent that the research and development project funding is determined outside of its own function on the basis of progress and prospects, the same kinds of relations observed earlier dominate the project life cycle.

What about the research and development project in which the work is performed within a research and development department on funds allocated by the manager of the R and D organization? Is this not perhaps a basically different situation? Again the

answer must be a definitive "No". Even here we can trace through the entire life cycle of project activities, substituting the manager of research and development at every point we previously referred to the customer, and the project group every time we previously discussed the firm. The same characteristics of product value versus cost, technological change, conservatism of the manager and of the group, experience, ability, integrity, and the other factors of consequence, still apply in the same manner to the same basic decisions. The same questions as to project evaluation, progress determination, funding, scheduling, etc. are all present. And again, while some of the time delays in communication and action and other parameters might be changed, the fundamental system principles and system dynamics remain undisturbed.

In review, we have discussed research and development projects performed by military-oriented research and development firms, industrial new product development organizations, decentralized research and development departments, or project groups within a research division, sponsored by comparable customers, and intended for military, commercial, and consumer markets. All of these research and development activities seem to fit the basic dynamic systems theory of research and development. All these forms of research and development at least contain the elements demonstrated to be factors of consequence in the original study. All the project possibilities appear suited to the same methodology applied here, with good chance that basically similar conclusions would hold for every case. Indeed, the understandings of military-based research

and development projects which have been developed in this investigation have general applicability across-the-board to all research and development.

#### The Need for Further Extensions of This Study

The introductory chapter of this volume described the Industrial Dynamics approach to industrial or economic problems. It consists of several phases:

1. problem identification;
2. verbal description of the dynamic system theory affecting the problem;
3. mathematical model development;
4. computer simulation of the represented system;
5. analysis of results to determine model validity and factor sensitivity;
6. double-checking of and data collection on the sensitive areas of the model;
7. simulation experimentation to help identify improved system parameters and policies;
8. implementation of results of investigation in the real-world problem areas;
9. evaluation of the effectiveness of the changes, and return to the first term of procedure listed above for continuing improvement if necessary.

The Industrial Dynamics philosophy and methodology were applied in the study now complete to the problems of research and development

management. It helped greatly in the creation of a much strengthened understanding of the area. For this reason it seems worthwhile to outline further extensions of this study, amenable to the same approach, which seem able potentially to contribute to an even superior recognition of the determinant factors of project life cycles.

The first type of extension should consist of work entirely within the framework of the existing model. Many parameters and policies were used in this study which might be questioned as to accuracy. These could be subjected to even more intensive investigation to see if, perhaps, any light can be shed on still other areas of importance. With respect to the whole subject of intrinsic value, for instance, one could study very different shapes of value inputs than were examined in Chapter 2 and perhaps bring up new findings. The preceding discussion regarding the general applicability of this study suggested several parameter or policy changes which might be more appropriate to a non-military research and development project. These and others could be examined to test the claim of general applicability of the conclusions of this study. Other decision-making assumptions could also be tried; e.g., the delay in government might be represented as a function of project size. In general, every constant used in the model could, conceptually, be regarded as dependent on other factors. Such dependencies might be included, changing many of the constants to variables, and perhaps tying the system into a more interwoven network of critical

factors.

A second extension of the approach used here might be the addition of an explicit competitor firm, with its own characteristics, also considering the project. The contract award decision by the customer could then be presented with more direct realism, and the effects of various customer and firm policies then studied. One would want definitely to include feedback effects between the customer policies and the behavior of the two competing firms, as was discussed on several occasions in previous sections. Such an approach might point up more clearly the dynamics of the conflicts inherent in government contracting practices today, and also provide a vehicle for studying alternative policies.

Another kind of extension that might help clarify our research and development understandings would be one which visibly demonstrated the longer-than-single-project relationships which endure in research and development and which certainly are important to project behavior. For example, the customer's confidence in the firm is surely not a constant parameter, as was assumed in our single project studies. Rather, it derives from customer experiences with the firm in a number of previous projects and carries over, as a changing variable, from one project to another. The firm's willingness to accept risk might, as another example, be dependent upon how successful a similar or opposite policy on an earlier project is evaluated as being. For the study of such longer-life effects it is probably sufficient as a



start to represent two sequential projects between customer and firm. The values of many of the factors of consequence in the second project ought then to reflect the learning resulting during and after the first undertaking. This extension would also provide an opportunity to study the effects of various learning delays or behaviors in general on long-run success of the customer and/or firm. It should also enable further study of the difference between long-run and short-run effects of policies such as the risk-assumption propensity and integrity of the firm.

A different type of multi-project extension of this study also seems promising. Instead of examining two or more projects in sequence, one could study two or more projects in parallel in the firm or under the customer's sponsorship. Here, the criteria for investment decisions could be put into sharper focus, and a good opportunity would be presented for examination of the effects on success of various policies of resource allocation. Some of the work necessary for such an extension has already been initiated in recent theses by Sloan Fellows of the M.I.T. School of Industrial Management, but their work requires revision to put it more in the context of project undertakings.<sup>2</sup>

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<sup>2</sup> Donald C. Beaumariage, "A Dynamic Model Study of a Military Product Development Organization" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1960); and Philip W. Lett, "An Industrial Dynamics Analysis of a Defense Product Development Organization" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1961).

The final kind of Industrial Dynamics-type extension to the basic work described in this volume is one which seeks to add more organizational depth to some of the relationships treated in simple aggregate form. For example, both the customer and firm might be represented in closer form to their real vertical structures, providing communication paths up and down the organization, and representing various levels of information filtering and processing, and decision-making. Such a representation could help in the examination of the effects of integrity or of the reward structure on the communicated information within the firm. It would also show up various important internal sources of amplification within the organization. Another area wherein more depth of representation might be deserved is the notion of engineering productivity. Explicit recognition of such factors as morale, work load, corporate success, vertical mobility and others might turn up interesting conclusions as to what is important to determining the output of an R and D organization. This kind of study seems deserved on its own account because of the general nature of the question, and in fact, might more readily be treated initially in a context other than that of a research and development project.

#### The Need for Other Research

One part of the Industrial Dynamics approach outlined above is the search for more accurate knowledge about those factors which seem of consequence to the problem under investigation.

Our study has suggested many such areas which shall be designated below. The first suggestion for data collection and analysis is a general one; namely, all of the factors of consequence in research and development described early in this chapter deserve careful measurement under various sets of conditions. For example, what magnitude of intentional cost underestimation is present in research and development proposals? To what extent do companies risk their own funds in research and development projects? How long does the customer usually take to process funding requests for research and development? How rapidly are new projects in fact able to add more engineers to their staffs without loss of effectiveness? These and many other studies are clearly suggested by the list of factors consequential to research and development results. Some involve aspects very difficult to identify and/or measure in real organizations. This intangibility does not deny the need for the study. It poses instead more challenge and most likely more reward to the enterprising researcher able to make headway in those areas.

In addition to research aimed at determining the factual value ranges for the factors of consequence, more study seems demanded of those policies and decisions affected by these factors. Here, the closed-loop systems theory presented in this work, and reviewed in this chapter, offers the suggested breakdowns possible for such inquiry. The activities listed on pages 476 and 477 are the decision areas influenced by the factors of importance to research and

development. One inquiry could seek more knowledge as to how the need for a new product is actually perceived by a customer or firm. Another could attempt to determine the process by which companies estimate project costs, or decide to invest their own funds into a project effort. All these studies are needed to clarify the factual basis of the theory developed here.

Hardly any competent research work has been done on any of these questions, or at least hardly any is publicly available. The two prime data-collecting groups at work on research and development have not yet contributed a factual base for answering any of our questions. SCARDE (Study Committee for Analysis of Research, Development and Engineering)--a subgroup of COLRAD (College of Research and Development of The Institute of Management Sciences) has collected some relatively superficial manpower and cost data on research and development projects, but no important results are yet forthcoming. The second group, the National Science Foundation, has concentrated mostly on economic-type data, e.g., men and money inputs to research and development by company and industry, and has so far contributed almost nothing to understanding or improving the process of research and development management. Thus, the field is apparently wide open for competent students of organizations and management to make fame and fortune while helping meet a fundamental national need for research and development knowledge.

The third kind of research work which appears desirable is the study of system interrelationships in research and development.

For example, the conclusions cited earlier in this chapter pointed out the possibility that customer contracting policies and the objectives of research and development companies might be in basic conflict. The author has now begun a research study (under a grant by the National Aeronautics and Space Administration to the M.I.T. School of Industrial Management) to determine the facts of this potential conflict and to establish the system redesign that would be necessary to eliminate such conflict. The system involves the translation of organizational objectives into policies and practices, the motivation of contractor organizations and their responses to believed customer policies, and the effects through decision-making and actions of all this on contract proposals and performance obtained in research and development. Other systems of interrelationships deserve similar research treatment.

