JOHN N. WARFIELD

Systems Engineering

August 10, 1955

ORDNANCE RESEARCH LABORATORY

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The PENNSYLVANIA STATE UNIVERSITY
College of Engineering & Architecture

University Park, Pennsylvania

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THIS REPORT WAS WRITTEN BY
John N. Warfield

SERIAL NO. NOrd 7958-307

APPROVED FOR DISTRIBUTION

Gilford G. Quarles

DIRECTOR

Abstract

THE PRINCIPAL aim of this report is to provide the systems engineer or prospective systems engineer with material that he can use to help himself in the engineering of a system. It has been attempted to include only material common to most systems problems, avoiding discussion of techniques involving technical considerations. An introduction to systems engineering is given, in which the purpose of systems engineering is stated, the systems engineer is defined, the factors surrounding a typical systems-engineering problem are enumerated, and the systems design process is outlined. The system survey, a preliminary step in the systems-engineering process, and the organized project plan are discussed, and a check list is given for each. Ideal and optimum tests are defined. Product development, based on the development cycle, is examined from the systems-engineering viewpoint. The subject of system tests is treated, and a test check list is given. The report concludes with a discussion of the completion and reinstigation of projects.

Preface

The effective pursuit of research and development in underwater ordnance demands, as in similar scientific fields, more than merely technical knowledge over a broad spectrum of scientific learning. It demands a systems perspective in the application of this knowledge. The Ordnance Research Laboratory, in the interest of encouraging systems thinking within its staff, conducted in the spring of 1955 a semester seminar on this subject. This seminar was organized and led by Dr. John N. Warfield of the Electrical Engineering Department of the University. The notes upon which the discussions were based are published here in the hope that they may be of help to other individuals and organizations concerned with systems engineering.

Foreword

SOME OF the thinking that went into the development of this report should be understood before the report is read. In the first place, systems engineering involves a gamut of material ranging from the highly philosophical to the highly technical. Furthermore, the lateral displacement of information in this range is tremendous: systems engineering may involve techniques from many academic disciplines. Accordingly, it was felt that the chief aim of the report should be to present material common to most systems problems and that, in general, discussion of engineering problems of specialized nature should be avoided. Accordingly, techniques of system analysis and synthesis that involve technical considerations have been omitted.

As a result of these ideas, this report is built around a procedural approach or philosophy of systems engineering, the principal aim being to provide the systems engineer or prospective systems engineer with material that will be helpful to him in the engineering of a system. Much of the material presented is based on the feeling that the greatest obstacles to successful systems engineering are:

(a) poor communication between people engaged in the work,

(b) failure to define ultimate aims,

(c) decisions based on prejudice rather than logic,

(d) failure to consider the interrelation between various elements in the proposed system, or the larger system of which it happens to be a part, and

(e) failure to establish a prediction of the future course of activity along which system development can proceed with a minimum of lost time and expenditures.

It was realized at the outset in preparing this material that the key to success in systems engineering (as in any other human enterprise) is the individual or group involved, and that no set of procedures could substitute for good judgment. However, it was felt that even good judgment could benefit on occasion by reviewing basic principles. Furthermore, the material was aimed at problems involving something that might be called "group judgment" - an item quite distinct from individual judgment. It has often seemed rather tragic to the author of this report that group judgment should be so inefficiently used as it sometimes is; some of the reasons for this inefficiency may be found in the items listed as (a) through (e) above. Hence, a point which is stressed implicitly in this report is that the systems engineer should develop a capability for communicating his problems to others so that the highly essential group-discussion technique can be of maximum value to him in his decision-making capacity.

Many of the things discussed in this report will seem obvious to the reader. The author is not ashamed of this. It is the objective of this report to make all the items discussed obvious to the reader; if some things that are not already obvious are made so, the report will have served its purpose.

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Introduction to Systems Engineering

WITHIN the past few years the term "systems engineering" has come to be used rather widely. It can be seen, for example, in advertisements for technical personnel (figure 1). It is heard in everyday conversations between technical people. In these situations, systems engineering seems to refer to a mode of engineering practice that is highly desirable in certain types of technical personnel. Is there any really new concept that the term is meant to convey?