The final suggestion for research follows that phase of the typical Industrial Dynamics approach which in fact was definitely not applied in the current study. Recommendations for changed policies and organizational structures should be implemented and their effects observed. This is the only way in which many of the potential suggestions of other research approaches can ever be tested. Some government contracting policies which have been suggested are not anywhere in existence. Thus, no data on comparable effectiveness of one policy versus an alternative can be obtained and evaluated until such real organizational experimentation is attempted. The government and progressive research and development companies should be willing to try different approaches to initial staffing,

for example, or to training program management, or to project duration scheduling, as have been suggested in this work. Such real-world experimentation eventually must be tried before much benefit of the entire approach used in this investigation can be derived.

A basic tenet for management of research and development is a belief in the value of research and development activities. Hopefully, such management will quickly realize the potential payoff of research into their own functioning and organizations. Initial successes in managerial research into the management of research and development itself can serve as a springboard for research-based managerial improvement throughout the corporation and in our nation as a whole.

## BIBLIOGRAPHY

- Abbott, Ira H., "Research Plans and Programs", NASA Industry Conference Report, July 28-29, 1960.
- Adelman, I. and Adelman, F., "The Dynamic Properties of the Klein-Goldberger Model", Econometrica, Vol. 27 (October 1959).
- Asher, Harold, "Cost-Quantity Relationships in the Airframe Industry", Project Rand Report, R-291, July 1, 1956.
- Bailey, Robert A., "Application of Operations-Research Techniques to Air-Borne Weapon System Planning", Aeronautical Engineering Review, Vol. 13, No. 11 (October 1954).
- Banks, R. R., "The Birth of an Engine", Aeronautical Engineering Review, Vol. 12, No. 6, (June 1953).
- Barnard, Chester I., The Functions of the Executive (Cambridge: Harvard University Press, 1938).
- Beaumariage, Donald C., "A Dynamic Model Study of a Military Product Development Organization" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1960).
- Bishop, Robert, Economic Analysis (unpublished manuscript of textbook).
- Butterfield, Herbert, The Origins of Modern Science (New York: The Macmillan Company, 1953).
- Cartwright, Dorwin, and Zander, Alvin, Group Dynamics, Research and Theory, First Edition (Evanston, Illinois: Row, Peterson and Company, 1953).
- Cartwright, Dorwin, and Zander, Alvin, Group Dynamics, Research and Theory, Second Edition (Evanston, Illinois: Row, Peterson and Company, 1960).
- Compton, Karl Taylor, A Scientist Speaks (Cambridge: M.I.T. Press, 1955).
- Cragin, Stuart W., Jr., et al., Simulation, Management's Laboratory (Cambridge: Simulation Associates, 1959).
- Demler, Major General M. C., Speech to the National Aeronautical Electronics Conference, Dayton, Ohio, May 4-6, 1959.
- Dorfman, Robert, "Operations Research", The American Economic Review, Vol. L, No. 4 (September 1960).

- Ebersole, J. F., "The Influence of Interest Rates", Harvard Business Review, 1938.
- Electronic Industries, Vol. 19, No. 11 (November 1960).
- Fiedler, Fred E., "The Leader's Psychological Distance and Group Effectiveness" in Group Dynamics, Research and Theory, Second Edition, edited by Dorwin Cartwright and Alvin Zander (Evanston, Illinois: Row, Peterson and Company, 1960).
- Forrester, Jay W., Industrial Dynamics (Cambridge: The M.I.T. Press, and New York: John Wiley and Sons, Inc., 1961).
- Forrester, Jay W., "Industrial Dynamics - A Major Breakthrough for Decision-Makers", Harvard Business Review, Vol. 36, No. 4 (July-August 1958).
- Foster, Richard B., and Hoerber, Francis P., "Cost-Effectiveness Analysis for Strategic Decisions", Journal of the Operations Research Society of America, Vol. 3, No. 4 (November 1955).
- Freeman, Raoul J., "A Stochastic Model for Determining the Size and Allocation of the Research Budget", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960).
- Gloskey, Carl R., "Research on a Research Department: An Analysis of Economic Decisions on Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 4 (December 1960).
- Goode, Harry H., "Intracompany Systems Management", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960).
- Grasberg, Alexander G., "Merit Rating and Productivity in an Industrial Research Laboratory: A Case Study", IRE Transactions on Engineering Management, Vol. EM-6, No. 1 (March 1959).
- Haine, R. W., and Lob, W., "The Application of Closed-Loop Techniques to Engineering Project Planning", IRE Transactions on Engineering Management, Vol. EM-7, No. 3 (September 1960).
- Heaton, Donald H., Col., NASA Scientific and Technical Programs, Hearings before the Committee on Aeronautical and Space Sciences, United States Senate, February 28 and March 1, 1961 (Washington: U. S. Government Printing Office, 1961).
- Heller, W. W., "The Anatomy of Investment Decisions", Harvard Business Review, March, 1951.
- Henderson, H. D., "The Significance of the Rate of Interest", Oxford Economic Papers, October, 1938.



- Hickey, John E., Jr., "What Price Reliability?" Electronic Industries, Vol. 20, No. 9 (September 1961).
- Hirsch, I., Milwitt, W., Oakes, W. J., and Pelton, R. A., "The Relation of Utilization to the Shortage of Scientists", IRE Transactions on Engineering Management, September, 1958.
- Hosier, W. A., "Pitfalls and Safeguards in Real-Time Digital Systems with Emphasis on Programming", IRE Transactions on Engineering Management, Vol. EM-8, No. 2 (June 1961).
- IRE Transactions on Engineering Management, Vol. EM-7, No. 3 (September 1960).
- Johnson, Ellis A., "The Crisis in Science and Technology and its Effects on Military Development", Operations Research, Vol. 6, No. 1 (January-February 1958).
- Katz, Abraham, "An Operations Analysis of An Electronic Systems Firm", (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1958).
- Kershner, R. B., "The Size of Research and Engineering Teams", IRE Transactions on Engineering Management, June 1958).
- Klein, Burton and Meckling, William, "Application of Operations Research to Development Decisions", Operations Research, (May-June 1958).
- Kornreich, D. W., "Utilization of Normalized Data for Defense Contracts", Proceedings of the Nineteenth National Meeting of the Operations Research Society of America, May 25-26, 1961.
- Lambert, Vernon L., and Sackett, Hubert F., "Research and Development Cost Estimation", IRE Transactions on Engineering Management Vol. EM-6, No. 1 (March 1959).
- Larsen, Louis R., "New Product Development--Basis for Growth", Industrial Science and Engineering, Vol. 5, No. 6 (November 1958).
- Leavitt, Harold J., Managerial Psychology (Chicago: The University of Chicago Press, 1958).
- Lett, Philip W., "An Industrial Dynamics Analysis of a Defense Product Development Organization" (unpublished Master of Science thesis, M.I.T. School of Industrial Management, 1961).
- Marcott, Creighton M., "The Challenge of Space", Electronic Industries, April 1960.
- Marcson, Simon, "Role Adaptation of Scientists in Industrial Research", IRE Transactions on Engineering Management, Vol. EM-7, No. 4, (December 1960).

- Marcson, Simon, "Role Concept of Engineering Managers", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960).
- Marcson, Simon, The Scientist in American Industry (Princeton, New Jersey: Industrial Relations Section, Princeton University, 1960).
- Marglin, Stephen, unpublished notes on investment planning (Cambridge: Harvard University, 1962).
- Marshall, A. W., and Meckling, W. H., "Predictability of the Cost, Time, and Success of Development", Rand Corporation Report, P-1821 (December 11, 1959).
- McGregor, Douglas, The Human Side of Enterprise (New York: McGraw-Hill Book Company, 1960).
- McKinsey and Company, Inc., An Evaluation of NASA's Contract Policies, Organization and Performance (Washington: National Aeronautics and Space Administration, 1960).
- Medros, Ralph, "Introducing New Jet Engine Production with Reduced Lead Times", paper presented at the SAE National Aeronautic Meeting, April 2-5, 1957.
- Meyer, John R., and Kuh, Edwin, The Investment Decision, Harvard University Press (Cambridge, 1957).
- National Science Foundation, Funds for Research and Development in Industry, 1958 (Washington: United States Government Printing Office, 1961).
- National Science Foundation, "Methodological Aspects of Statistics on Research and Development Costs and Manpower" (Washington: United States Government Printing Office, 1959).
- Nelson, Richard R., "Invention, Research, and Development: A Survey of the Literature", U. S. Air Force Project Rand Research Memorandum, RM-2146 (April 15, 1958).
- Nelson, Richard R., "The Simple Economics of Basic Scientific Research-- A Theoretical Analysis", U. S. Air Force Project Rand Research Memorandum, P-1288 (April 28, 1958).
- Norden, Peter V., "Curve Fitting for a Model of Applied R and D Scheduling", IBM Journal of Research and Development, Vol. 2, No. 3 (July 1958).
- Norden, Peter V., "On the Anatomy of Development Projects", IRE Transactions on Engineering Management, Vol. EM-7, No. 1 (March 1960).

- Orcutt, G. H., et. al., "Simulation: A Symposium", The American Economic Review, Vol. L, No. 5 (December 1960).
- Parkinson, C. Northcote, "Haste and Waste in Science", Think, February 1960.
- Pearlman, Jerome, "Engineering Program Planning and Control Through the Use of PERT", IRE Transactions on the Engineering Management, Vol. EM-7, No. 4 (December 1960).
- Platt, William J., "Pre-Testing Company Planning", Stanford Research Institute Third Annual Industrial Economics Conference, January 1958.
- Pugh, Alexander L., III, DYNAMO Users Manual, The M.I.T. Press, 1961.
- Randle, C. Wilson, "Problems of R and D Management", Harvard Business Review, Vol. 37, No. 1 (January-February 1959).
- Rechtin, Eberhardt, (Dr.), "Why the Space Race?", I R E. Student Quarterly, Vol. 7, No. 4 (May 1961).
- Raymond, Richard C., (Dr.) "Avoiding Obsolescence in System Planning" (General Electric Technical Military Planning Operation, May 1959).
- Rhodes, Richard V., NASA Scientific and Technical Programs, Hearings before the Committee on Aeronautical and Space Sciences, United States Senate, February 28 and March 1, 1961 (Washington: U. S. Government Printing Office, 1961).
- Roberts, Edward B., "The Digital Computer as an Element of a Financial Control System" (unpublished Master of Science thesis, M.I.T. Department of Electrical Engineering, June, 1958).
- Roberts, Edward B., "Simulation Techniques for Understanding Research and Development Management", IRE National Convention Record, 1959, part 10.
- Rubenstein, Albert H., "Setting Criteria for R and D", Harvard Business Review, Vol. 35, No. 1 (January-February, 1957).
- Rubenstein, Albert H., and Haberstroh, Chadwick J., Some Theories of Organization (Homewood, Illinois: Richard D. Irwin, Inc., 1960).
- Swander, Richard C., "Proselyting---Good Business?", IRE Transactions on Engineering Management, Vol. EM-6, No. 1 (March 1959).
- Stanly, A. L., "Logic and Illogic in Engineering and Management", IRE Transactions on Engineering Management, Vol. EM-5, No. 4 (December 1958).

Stever, Guyford H., Informal talk to M.I.T. Seminar on Research and Development for Military Purposes, February 15, 1961.

Thomas, William I., "Control and Attention", in Sociological Theory, edited by Edgar F. Borgatta and Henry J. Meyer (New York: Alfred A. Knopf, 1956).

Versteeg, H., "Analysis of Engineering Performance", IRE Transactions on Engineering Management, Vol. EM-8, No. 2 (June 1961).

## BIOGRAPHICAL NOTE

Edward Baer Roberts was born on November 18, 1935 in Chelsea, Massachusetts. He attended primary and secondary schools in Chelsea and entered the Massachusetts Institute of Technology in September, 1953. At M.I.T. he majored in electrical engineering and was a member of the Cooperative Course in Electrical Engineering, working with the General Electric Company from 1955 to 1958. In June, 1958, he received the S. B. and S. M. degrees in Electrical Engineering. He then enrolled in the graduate School of Industrial Management of M.I.T. and received the S. M. degree in Industrial Management in February, 1960. This was followed by transfer to the M.I.T. Department of Economics, which resulted in the Ph.D. degree completed in June, 1962.

In 1957, while still in the graduate program in electrical engineering, Mr. Roberts became interested in the work of the Industrial Dynamics Research Group. He was appointed Research Assistant in the Industrial Dynamics group in February, 1958, was promoted to Instructor in February, 1960, and became Assistant Professor of Industrial Management in September, 1961. He is a member of the following honorary societies: Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Tau Kappa Alpha; and of the following additional professional groups: Institute of Radio Engineers, The Institute of Management Science, American Economic Association, and American Association of University Professors.

Since 1959, Mr. Roberts has done extensive lecturing and consulting on Industrial Dynamics and research and development management, and is a director of Electromagnetics Corporation. He wrote the article, "Simulation Techniques for Understanding Research and Development Management", Proceedings of the National Convention of the Institute of Radio Engineers, 1959.

APPENDIX A

LISTING OF MODEL AS PREPARED FOR DYNAMO SIMULATION

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M2042-247,DYN,TEST,4,5,0,0 EDWARD ROBERTS PH.D. DISSERTATION
RUN 3804ER
NOTE THE DYNAMICS OF RESEARCH AND DEVELOPMENT
NOTE
NOTE CHAPTER 2 THE PERCEPTION OF PRODUCT NEED AND VALUE
NOTE
NOTE THE UNDERLYING NEED FOR A PRODUCT
NOTE
59A IPV.K=TABLE(PVTAB,TIME.K,0,180,6) INTRINSIC PRODUCT VALUE 2- 1
PVTAB*=0/0/1E6/10E6/30E6/60E6/100E6/150E6/170E6/185E6/200E6/200E6/
<1 200E6/200E6/190E6/150E6/100E6/70E6/50E6/40E6/30E6/20E6/10E6/1E6/0/
<2 0/0/0/0/0/0
NOTE
NOTE UPPVF.FIRM PERCEPTION OF PRODUCT NEED AND VALUE
NOTE
7A DRPVF.K=DMRV+DVRVF.K DELAY IN RECOGNIZING PRODUCT VALUE 2- 2
28A DVRVF.K=(DRPVT)EXP(-DVRV1.K) DELAY, VARIABLE, IN REC VALUE 2- 3
DRPVT=60 DELAY IN RECOGNIZING PRODUCT VALUE TIME-CONSTANT
20A DVRV1.K=KLEVF.K/12 2- 3A
30A DMRV=6.0 DELAY, MINIMUM, IN RECOGNIZING VALUE
20A DF1.K=DRPVF.K/3.0 2- 4
NOTE
NOTE LRPVF IS THE OUTPUT OF A THIRD-ORDER SMOOTHING OF IPV
3L LEVF1.K=LEVF1.J+(DT)(1/DF1.J)(IPV.J-LEVF1.J) 2- 5
5N LEVF1=0 2- 6
3L LEVF2.K=LEVF2.J+(DT)(1/DF1.J)(LEVF1.J-LEVF2.J) 2- 7
5N LEVF2=0 2- 8
4L LRPVF.K=LRPVF.J+(DT)(RPVF.JK+0.0) 2- 9
5N LRPVF=0 2-10
NOTE LRPVF IS THE LEVEL OF RECOGNIZED PRODUCT VALUE BY THE FIRM
21R RPVF.KL=(1/DF1.K)(LEVF2.K-LRPVF.K) RECOGNITION RATE OF CHANGE 2-11
3L RPVSF.K=RPVSF.J+(DT)(1/DSRPV)(RPVF.JK-RPVSF.J) 2-12
5N RPVSF=0 2-13
30N DSRPV=3.0 DELAY IN SMOOTHING RECOGNIZED PRODUCT VALUE
NOTE
14A PFPVF.K=LRPVF.K+(RPVSF.K)(PHF) PROJECTED FUTURE VALUE BY FIRM 2-14
12N PHF=(WARF)(PLPF) PROJECTION HORIZON OF THE FIRM 2-15
30A PLPF=48 PLANNING PERIOD OF THE FIRM
32A WARF=1 WILLINGNESS TO ACCEPT RISK BY THE FIRM
NOTE RATE OF CHANGE OF ESTIMATE OF FUTURE VALUE
21R RCEVF.KL=(1/DAEVF)(UPPVF.K-EFPVF.K) 2-16
36A UPPVF.K=MAX(PFPVF.K,0) USED PROJECTION OF PROJECT VALUE 2-17
39A DAEVF=6 DELAY IN ADJUSTING ESTIMATE OF VALUE
NOTE THIS SETS EFPVF.= TO FIRST ORDER SMOOTHING OF UPPVF
NOTE ESTIMATED FUTURE PRODUCT VALUE
4L EFPVF.K=EFPVF.J+(DT)(RCEVF.KJ+0) 2-18
5N EFPVF=0 2-19
NOTE
NOTE TETA.K= CUSTOMER PERCEPTION OF PRODUCT NEED AND VALUE
7A DRPVC.K=DMRV+DVRVC.K DELAY IN RECOGNIZING PRODUCT VALUE 2-20
28A DVRVC.K=(DRPVT)EXP(-DVRV2.K) DELAY, VARIABLE, IN REC VALUE 2-21
20A DVRV2.K=KLEVC.K/12 2-21A
20A DC1.K=DRPVC.K/3.0 2-22
NOTE
NOTE CUSTOMER RECOGNITION OF PROJECT NEED
3L LEVC1.K=LEVC1.J+(DT)(1/DC1.J)(IPV.J-LEVC1.J) 2-23
5N LEVC1=0 2-24
3L LEVC2.K=LEVC2.J+(DT)(1/DC1.J)(LEVC1.J-LEVC2.J) 2-25
5N LEVC2=0 2-26