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FIG. 1. AN ADVERTISEMENT FOR SYSTEMS ENGINEERS

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If the term "systems engineering" is worthwhile in an already crowded vocabulary, we should be able to find something in the history of engineering practice that illustrates the need for such a concept as systems engineering. As a first example, let us go back to 1928 for a look at an engineering job involving the St. Francis dam of the Los Angeles water supply system. This dam was "a big concrete dam, which had been built and inspected by leading engineers. Just before midnight on March 12, 1928, the . . . dam . . . burst. The released water swept down a narrow valley where, in ranch buildings and construction camps, people were peacefully sleeping. More than four hundred lives were lost, and millions of dollars of damage was done to property. Thousands of acres of valuable farm lands and orchards were covered by gravel and sand deposits. Many workmen of the Southern California Edison Company, who were camped in the valley, were drowned.

". . . The dam was 650 feet long, and up to 205 feet high, including 30 feet built below the bed of the river. It was made of concrete, and at the base the thickness was 170 feet. . . . it was a huge and heavy structure, even for a part of the country accustomed to great engineering units; and it had been inspected by engineers supposed to be competent and trustworthy.

"Being an arched dam, it curved upstream, since this design for withstanding the pressure of water is considered the strongest. On the downstream side, the concrete surface was stepped down like an Egyptian pyramid. The structure was a huge rigid unit of massive masonry. It depended upon its enormous weight and friction along the base to hold it in place, for the foundation was not particularly deep. American engineers have expressed firm faith in this accepted theory of gravity-dam design. In this case the general design was not at fault.

"Despite the reputed skill of the engineers in charge of this dam and the great weight of this mass of concrete, the waters behind it undermined the dam until it burst into giant blocks, some of them weighing thousands of tons. Several of these huge masses were carried a mile or more down the canyon. This modern engineering structure, which was only two years old, had been built over a geological fault zone, where two different rock formations come together. Such a contact between rocks is generally considered a line of weakness by anyone familiar with geology. Investigations after the calamity disclosed the fact that this weakness in the rock had been a serious one.

"One of the rock formations was a reddish conglomerate, which means a pudding-stone of gravel and sand cemented together by nature. It was found that this rock disintegrated quickly when wet, although it appears firm and solid when dry. Specimens put into water by the Governor's investigating commission gave off air bubbles as they flaked into loose sand fragments, and in a few minutes turned into mud. The other rock formation, a mica schist, showed lines of weakness in its layers that suggested the possibility of landslides when it was put under pressure. The commission reported that a dam built upon such a foundation was inevitably doomed to ultimate failure, especially a rigid monolith such as the St. Francis dam.

"The rock weaknesses in the site were well known to geologists before the dam was built. Most geologists, if consulted, would have advised against building an important structure over such a line of weakness. But geological advice was not considered worthwhile by the engineers in charge of the work. Geological theories about rock structures are likely to impress practical men as merely unnecessary frills and expense.

"...The responsible engineer on the design and construction of the St. Francis dam was William Mulholland, a trusted veteran in his profession and in Los Angeles public life. For many years he had served the people of that district on similar work, and he had impressive achievements to his credit, including a number of dams and a great aqueduct system. Only a few hours before this failure, he inspected the dam for leaks that subordinates had reported, but found nothing alarming.

"...It is probable that, like many American engineers, Mulholland was so absorbed in one set of specialized problems that he overlooked others. The matter of a secure foundation was obscured by the pressing details of construction, so that geology was sacrificed to questions of design, administration and surface appearances. A few months after the catastrophe, Mulholland, who was over seventy years old, resigned. He announced that he wished to give younger men a chance at the work which his duties had included. The Los Angeles municipal administration expressed regret at his retirement!"*

Another significant lesson in the foundations of engineering is provided by the Hales Bar dam on the Tennessee River near Chattanooga. "This dam, which was built over a cavernous and soluble limestone, did not burst but came perilously near it. When bad leaks developed, brute force methods were adopted to stop them. Trainloads of crushed rock, gravel, clay, cement, and concrete with wire-mesh reinforcing were dumped into the water that was draining into the leaks, but they were not sufficient to plug the holes and crevices. Neither were carloads of baled hay, wrecked bed-springs, carpets, burlap, and old corsets. After years of efforts, the leaks were finally reduced to negligible proportions by the use of thousands of barrels of hot liquid asphalt, which was pumped into the porous rock under pressure. These various methods had taken more than ten years of time and ten millions of dollars, to conquer the leakage in the foundation!