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L LRPVC.K=LRPVC.J+(DT)(RPVC.JK+0.0) 2-27  
 N LRPVC=0 2-28  
 OTE LRPVC IS THE CUSTOMERS LEVEL OF RECOGNIZED PRODUCT VALUE  
 1R RPVC.KL=(1/DC1.K)(LEVC2.K-LRPVC.K) RECOGNITION RATE OF CHANGE 2-29  
 L RPVSC.K=RPVSC.J+(DT)(1/DSRPV)(RPVC.JK-RPVSC.J) 2-30  
 N RPVSC=0 2-31  
 4A PFPVC.K=LRPVC.K+(RPVSC.K)(PHC) PROJECTED FUTURE VALUE BY CUSTMR 2-32  
 2N PHC=(PLPC)(WARC) PROJECTION HORIZON OF THE CUSTOMERS 2-33  
 PLPC=60 MONTHS PLANNING PERIOD OF CUSTOMER  
 1R WARC=.50 WILLINGNESS TO ACCEPT RISK BY CUSTOMER  
 OTE RATE OF CHANGE OF ESTIMATE OF FUTURE VALUE  
 1R RCEVC.KL=(1/DAEVC)(UPPVC.K-EFPVC.K) 2-34  
 6A UPPVC.K=MAX(PFPVC.K,0) USED PROJECTION OF PRODUCT VALUE 2-35  
 4R DAEVC=8 DELAY IN CUSTOMERS ADJUSTMENT OF VALUE ESTIMATE  
 OTE ESTIMATED FUTURE PRODUCT VALUE  
 L EFPVC.K=EFPVC.J+(DT)(RCEVC.JK+0) 2-36  
 N EFPVC=0 2-37  
 OTE  
 OTE CHAPTER 3 THE ESTIMATION OF PROJECT EFFORT AND COST  
 OTE  
 OTE FIRM ESTIMATE OF PROJECT EFFORT AND COST  
 OTE  
 L BNKPF.K=BNKPF.J+(DT)(RGEJF.JK+0) ESTIMATED JOB SIZE 3- 1  
 2N BNKPF=(MSEF)(NLKP) INITIAL SIZE OF JOB ESTIMATE 3- 2  
 6R NLKP=6000 NEEDED LEVEL OF KNOWHOW FOR PRODUCT(MAN-MOS.,EFFECTIV)  
 OTE  
 OTE INFLUENCE OF PREVIOUS EXPERIENCE ON SIZE ESTIMATES  
 9N IESEF=TABLE(IETAB,PDPEF,-1,+1,0.2) 3- 3  
 OTE TABLE OF INFLUENCE OF EXPERIENCE ON SIZE ESTIMATES  
 OTE IETAB\*=-0.95/-0.90/-0.83/-0.75/-0.65/-0.50/-0.25/0/.6/1.6/3  
 OTE PDPEF=-0.25 PERCENT DEVIATION OF PREVIOUS EXPERIENCE  
 OTE MODIFIER OF SIZE ESTIMATES MADE BY THE FIRM  
 9N EAEF=TABLE(EAETB,QF,0,1,0.1) 3- 4  
 4N MSEF=1+(EAEF)(IESEF) 3- 5  
 9N EAETB\*=1.0/.99/.96/.91/.84/.75/.64/.51/.36/.19/0  
 4N QF=1.0 QUALITY OF THE FIRM  
 1A GEAF.K=(1/BPPCF.K)(ESPCF.K-BPPCF.K) GAP IN ENGRG ACCOMPLISHMENT 3- 6  
 2A GENKF.K=(GEAF.K)(BNKPF.K) GAP IN ESTIMATE OF JOB SIZE 3- 7  
 2R RGEJF.KL=(FOGRF.K)(GENKF.K) RECOGNIZED GAP IN ESTIMATE OF JOB 3- 8  
 OTE ESTIMATED SCHEDULE OF PERCENT COMPLETION BY FIRM  
 4A ESPCF.K=(TEEF.K)(ETEF.K)/BNKPF.K 3- 9  
 9A FOGRF.K=TABLE(IPPGR,DPPCF.K,0,1.5,.1) TIME-SIGNIFICANCE OF GAP 3-10  
 6A DPPCF.K=MAX(PPC.K,BPPCF.K) DOMINANT COMPLETION 3-11  
 OTE TABLE OF INFLUENCE OF TIME ON GAP-RECOGNITION  
 6A IPPGR\*=0/0/0/.05/.12/.20/.35/.60/.80/.99/1.0/1/1/1/1  
 OTE TECHNOLOGICAL EFFECTIVENESS DUE TO STATE OF THE ART DEVELOPMENT  
 9A TE.K=TABLE(TETAB,TIME.K,0,180,6) 3-12  
 TETAB\*=.25/.25/.25/.25/.26/.27/.28/.30/.32/.35/.38/.42/.46/.51/.57  
 1R /.63/.70/.77/.82/.86/.89/.91/.93/.94/.95/.96/.97/.98/.99/.995/1.0  
 OTE AVAILABLE TECHNOLOGICAL EFFECTIVENESS AT THE FIRM  
 L ATEF.K=ATEF.J+(DT)(RCTAF.JK+0) 3-13  
 N ATEF=ITE 3-14  
 1R RCTAF.KL=(1/DTITF)(TE.K-ATEF.K) RATE OF CHANGE OF TECH. PROGRESS 3-15  
 ITE=0.25 INITIAL TE VALUE  
 OTE DTITF=8 DELAY IN INFORMATION TRANSMITTAL  
 OTE SMOOTHED TECHNOLOGICAL PROGRESS RATE, SEEN BY FIRM  
 L STPRF.K=STPRF.J+(DT)(1/DRTPF)(RCTAF.JK-STPRF.J) 3-16  
 N STPRF=0 3-17