"...The subject of the failure of engineering structures due to over-concentration upon one phase of the work and neglect of other phases, is merely one example of the tendency of modern technical workers to specialize so much that they do not see the woods for the trees. ... Similar characteristics may be detected wherever scientists have been given unbalanced training that encourages them to specialize too early in their career, so that they lose the faculty of envisaging a problem as a whole because they are engrossed in details.

"Technical experts who are too close to their work are likely to become dangerously one-sided in their judgment and may do much damage through unfortunate efforts unguided by sound wisdom. It is possible to neglect the proper foundation in education, as well as in a dam, and to erect a glittering superstructure that pleases the specialists. But a better policy is to learn the fundamentals well and to broaden one's knowledge at every opportunity while improving cultural interests and one's general understanding of human nature. ... Wisdom can be more important than knowledge."*

The examples of the failures of dams just cited could be repeated in principle in terms of the failures of other engineering equipment, if not in operation, at least at the "final test" stage. Such failures are often preceded by tremendous investments of engineering manpower and money. This is especially true in a period when national security demands that certain goals be met at certain times. Perhaps the reader may be able to supply from his own background examples of the type of situation mentioned here. One wonders

*Personality and English in Technical Personnel, P. B. McDonald, Copyright 1946, D. VanNostrand Company, Inc.

whether there would not be as much to learn from a recording of engineering failures as from the published successes.

Clearly, valuable information often accrues from engineering projects that are not successfully completed. Nevertheless, the fact remains that the objective of an engineering project is not to create a device which is a failure; hence the valuable information that accrues is quite properly to be regarded as a fortunate by-product, rather than a justification.

The failure of supposedly completed engineering projects is, in fact, only a small part of the background that produced the concept of systems engineering. More important than the failure of supposedly completed engineering systems is the failure to complete engineering systems to which vast amounts of manpower and funds have been committed.

When a project involves only a small amount of engineering time and money, incompletion may be tolerated; but when the project involves millions of dollars and many man-years of effort (perhaps even the national security) a tremendous toll may be taken by failure to complete a system. One can only guess what the results would have been had atomic-bomb development been completed first by the enemy in World War II rather than by the Allies.

It becomes absolutely essential, when the future of engineering is considered, to evaluate engineering methods and to establish basic concepts of engineering practice. Such an evaluation cannot be half-hearted, but must be coldly impassive and, occasionally, brutally critical in view of the ultimate aim of strengthening the foundations of the engineering profession. The profession, at least, must not be built with a "fault zone" at its foundation. With this in mind, the status of the engineer who is called upon to supervise a project will now be discussed.

Let us consider figure 2. This diagram illustrates the typical situation in which the