NOTE	DRTPF=2 DELAY IN RESPONDING TO TECHNOLOGICAL PROGRESS	
NOTE	ESTIMATE OF CURRENT TECHNOLOGICAL EFFECTIVENESS AT FIRM	
L	$E_{TEF.K} = E_{TEF.J} + (DT)(R_{CEEJ.K} + R_{CPEJ.K})$	3-18
4N	$E_{TEF} = (M_{TEF})(EN_{PRF}) / EN_{AWF}$ INITIAL T.E. ESTIMATE	3-19
NOTE	INFLUENCE OF RISK-TAKING PROPENSITY ON ESTIMATE OF TECH. EFFECT.	
4N	$M_{TEF} = 1 + (I_{WARF})(E_{AEFF})$	3-20
9N	$I_{WARF} = \text{TABLE}(I_{WTAB}, W_{ARF}, 0, 1, 0.2)$	3-21
NOTE	TABLE OF INFLUENCE OF WILLINGNESS TO ACCEPT RISK ON TE ESTIMATES	
NOTE	$I_{WTAB*} = -.9 / -.75 / -.60 / -.40 / -.25 / 1.5$	
1R	$R_{CEEJ.KL} = (1/DR_{TEF})(R_{TEF.K} - E_{TEF.K})$ RATE OF CHANGE OF EST EFFECT	3-22
4A	DRTEF=2 DELAY IN RECOGNIZING T.E. AT FIRM	
4A	$R_{TEF.K} = (P_{RBF.JK})(B_{NKPF.K}) / EN_{AWF.K}$ REALIZED T.E. AT FIRM	3-23
NOTE	RATE OF CORRECTION OF PREVIOUS EFFECTIVENESS ESTIMATE	
4R	$R_{CPEJ.KL} = (P_{ECBF.K})(E_{TEF.K}) / D_{RAAF.K}$	3-24
NOTE	ESTIMATE OF FUTURE TECHNOLOGICAL EFFECTIVENESS	
4A	$E_{FTEF.K} = E_{TEF.K} + (X_{PTPF.K})(S_{TPRF.K})$	3-25
4A	$X_{PTPF.K} = (B_{PPIF.K})(N_{PD}) / 2$ EXTRAPOLATION PERIOD FOR TECH PROGRESS	3-26
NOTE	NPD=24 NORMAL PROJECT DURATION	
NOTE	ESTIMATE OF EFFORT REQUIRED = $T_{EEF} + (B_{PPIF})(B_{NKPF} / E_{FTEF})$	
2A	$E_{ERF.K} = (1/E_{FTEF.K})((T_{EEF.K})(E_{FTEF.K}) + (B_{NKPF.K})(B_{PPIF.K}))$	3-27
NOTE		
2A	$E_{TCPF.K} = (E_{MECF})(E_{ERF.K})$ ESTIMATED TOTAL COST OF PROJECT	3-28
2N	$E_{MECF} = (M_{ESOH})(A_{BSCM})$ ESTIMATED MONTHLY ENGRG COST FACTOR	3-29
0N	$M_{ESOH} = E_{SOHR} / 12$ MONTHLY ENG SALARY AND OH RATE	3-30
6N	$A_{BSCM} = (1+0+0) / (1-A_{VABS}+0)$ ABSENTEEISM COST FACTOR	3-31
6R	$E_{SOHR} = 30000$ ENGRG SALARY AND OVERHEAD, ANNUALLY	
6A	$A_{VABS} = 0.115$ AVERAGE ABSENTEEISM	
A	$E_{CCPF.K} = E_{TCPF.K} - T_{ECF.K}$ EXPECTED ADDITIONAL COST	3-32
NOTE		
NOTE	CUSTOMER ESTIMATE OF PROJECT EFFORT AND COST	
NOTE		
L	$B_{NKPC.K} = B_{NKPC.J} + (DT)(R_{GEJC.K} + 0)$ ESTIMATED JOB SIZE	3-33
2N	$B_{NKPC} = (M_{SEC})(N_{LKP})$ INITIAL SIZE OF JOB ESTIMATOR	3-34
9N	$I_{ESEC} = \text{TABLE}(I_{ETAB}, P_{DPEC}, -1, 1, 0.2)$	3-35
9N	$E_{AEEC} = \text{TABLE}(E_{AETB}, Q_{C}, 0, 1, 0.1)$	3-36
4N	$M_{SEC} = 1 + (E_{AEEC})(I_{ESEC})$	3-37
NOTE	$P_{DPEC} = -0.175$ PERCENT DEVIATION OF PREVIOUS EXPERIENCE	
NOTE	$Q_{C} = 0.6$ QUALITY OF CUSTOMERS MANAGEMENT	
1A	$G_{EAC.K} = (1/B_{PPCC.K})(E_{SPCC.K} - B_{PPCC.K})$ GAP IN ENGRG ACCOMPLISH.	3-38
2A	$G_{ENKC.K} = (G_{EAC.K})(B_{NKPC.K})$ GAP IN ESTIMATE OF JOB SIZE	3-39
2R	$R_{GEJC.KL} = (F_{OGRC.K})(G_{ENKC.K})$ RECOGNIZED GAP IN ESTIMATE OF JOB	3-40
NOTE	ESTIMATED SCHEDULE OF PERCENT COMPLETION BY CUSTOMER	
4A	$E_{SPCC.K} = (T_{EEF.K})(E_{TEC.K}) / B_{NKPC.K}$	3-41
9A	$F_{OGRC.K} = \text{TABLE}(I_{PPGR}, D_{PPCC.K}, 0, 1.5, .1)$ TIME SIGNIFICANCE OF GAP	3-42
6A	$D_{PPCC.K} = \text{MAX}(P_{PC.K}, B_{PPCC.K})$ DOM. COMP. INDICATOR	3-43
NOTE		
L	$A_{TEC.K} = A_{TEC.J} + (DT)(R_{CTAC.K} + 0)$ AVAILABLE T.E.	3-44
0N	$A_{TEC} = I_{TE}$	3-45
1R	$R_{CTAC.KL} = (1/D_{TITC})(T_{E.K} - A_{TEC.K})$	3-46
NOTE	SMOOTHED TECHNOLOGICAL PROGRESS RATE, SEEN BY CUSTOMER	
L	$S_{TPRC.K} = S_{TPRC.J} + (DT)(1/D_{RTPC})(R_{CTAC.K} - S_{TPRC.J})$	3-47
0N	$S_{TPRC} = 0$	3-48
6A	$D_{TITC} = 6$ DELAY IN INFORMATION TRANSMITTAL TO CUSTOMER	
NOTE	DRTPC=2 DELAY IN RESPONDING TO TECHNOLOGICAL PROGRESS	
NOTE	ESTIMATE OF CURRENT TECHNOLOGICAL EFFECTIVENESS, BY CUSTOMER	
L	$E_{TEC.K} = E_{TEC.J} + (DT)(R_{CEEJ.K} + R_{CPEC.JK})$	3-49
3N	$E_{TEC} = (M_{TEC})(A_{TEC})(C_{NFC})$	3-50
4N	$M_{TEC} = 1 + (I_{WARC})(E_{AEEC})$	3-51

2N	IWARC=TABLE(IWTAB,WARC,0,1,0,2)	3-52
	CNFC=0.6 CONFIDENCE IN FIRM BY CUSTOMER	
LR	RGEEC.KL=(1/DRTEC)(RTEC.K-ETEC.K) RATE OF CHANGE OF EST EFFECT	3-53
4A	RTEC.K=(PRBC.JK)(BNKPC.K)/ENAWF.K REALIZED T.E. BY CUSTOMER	3-54
0TE	RATE OF CORRECTION OF PREVIOUS EFFECTIVENESS ESTIMATE	
4R	RCPEC.KL=(PECBC.K)(ETEC.K)/DRAAC.K	3-55
	DRTEC=8 DELAY IN RECOGNIZING T.E. AT FIRM	
0TE	INFLUENCE OF RISK-PROPENSITY ON ESTIMATE OF TECH. EFFECTIVENESS	
0TE	ESTIMATE OF FUTURE TE	
4A	EFTEC.K=ETEC.K+(XPTPC.K)(STPRC.K)	3-56
4A	XPTPC.K=(BPPIC.K)(NPD)/2 EXTRAPOLATION PERIOD FOR TECH PROGRESS	3-57
0TE		
0TE	ESTIMATE OF EFFORT REQUIRED=TEEF+(BPPIC)(BNPKC/EFTEC)	
2A	EERC.K=(1/EFTEC.K)((TEEF.K)(EFTEC.K)+(BNKPC.K)(BPPIC.K))	3-58
2A	ETCPC.K=(EMECF)(EERC.K) ESTIMATED TOTAL COST	3-59
4A	ECCPC.K=ETCPC.K-TECF.K	3-60
0TE		
0TE		
0TE	CHAPTER 4 FUNDING THE R AND D PROJECT	
0TE		
0TE	THE FIRMS BID FOR SUPPORT	
0TE		
2A	PACRF.K=(12)(TCEF.K) PROJECTED ANNUAL COST OF RESEARCH	4-1
4A	MRSLF.K=MIN(ECCPF.K,PACRF.K) MAX RES SUPPORT LEVEL	4-2
0R	SACRF.KL=SWITCH(MRSLF.K,0,RFPF.K) SUPPORTABLE ANNUAL RES COST	4-3
0R	RACRF.KL=DELAY3(SACRF.K,DRSCF) REQUESTED SUPPORT	4-4
4A	TRGDF.K=TECC.K+RACRF.K TOTAL RES GRANTS DESIRED	4-5
2A	DRSCF=2 DELAY IN REQUESTING SUPPORT OF COSTS	
0TE		
0R	RQCPF.KL=SWITCH(RQFIF.K,TRQCF.K,RFPF.K) REQUESTED CHANGES	4-6
LA	RQFIF.K=CLIP(TRQCF.K,0,VCRC.K,ROICC) REQUESTED FUNDS INITIALLY	4-7
4A	TRQCF.K=TRQIF.K+TRQDF.K TRIAL REQ FOR CHANGES IN FUNDS	4-8
LA	TRQIF.K=CLIP(RQRIF.K,0,BORFF.K,BPFRF.K) TRIAL REQUESTED INCR.	4-9
0A	RQRIF.K=BORFF.K/DT REQUEST RATE OF CHANGE	4-10
4A	BORFF.K=BFRF.K-RFPF.K BIDDABLE OVERRUN IN FUNDS	4-11
4A	BFRF.K=TECF.K+(IMBF.K)(ECGPF.K) BIDDABLE FUNDS REQUEST BY FIRM	4-12
0TE	IF BIDDABLE FUNDS ARE BP PERCENT GREATER THAN REQUESTED	
0TE	TOTAL FUNDS, RFPF, THE FIRM WILL ASK FOR MORE MONEY	
2A	BPFRF.K=(BP)(RFPF.K) BREAKING POINT IN FUNDS REQUEST.	4-13
4A	BP=0.05	
0TE		
5A	IMBF.K=(ICF)(1)+(1)(IMBF1.K)+(-ICF)(IMBF1.K)+(0)(0) INTEGRITY	4-14
0TE	AS A MODIFIER OF BIDS BY THE FIRM	
4A	ICF=.9	
9A	IMBF1.K=TABLE(IMTAB,BPPCF.K,0,1.5,.25)	4-15
4A	IMTAB*=0/0/0/.60/1/1/1	
0TE		
1A	TRQDF.K=CLIP(RQRDF.K,0,EURFF.K,BPFRF.K) REQUESTED DECREASES IN S	4-16
0A	RQRDF.K=-EURFF.K/DT RATE OF CHANGE--DOWNWARDS	4-17
4A	EURFF.K=RFPF.K-ETCPF.K EXPECTED UNDERRUN IN FUNDS	4-18
L	RFPF.K=RFPF.J+(DT)(RQCPF.K+0.0) REQUESTED FUNDS FOR PROJECT	4-19
N	RFPF=0	4-20
5A	TCRFF.K=MAX(RFPF.K,TRGDF.K) TOTAL CURRENT REQUESTS FOR FUNDS	4-21
0TE		
0TE	THE CUSTOMERS EVALUATION OF THE FUNDS REQUEST	
0TE		
0TE	CUST. IS INFLUENCED BY FIRM--EST. OF ADD. COST ADOPTED BY CUST.	
4A	ETCAC.K=ETCPC.K+(CNFC)(DECFC.K) CUSTOMER IS	4-22