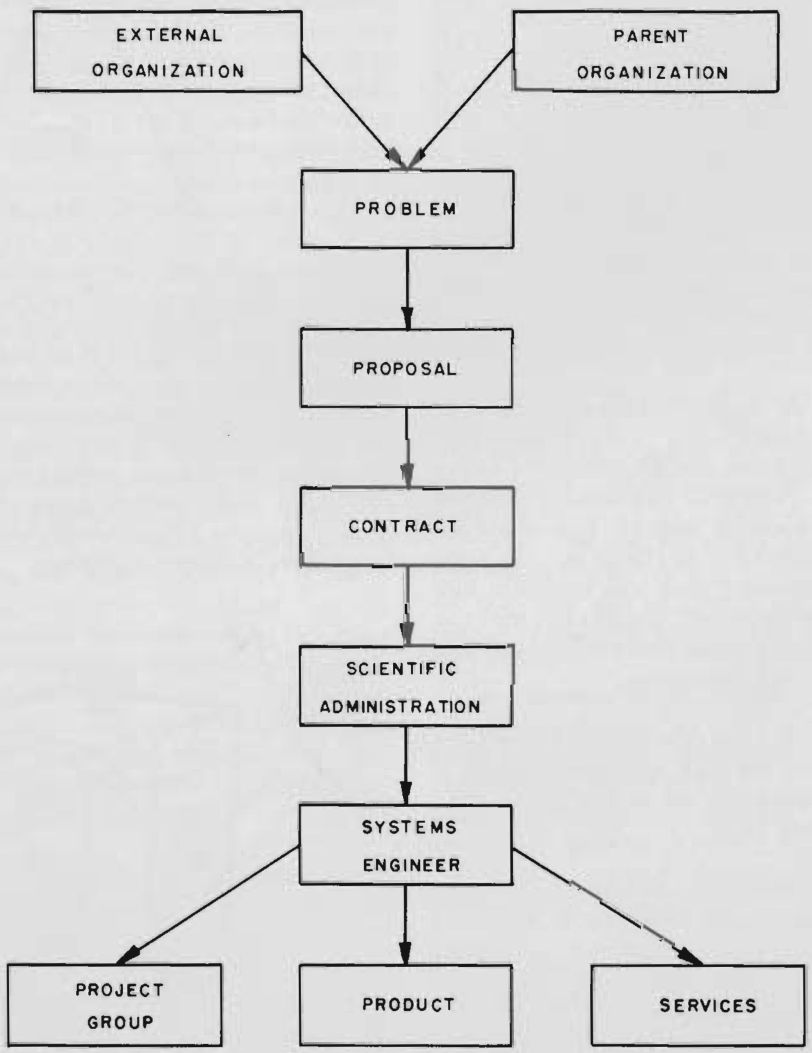

FIG. 2. FACTORS THAT ENTER INTO THE ENGINEERING OF A PRODUCT

engineer finds himself when he is called upon to supervise a project. (While it is not necessarily true that every systems engineer will be a project engineer, it is true that every project engineer should be a systems engineer, in the broad sense of the term. This will be clearer later, when the definition of systems engineer is given.)

Figure 2 shows many of the important factors that enter into the engineering of a product. The first consideration is, of course, the problem. The problem may arise within, or external to, the parent organization. In any case, once the problem is recognized, a proposal is prepared and a contract is granted; or, in the absence of a contract, a problem assignment is made. This is made normally to a scientific administrator who, in turn, assigns the problem as a project to the systems engineer. The systems engineer, to help him accomplish his job, usually has a project group directly under his supervision, and normally has the services of other special groups that the scientific administrator makes available to him. The final aim of the systems engineer should be to create a product that solves the problem in a manner deemed optimum by him in the light of his own decisions and all the facts he can muster to support them. A systems engineer should be prepared to accept full responsibility for the success or failure of the project, bearing in mind that there will always be limitations upon him which influence the quality of the product. However, in assessing these limitations, he should make sure that he has not imposed upon himself undue additional limitations in attempting to solve the problem. This point will be covered more fully later.

While it would be highly desirable for the systems engineer to enter the picture shown in figure 2 at the stage when the proposal is being prepared, often the proposal has been prepared and the contract awarded before the systems engineer is made cognizant of the task. In view of this, it will be assumed that the problem has been recognized, the proposal prepared, and the contract granted prior to the introduction of the systems engineer to the problem.

When the systems engineer enters the picture, he may be visualized as shown in figure 3. He is ready to do battle but he is not quite sure just what he is getting into.

Now we come to one of the points upon which a distinction will be made between a systems engineer and a nonsystems engineer. It is precisely at this point in the effort to develop a product that the success or failure of the project may be determined. (Unfortunately, it is also at this point that an engineer is forced, all too often, to do a great deal of nonengineering work involving many details that use much of his precious time.) At this stage the systems engineer should be behaving as shown in figure 4. Appearances to the contrary, this man is working. He is just sitting and thinking about the problem. A period of uninterrupted thought at this stage of the work is essential to the success of the project. A brief period of concentrated thought may be better than a month of indecision, conferences, bickering, and nondirected discussion.

FIG. 3. A MAN WITH A PROBLEM

This period of thinking about the problem corresponds to the first of Helmholtz's stages in the formation of a new thought. The problem should be "investigated . . . in all directions." Naturally this will involve, in addition to the thought process, a substantial effort to obtain pertinent information from numerous sources. The foregoing efforts will hereafter be referred to as the "system survey."