NOTE DIFFERENCE IN KNOWN COST ESTIMATES, INCLUDING POSSIBLE NO BID  
 3L  $DECFC.K = DECFC.J + (DT) (1/DRRFC) (DECRC.JK - DECFC.J)$  4-23  
 5N  $DECFC = 0$  4-24  
 7A  $DRRFC = 3$  DELAY IN RESPONDING TO REQUESTS FOR FUNDS  
 NOTE DIFFERENCE IN ESTIMATED COST, RATE OF CHANGE  
 8R  $DECRC.KL = (IBF.K) (RFPF.K - ETCPC.K)$  4-25  
 9A  $IPF.K = SWITCH(0, 1, RFPF.K)$  INDICATES A BID BY THE FIRM 4-26  
 NOTE  
 14A  $EVAUC.K = EFPVC.K + (CNFC) (DEVFC.K)$  CUSTOMER IS INFLUENCED 4-27  
 NOTE BY THE FIRM IN DETERMINING THE ESTIMATE OF VALUE ACTUALLY USED  
 7A  $DEVFC.K = FEVPC.K - EFPVC.K$  DIFFERENCE BETWEEN THE ESTIMATE OF 4-27A  
 NOTE VALUE PRESENTED BY THE FIRM AND THAT MADE INTERNALLY BY CUSTOMER  
 NOTE THE FIRMS ESTIMATES OF PROJECT VALUE ARE SENT TO  
 NOTE THE CUSTOMER, BUGGERED BY THE FIRMS INTEGRITY  
 9A  $FEVPC.K = (EMXVF.K) (1 + 0.0 + 1 - ICF)$  4-28  
 NOTE FIRMS VALUE ESTIMATE KNOWN TO CUSTOMER  
 36A  $EMXVF.K = MAX(EFPVF.K, LRPVF.K)$  EFFECTIVE MAX VALUATION BY FIRM 4-29  
 20A  $VCRC.K = EVAUC.K / ECCPC.K$  VALUE-COST RATIO 4-30  
 20A  $TSPIC.K = VCRC.K / ROICC$  TRIAL SPINC 4-31  
 4A  $ROICC = 2.00$  RETURN ON INVESTMENT CRITERION OF CUSTOMER  
 34A  $SPINC.K = MIN(TSPIC.K, 1)$  SUITABILITY OF PROJECT FOR INVESTMENT BY C. 4-32  
 NOTE CUSTOMERS WILLINGNESS TO SUPPORT THE COSTS OF THE FIRM  
 58A  $WSCFC.K = TABHL(PCSF, SPINC.K, 0, 1, 0.1)$  4-33  
 NOTE TABLE OF PROBABILITY OF CUSTOMER SUPPORT TO FIRM  
 26A  $PCSF = 0/0/0/0.1/.2/.3/.5/.75/.9/.95/1.0$   
 NOTE  
 NOTE TOTAL FUNDS WILLING TO BE COMMITTED BY CUSTOMER  
 12A  $TFWCC.K = (WSCFC.K) (ETCAC.K)$  4-34  
 NOTE  
 NOTE ALLOCATIONS, TOTAL, DESIRED BY CUSTOMER  
 34A  $MADC.K = MIN(TFWCC.K, RRFC.K)$  4-35  
 NOTE DELAYED RESEARCH FUNDS REQUESTED FROM THE CUSTOMER  
 3L  $RRFC.K = RRFC.J + (DT) (1/DRRFC) (TCRFF.J - RRFC.J)$  4-36  
 5N  $RRFC = 0$  4-37  
 1L  $AAC.K = AAC.J + (DT) (RFAC.JK + 0)$  TOTAL ACTUAL ALLOCATIONS BY CUST 4-38  
 5N  $AAC = 0$  4-39  
 NOTE FUNDS AVAILABLE FOR ALLOCATIONS BY THE CUSTOMER  
 1L  $FAC.K = FAC.J + (DT) (FINC.JK - RFAC.JK)$  4-40  
 6N  $FAC = 0$  4-41  
 41R  $FINC.KL = PULSE(VLARG, INTMC, VLARG)$  FINANCIAL INPUT TO CUSTOMER 4-42  
 32A  $VLARG = 1E10$  ONE BILLION  
 20A  $INTMC = 0$  INPUT TIME OF CUSTOMERS FUNDS  
 NOTE RESEARCH ALLOCATIONS OR CANCELLATIONS RATE  
 54R  $RFAC.KL = MIN(TRFAC.K, MRFAC.K)$  4-43  
 20A  $MRFAC.K = FAC.K / DT$  MAXIMUM RFAC RATE 4-44  
 56A  $TRFAC.K = MAX(READC.K, -LCRAF.K)$  TRIAL RFAC 4-45  
 NOTE DESIRED ALLOCATION RATE BY CUSTOMER  
 21A  $RFADC.K = (1/DBFC.K) (MADC.K - AAC.K)$  4-46  
 20A  $LCRAF.K = UCAF.K / DT$  LIMIT ON CANCELLATIONS 4-47  
 NOTE DELAY IN BUDGETING RESEARCH FUNDS  
 7A  $DBFC.K = DMBFC + XDBFC.K$  4-48  
 6N  $DMBFC = 6.0$  DELAY, MINIMUM, IN BUDGETING RESEARCH FUNDS  
 6N  $DBFTC = 12$  MONTHS DBFC TIME-CONSTANT  
 18A  $XDBFC.K = (DBFTC) (1 - SPINC.K)$  EXTRA DBFC 4-48A  
 NOTE UNSPENT RESEARCH ALLOCATIONS FROM CUSTOMER AT FIRM  
 1L  $UCAF.K = UCAF.J + (DT) (RFAC.JK - RECFF.JK)$  4-49  
 6N  $UCAF = 0$  4-50  
 NOTE