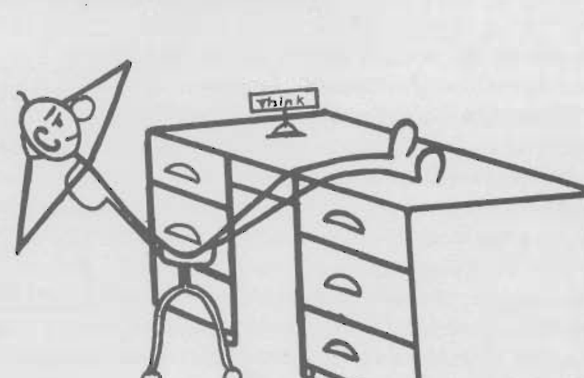

FIG. 4. A MAN WORKING ON A PROBLEM

At the conclusion of this initial period in which the systems engineer devotes a great deal of thought to the problem and collects pertinent information, he should prepare a plan. This plan should show in writing the systems engineer's concept of the project specifications or requirements. There are three reasons for doing this:

(1) to fix in the systems engineer's mind the goal of the project,

(2) to establish a basis for discussion with others, and

(3) to keep management informed.

The plan should also show factors that will enter ultimately into the prosecution of the project; such things as time, funds, personnel, supply, consulting assistance, supervisory duties, the role of management, and possible bottlenecks that are expected to show up later on in the project should be listed. Needless to say, if such a plan is prepared, the systems engineer will find that he can obtain many valuable ideas from discussion with others. Contrast this method of obtaining suggestions following the preparation of a plan with the committee method, in which no plan having been prepared, ideas fly at random, with the common result that a long-winded individual monopolizes the discussion and succeeds only in wasting large amounts of everyone's time.

In order to prepare a sound plan it is essential that the project engineer should be able to think abstractly. This is not as difficult as is sometimes believed. What is desired is that the systems engineer visualize the system requirements abstractly; in other words, that he prepare a block diagram showing not hardware but the essential functional nature of the devices or quantities that could enter into system requirements. The purposes of preparing an abstract (functional) diagram are essentially the same as those for preparing the over-all plan: (1) the project requirements are emphasized to the systems engineer, (2) a basis for discussion is established that will permit others to suggest improvements in the plan, and (3) management is kept informed as to what will transpire on the project, hence may be of service in suggesting or obtaining services or equipment.

Occasionally a project is set up calling for a product that cannot be designed logically on the basis of available information. This contingency could be an outgrowth of the simple fact that desirability and physical realizability are not synonymous. If such a project is assigned to the systems engineer, it is important to him, as well as to others concerned, that such possible obstacles to the completion of the project be uncovered early rather than after large sums of money have been spent, much engineering time has been wasted, and no product has been obtained. An added advantage in outlining the project abstractly is that the abstract requirements may indicate auxiliary tasks that need to be performed in order to make certain facts or items available at the time required in the course of the project. It may also reveal the need for outside help of the type that management may be prepared to provide if made aware in sufficient time that it may be needed.

Two concepts that should underlie the system survey and, later, the activity of the project are:

(1) the ideal system, and

(2) the optimum system.

"Ideal" implies the ultimate in functional desirability and carries no implications as to physical realizability, development time, or cost. "Optimum" implies that the system is one of a large set of systems, any of which could be developed within the same set of physical and economic constraints; and that it is the one which, subject to the constraints, most nearly approaches the ideal from a functional standpoint. These terms will be discussed in greater detail in a later section.

Another factor that the systems engineer should consider in the early planning stage is the type of tests that will be run eventually upon the system. He should, if possible, decide, before any system development is begun, what tests will be run, and why. He should decide, beforehand, what functional units will be essential in running these tests, what data will be obtained, and why. He should know what the data obtained are expected to reveal about the system so that he does not end up with a product that cannot be tested or that, if tested, yields meaningless data.

A systems engineer should set the minimum requirements that he feels are essential to complete the project. Many projects seem to run on indefinitely without concrete results. The man who can complete a project is the man who will be called upon to direct a bigger and better one and who is, in the final analysis, the kingpin of engineering progress.