6R	RECFF.K=ARECF.K	RATE OF EXPENDITURES OF CUSTOMER FUNDS	4-51
54A	ARECF.K=MIN(MREPC.K,TCEF.K)	AUXILIARY RECFF	4-52
49A	MREPC.K=SWITCH(MRERC.K,MPERC.K,IBF.K)	MAX RATE EXP. PERMITTED	4-53
54A	MRERC.K=MIN(MREDC.K,MREAC.K)	MAX. RESEARCH EXPEND. RATE	4-54
20A	MREDC.K=UCAF.K/SRP	DESIRED MAX. EXPEND. DURING RESEARCH STAGE	4-55
C	SRP=12	SCHEDULED RESEARCH PERIOD	
12A	MREAC.K=(0.50)(TCEF.K)	MAX RESRCH EXPENDITURE RATE ALLOWED	4-56
20A	TMPER.K=UCAF.K/SPDC.K		4-57
NOTE	CUSTOMER WILL NOT BOTHER TO SUPPORT LESS THAN 1 MAN DURING DEVEL.		
51A	MPERC.K=CLIP(TMPER.K,0,MPERC.K,MRESC)	MAX PROJECT EXPEND. RATE	4-58
12N	MRESC=(1)(MESOH)	MIN. RATE OF EXPENDITURE FOR SUPPORT BY C	4-59
NOTE			
7A	SPDC.K=MPCTC.K+ASPDC.K	SCHEDULED PROJ DURATION BY CUST	4-60
56A	MPCTC.K=MAX(MPCT1.K,DT)	MIN PROD COMPLETION TIME	4-61
13A	MPCT1.K=(BPPIC.K)(.5)(NPD)		4-62
28A	ASPDC.K=(XPDC.K)EXP(EXPD.K)	ADDITIONAL SPDC	4-63
7A	XPDC.K=NPD-MPCTC.K	EXTRA PD	4-64
NOTE	OVEREXPENDITURE EXPECTATIONS CAUSE STRETCHOUT		
NOTE	IN MAXIMUM FUNDING BY CUSTOMER, MREPC		
54A	EXPD.K=MIN(75,BEXPD.K)	KEEP EXPD IN BOUNDS	4-65
12A	BEXPD.K=(EOESD)(POEEC.K)	BASIC EXPD	4-66
38A	EOESD=20	EFFECT OF OVEREXPENDITURES ON SCHEDULING DECISION	
NOTE	PERCENT OVEREXPENDITURE EXPECTED		
49A	POEEC.K=SWITCH(0,POEE1.K,AAC.K)		4-67
26A	POEE1.K=(ECCPC.K-EVAUC.K+0)/(EVAUC.K+MVRC+0)		4-68
6N	MVRC=VSMAL	MINIMAL VALUATION OF RESEARCH TO CUST	4-69
C	VSMAL=0.00001		
NOTE			
NOTE	THE FIRMS INVESTMENT DECISION		
NOTE			
20A	VCRF.K=EFPVF.K/ETCPF.K	VALUE-COST RATIO	4-70
20A	SPCBF.K=VCRF.K/ROICF	SUITABILITY OF PROJ TO C,BELIEVED BY F	4-71
C	ROICF=2.00	RETURN ON INVESTMENT CRITERION THAT THE FIRM	
NOTE	BELIEVES IS USED BY THE CUSTOMER FOR DECISION-MAKING		
NOTE	ESTIMATE PROBABILITY OF CUSTOMER SUPPORT TO FIRM		
58A	EPCSF.K=TABHL(PCSF,SPCBF.K,0,1,0.1)		4-72
NOTE	EXPECTED COSTS TO BE FINANCED BY THE CUSTOMER		
12A	EXCFC.K=(EPCSF.K)(ETCPF.K)		4-73
12A	EXPRF.K=(EPRF)(EXCFC.K)	EXPECTED PROFITS TO FIRM	4-74
C	EPRF=0.10	EXPECTED PROFIT RATE FOR FIRM	
12A	TMIDF.K=(WARF)(EXPRF.K)	MAXIMUM DESIRED INVESTMENT	4-75
56A	MIDF.K=MAX(TMIDF.K,TAIF.K)		4-76
7A	MAIDF.K=MIDF.K-TAIF.K	MAXIMUM ADDITIONAL INVESTMENT DESIRED	4-77
20A	MDRAF.K=MAIDF.K/EPCTF.K	MAX DESIRED ALLOCATION RATE	4-78
56A	TRAF.K=MAX(MDRAF.K,BRAF)	TRIAL RFAF	4-79
12N	BRAF=(MESOH)(LEI)		4-80
C	LEI=1	LEVEL OF ENGINEERS INITIALLY	
34R	RFAF.KL=MIN(TRAF.K,MFRAF.K)	RATE OF FUNDS ALLOC	4-81
20A	MERAF.K=FAF.K/DT	MAXIMUM FUNDING RATE AVAILABLE INTERNALLY	4-82
1L	FAF.K=FAF.J+(DT)(FINF.JK-IRF.JK)	INTERNAL FUNDS AVAILABLE TO FIRM	4-83
5N	FAF=BRBF		4-84
41R	FINF.KL=PULSE(VLARG,INTMF,VLARG)	FINANCIAL INPUT TO FIRM	4-85
C	INTMF=0	INPUT TIME OF FIRMS FUNDS	
NOTE			
NOTE	UNSPENT RESEARCH ALLOCATIONS OF THE FIRM		
2L	UIAF.K=UIAF.J+(DT)(RFAF.JK-IRF.JK-CAF.JK+0+0+0)		4-86
5N	UIAF=BRBF		4-87
NOTE	BASIC RESEARCH BUDGETED BY THE FIRM		

L2N	BRBF=(BPER)(BRAFF)	4-88
5	BPER=6.0 BUDGET PERIOD (MONTHS)	
NOTE	CANCELLED RESEARCH ALLOCATIONS OF THE FIRM	
41R	CAF.KL=PULSE(CXAF.K,BPER,BPER)	4-89
56A	CXAF.K=MAX(XUAF.K,0)	4-90
21A	XUAF.K=(1/DT)(UIAF.K-BRBF) EXCESS UNSPENT ALLOCATIONS	4-91
7R	IRF.KL=TCEF.K-ARECF.K INVESTMENT RATE	4-92
1L	TAIF.K=TAIF.J+(DT)(IRF.JK+0) TOTAL ACTUAL INVESTMENT BY FIRM	4-93
5N	TAIF=TECF	4-94
NOTE		
NOTE		
NOTE	CHAPTER 5 THE ACQUI. AND UTILIZA. OF ENGINEER. MANPOWER	
NOTE		
NOTE	THE FLOW OF ENGINEERING MANPOWER	
NOTE		
1L	ENGRF.K=ENGRF.J+(DT)(ENGJF.JK-ENGLF.JK)	5- 1
5NA	ENGRF=LEI	5- 2
54A	ENGDF.K=MIN(SENGF.K,WENGDF.K) ENGRS DESIRED	5- 3
20A	SENGF.K=EERAF.K/MESOH SUPPORTABLE ENGRS (ON EXPECTED FUNDING)	5- 4
56A	EERAF.K=MAX(TEEAF.K,BRAFF) EXPECTED ERAF	5- 5
14A	TEEAF.K=ERAF.K+(RCEAF.K)(TPEAF.K) TRIAL EXTRAP OF ERAF	5- 6
56A	ERAF.K=MAX(MREPC.K,RFAF.JK) EXPENDITURE RATE AVAILABLE	5- 7
1L	SERAF.K=SERAF.J+(DT)(RCEAF.J+0.0) SMOOTHED ERAF	5- 8
5NA	SERAF=BRAFF	5- 9
21A	RCEAF.K=(1/DRCEA)(ERAF.K-SERAF.K) RATE OF CHANGE OF ERAF	5-10
30R	DRCEA=1 DELAY IN RECOGNIZING CHANGE IN EXPENDITURES AVAILABLE	
51A	TPEAF.K=CLIP(DRCE,DTRE,RCEAF.K,0) TIME FOR PROJECTION OF ERAF	5-11
5NA	DRCE=6	
30R	DTRE=1	
15AL	WENGDF.K=(EDPS1.K)(SWENF.K)+(EDPS2.K)(SENGF.K) WEIGHTED NO.	5-12
7ATE	EDPS1.K=1-BPPIF.K SWITCH 1	5-13
7ATE	EDPS2.K=1-EDPS1.K SWITCH 2	5-14
42A	SWENF.K=ECCPF.K/((MESOH)(EPCTF.K)) ENGRS NEEDED BY THE FIRM	5-15
1L	EENGF.K=EENGF.J+(DT)(ENGHF.JK-ENGTF.JK) ENGRS EXPECTED	5-16
5N	EENGF=LEI	5-17
7A	ENGF.K=ENGDF.K-EENGF.K ENGINEERING MANPOWER GAP	5-18
NOTE	MAXIMUM TRAINEES TO BE HANDLED	
18A	MEITF.K=(TPSDF)(ENFEF.K+ENATF.K)	5-19
12N	TPSDF=(TEI)(TPSF) TPS DESIRED BY FIRM	5-20
38A	TEI=1 TRAINING EFFICIENCY INDEX	
34A	TPSF=2.5 TRAINEES PER STAFF ENGINEER AT THE FIRM	
NOTE	TRAINEES EXPECTED	
2LTF	EEITF.K=EEITF.J+(DT)(ENGHF.JK-ENLTF.JK-EITTF.J+0+0+0)	5-21
5N	EEITF=0	5-22
NOTE	MAXIMUM HIRING RATE	
21A	MEHTF.K=(1/DT)(MEITF.K-EEITF.K) MAX. HIRING TRIED	5-23
56A	MENHF.K=MAX(MEHTF.K,0) KEEP MAX HIRING +	5-24
20A	ENGCF.K=ENGF.K/DCEF TRIAL CHANGE, FOR HIRING RATE	5-25
3	DCEF=3.0 DELAY IN CHANGING ENGINEERS AT FIRM	
56A	TENHF.K=MAX(ENGCF.K,0.0) TRIED HIRING	5-26
54R	ENGHF.KL=MIN(TENHF.K,MENHF.K) LIVE FORCE OF ENGINEERS	5-27
NOTE	ENGINEERS BEING RECRUITED	
1L	ENBRF.K=ENBRF.J+(DT)(ENGHF.JK-ENGJF.JK)	5-28
5N	ENBRF=0	5-29
39R	ENGJF.KL=DELAY3(ENGHF.JK,DRCE) ENGRS. JOINING	5-30
2L	ENITF.K=ENITF.J+(DT)(ENGJF.JK-ENLTF.JK-EITTF.J+0+0+0) IN TRNG.	5-31
6NA	ENITF=0	5-32
14A	ENRTF.K=ENITF.K+(DT)(-EITTF.K) ENGRS REMAINING IN TRAINING	5-33

ORE ENLTF.KL=ENRTF.K/DETF LEAVING TRAINING AFTER COMPLETION 5-34  
 OTE DETF=18 DELAY IN ENGINEERING TRAINING  
 LTE ENFEF.K=ENFEF.J+(DT)(ENLTF.JK-ENFTF.J-ENREF.JK+0+0+0) FULLY EMPL 5-35  
 NTE ENFEF=LEI 5-36  
 OAE ENDTF.K=EEITF.K/TPSF DESIRED NUMBER OF TRAINERS 5-37  
 LA ENATF.K=ENATF.J+(DT)(ENREF.JK-ENTTF.J) TRAINERS 5-38  
 NTE ENATF=0 5-39  
 1A EDRTF.K=(1/DRET)(ENDTF.K-ENATF.K) DESIRED REASSIGNMENTS 5-40  
 DRET=1.0 DELAY IN REASSIGNING ENGRS TO--FROM  
 4A ENRPF.K=MIN(EDRTF.K,ENARF.K) ENGRG REASSIGNMENTS POSSIBLE 5-41  
 OAE ENARF.K=ENFEF.K/DT AVAILABLE FOR REASSIGNMENT 5-42  
 1RE ENREF.KL=CLIP(0,ENRPF.K,0,ENRPF.K) REASSIGNMENT RATE FROM ENGRG 5-43  
 1A ENTDF.K=CLIP(ENRPF.K,0,0,ENRPF.K) TRANSFERRING DECISION 5-44  
 4A ENGTD.K=MIN(-ENTRF.K,TEATF.K) DESIRED TRANSFERS 5-45  
 OAE ENTRE.K=ENRPF.K/DT ENGINEERING GAP TRANSFER RATE 5-46  
 A TEATF.K=ENARF.K+ETATF.K+EITAF.K TOTAL AVAILABLE TRANSFER RATE 5-47  
 OAE ETATF.K=ENATF.K/DT TRAINERS AVAILABLE FOR TRANSFER 5-48  
 OAE EITAF.K=ENITF.K/DT TRAINEES AVAILABLE FOR TRANSFERS 5-49  
 R ENGTF.KL=ENTTF.K+EITTF.K+ENFTF.K TRANSFERRING RATE 5-50  
 4A ENTTF.K=MIN(ENTDF.K,ETATF.K) TRANSFERRED AS TRAINERS 5-51  
 AR ENTAN.K=ENTDF.K-ENTTF.K ADDITIONAL TRANSFERS NEEDED 5-52  
 4A EITTF.K=MIN(ENTAN.K,EITAF.K) TRANSFERRED TRAINEES 5-53  
 ATE ENTFN.K=ENTAN.K-EITTF.K 5-54  
 4A ENFTF.K=MIN(ENARF.K,ENTFN.K) 5-55  
 OTE ENFTF=ENFTF.K-ENFTF.K  
 OTE ENGINEERS BEING TRANSFERRED  
 L ENBTF.K=ENBTF.J+(DT)(ENGTF.JK-ENGLF.JK) 5-56  
 NA ENBTF=0 5-57  
 OR ENGLF.KL=ENBTF.K/DTRE 5-58  
 OTE ENGLF=ENGLF.K-ENGLF.K  
 OTE ENGINEERING PRODUCTIVITY  
 OTE  
 2A UTEF.K=(QF)(ATEF.K) UTILIZED EFFECTIVENESS 5-59  
 L SKLVF.K=SKLVF.J+(DT)(1/DCKN)(KLEVF.J-SKLVF.J) HISTORIC KLEVF 5-60  
 NA SKLVF=KLEVF 5-61  
 2A DCKN=6-(DCKN.J-KLEVF.J)/KLEVF.J KNOWLEDGE ABSORPTION TIME  
 OTE MULTIPLIER TO ENGINEERING PRODUCTIVITY DUE TO INCREASED KNOWLEDGE  
 4AE MEPIK.K=1.0+(MPBFK)(INEPK.K) 5-62  
 ATE INEPK.K=1-KEXP.K OF INCREASE IN ENGRG PRODUCTIVITY FROM KNOWLEDGE 5-62A  
 8A KEXP.K=(1.0)EXP(-KEXP1.K) 5-62B  
 4A KEXP1.K=(3)(SKLVF.K)/NLKP 5-62C  
 OTE ENGRG PRODUCTIVITY REFLECTS MGT QUALITY, PROJECT EXPERIENCE,  
 OTE MAKEUP AND ALLOCATION OF ENGINEERING STAFF, AND THEIR ABSENCES  
 OTE RELATIVIZED ENGINEERING PRODUCTIVITY  
 6A REPRF.K=(PRIT)(ENITF.K)+(PRAT)(ENATF.K)+(PREBT)(ENBTF.K)+(1.0)(ENFE 5-63  
 1 F.K) 5-63  
 PRIT=0.4 PRODUCTIVITY OF ENGINEERS BEING TRAINED  
 8A PRAT=0.7 PRODUCTIVITY OF IN-TRAINING, ASSIGNED AS TRAINERS, AND BEING 5-64  
 2A PREBT=0.2 PRODUCTIVITY OF TRANSFERRED, RELATIVE TO THOSE FULLY EMPLOYED 5-65  
 NA PWAW=1-AVABS PERCENT WORKERS ACTUALLY AT WORK 5-64  
 2A RPEWF.K=(PWAW)(REPRF.K) RELATIVE PROD OF ENGRS AT WORK 5-65  
 OAE MPBFK=.60 MAXIMUM PRODUCTIVITY BENEFIT FROM KNOWLEDGE  
 3RE ENPRF.KL=(UTEF.K)(MEPIK.K)(RPEWF.K) 5-66  
 OTE LEVEL OF KNOWHOW OF THE FIRM  
 LA KLEVF.K=KLEVF.J+(DT)(ENPRF.JK+0) 5-67  
 NTE KLEVF=VSMAL 5-68  
 2AE KLEVC.K=(PKFTC)(KLEVF.K) KNOWLEDGE LEVEL OF CUSTOMER 5-69  
 OTE PKFTC=0.80 PERCENT OF KLEVF TRANSMITTED TO CUSTOMER





		10	
12A	PRF.K=(PPP)(ARECF.K)	PROFIT RATE TO FIRM	6-34
C	PPP=0.10		
1L	PROF.K=PROF.J+(DT)(PRF.J+0)	GROSS TOTAL PROFIT	6-35
6N	PROF=0		6-36
7A	NPROF.K=PROF.K-TAIF.K	NET PROFIT BEFORE TAXES	6-37
12A	NATPF.K=(CTR)(NPROF.K)	NET AFTER TAX PROFIT	6-38
C	CTR=.50	CORPORATE TAX RATE	

NOTE

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PRINT 1)IPV,DRPVF,LRPVF,UPPVF,EFPVF,DRPVC,LRPVC,UPPVC,EFPVC,BNKPF
PRINT 2)GEAF,ESPCF,FOGRF,TE,ATEF,ETEF,RTEF,EERF,ETCPF,ECCPF
PRINT 3)BNKPC,GEAC,ESPC,ATEC,ETEC,EFTEF,EFTEC,RTEC,EERC,ETCPC
PRINT 4)ECCPC,MRSLF,SACRF,RQCPF,RQFIF,TRQCF,TRQIF,RQRIF,TRQDF,RQRDF
PRINT 5)RFPF,TRGDF,VCRC,TFWCC,ETCAC,EVAUC,MADC,AAC,RFAC,RFADC
PRINT 6)DBFC,UCAF,TECC,RECFF,MRERC,MPERC,SPDC,VCRF,SPCBF,EPCSF
PRINT 7)EXPRF,MAIDF,TRAF,RFAP,UIAF,CXAF,IRF,TAIF,ENGRF,ENGDF
PRINT 8)SENGF,EERAF,ERAF,TEEAF,WENGD,SWENF,EDPS1,EENGF,ENGGF,MEITF
PRINT 9)EEITF,ENGHF,ENBRF,ENGJF,ENITF,ENLTF,ENFEF,ENDTF,ENATF,ENGTF
PRINT 10)ENBTF,ENGLF,UTEF,MEPIK,REPRF,RPEWF,ENPRF,KLEVF,KLEVC,PPC
PRINT 11)TCEF,TECF,ENAWF,TEEF,BPPCF,PRBF,RCBPF,GBPCF,DRAAF,SGBCF
PRINT 12)BPPIF,EPCTF,BPPCC,PRBC,RCBPC,GBPCC,DRAAC,SGBCC,RCPEF,RCPEC
PRINT 13)BPPIC,PRF,PROF,NPROF,NATPF,TCRFF,POEEC(0.2)
PRINT 13)VCRC(1.2)
SPEC DT=0.25/LENGTH=150/PRTPER=0/PLTPER=1
PLOT IPV=V,LRPVF=W,EFPVF=E,EVAUC=U(0,*)/ETCPF=T/TECF=F,AAC=A/TCRFF=R/EN
X1 GRF=G/PPC=P
NOTE THE LIFE CYCLE OF A RESEARCH AND DEVELOPMENT PROJECT
NOTE
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550

TOTAL 550\*