All this is not intended to convey the impression that it is possible to plan minutely every detail of a project. Neither is it meant to imply that the plan initially prepared will be followed strictly. In fact, it is highly probable that the plan will be modified or augmented several times before the project is completed. The important point is that an explicit rather than an implicit plan should be established.*

Now that we have discussed systems engineering generally, let us turn to a definition of systems engineering, after which details of some of the points mentioned will be discussed. It is generally understood that an engineer is a person who contrives to make new devices for the service of mankind. A system, on the other hand, may mean one of three things, according to the dictionary. The first definition is probably the most familiar one. A system is defined as "an aggregation or assemblage of objects united by some form of regular interaction or interdependence; a group of diverse units so combined by nature or art as to form an integral whole and to function, operate or to move in unison and often in obedience to some form of control." Note that this definition emphasizes the system as a group of objects combined to form an integral whole and to move in unison. A second definition of the word system is as follows: "an organized or methodically arranged set of ideas, a complete exhibition of essential principles or facts arranged in a rational dependence or connection, the intellectual content of a particular philosophy." The second definition emphasizes methodically arranged ideas as opposed to a group of objects. A third definition of system is "a formal scheme or method governing organization, arrangement and so on of objects or material or a mode of procedure." Note that this definition emphasizes a scheme or method governing organization.

If the spirit of the foregoing definitions is embodied in a single sentence, one may arrive at the following definition of a systems engineer: A systems engineer is a man who, when assigned to a project, is capable of coordinating and preparing or carrying out three things - first, an optimum scheme (system survey) showing the interrelation of all factors that will affect the project and sway future action; second, an optimum set of organized ideas (the plan of procedure) pertaining to carrying out the project; and third, an optimum physical realization (the product) of the devices necessary to terminate the project.

The process that involves the three steps just listed is called the systems design process. The systems design process is indicated in the block diagram of figure 5. Note that product evaluation is carried out in every stage of the process. This block diagram is deceptively simple. The expansion of the block diagram into the systematic attack in systems design will be the subject of the discussion to follow.

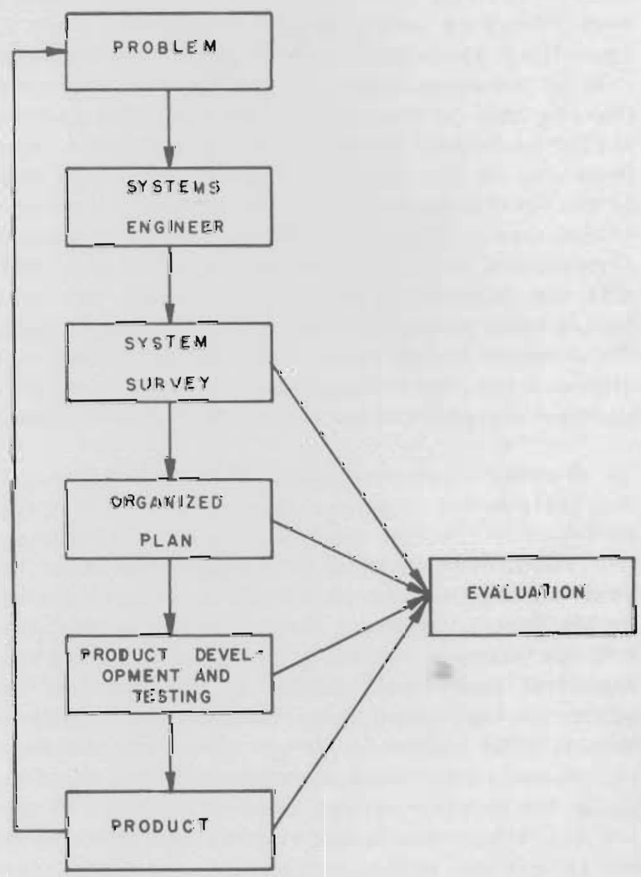

FIG. 5. THE SYSTEMS DESIGN PROCESS

In particular, the system survey, with the objective of establishing the relevant ideas, will be discussed. The system survey leads to the organized plan, which embodies the systems engineer's concepts of the product specifications and requirements. The organized plan aims at the development of an optimum product most nearly approaching the ideal. Product development and system tests are considered, followed by notes on the subject of project completion.

*There is a simple and effective analogy between project activity and the process of navigation. Suppose a ship leaves port. The captain believes the ship's destination is Key West. The first mate thinks the ship is to go to Nova Scotia. The navigator sets his course for the South Seas. Will the voyage be successful? What is needed is a plan of the proper course, which will permit all hands concerned to apply themselves to following this course. If winds blow the ship off course, a revised course based on the original one can be adopted and the voyage can proceed with a minimum of lost time.

The System Survey

The Pat Problem as a Stimulus to Concerted Effort

IN RESEARCH and development, certain special problems often persist or recur in various ways over a period of years. Although these problems may assume many different forms, their distinctive sameness makes it possible to develop methods of attack that apply equally well to all forms. As a matter of fact, the "pat problem" is basic to much scientific progress. For example, the fundamental principles of feedback control were discovered in the early 1930's, but it was only in the early 1940's that emphasis was directed to this problem by individuals who, under wartime pressure, formalized it as a problem and thus directed attention to it by numerous investigators. As a result, today there is a highly developed body of theory that can be used to analyze and synthesize feedback control systems of many kinds. The pat problem is an established idea in the field of mathematics and is widely used.*

A similar idea of problem definition may be applied on a smaller scale within an organization or project. It appears highly desirable that recurrent problems should be formulated and assigned distinctive names so that, as contributions are made by various individuals in the organization or project, one learns to associate the contributions with the particular kind of problem. This is also very helpful when one wishes to explain to others what is going on, and it might be added that this task of explanation is one that the systems engineer should be able to handle well. Hence, in planning the organization of a project, one should be on the lookout for pat problems, and be prepared to give them descriptive names.

The Project Specifications

The system requirements incorporated in a contract are seldom sufficiently complete or exact for the systems engineer to know at the outset exactly what is to be done in developing the system. One of the good aspects of this is that more freedom is allowed the engineer in his work if the system requirements and specifications are somewhat vague. This does not mean, however, that the engineer should be excused from formulating the system requirements and specifications in his own mind. As was suggested previously, it is highly desirable that the systems engineer write down on paper his concept of the system requirements and specifications. Further, he should be sure that the requirements and specifications are compatible before proceeding. Thus, the systems engineer should write down first of all what he thinks the system is supposed to do functionally. Next, if the system is to be part of a larger system, he should write down what other parts of the larger system it will be working with. Finally, he should write down which of these other parts of the larger system are involved in his own project.* At this time he will probably notice that certain essential information has not been supplied to him. Notes should be made of this deficiency and every effort should be made to see that the deficiency is corrected before proceeding too far. If specifications are incompatible with requirements, this should be noted and corrected.

The Role of New Ideas in the System Survey

In making the system survey, one will not usually be able to foresee exactly how recently published ideas or techniques or newly perfected hardware can enter into the systems design picture. Thus, it is difficult to insert new ideas into the early planning. For this reason it is important not to establish old ideas in the early planning, but to keep the plan relatively flexible. For example, where it is desired that a certain function be accomplished in the system, it should not be concluded immediately that this function should be accomplished in a certain way. It is well to

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*For example, "The Dirichlet problem" is known to almost every mathematician.

*This should be done in functional terms. That is, attention should be directed to functional action within the system.

establish that it is possible for it to be accomplished in a certain way, but a certain amount of leeway should be permitted in the planning, especially wherever previous functional elements or components have proved unsuitable or unsatisfactory to some extent, so that new ideas developed in the course of the project may find their way into the project activity.

Other Factors that Enter into the System Survey

TIMING

One of the factors that distinguishes a systems engineer from a nonsystems engineer is the ability to coordinate the prosecution of a project so that the project staff members do not sit around for a month or two with nothing to do and then find themselves overloaded with work for three consecutive months, and so on. Thus, the question of timing should enter into the system survey. This means that the systems engineer must be prepared to estimate the amount of time required for each subtask within the project. However, this is not enough. He must also be prepared to examine the interdependence of the various subtasks that enter into the project so that if item A has to be completed before item B begins, he can find items C and D, which can be worked on in the event that item A is not finished when some members of the project team are ready to begin on item B.

In planning how the various factors involved in a project can be timed, it is helpful to prepare a time sequence chart. Such a chart is shown in figure 6. In this chart the horizontal numbers at the top of the chart represent individual time divisions of the project. They are not normally of equal duration, but are defined by initiation and termination of various project work items. The important factors in the timing of the project are listed in the left-hand column and their beginnings and endings are indicated by the beginnings and endings of the lines drawn across the chart.

It may be of interest to note that the sequence chart is one basis for the design of telephone switching circuits, in which decisions are made by relays; also for that of digital computers, in which thousands of decisions may be made in a second, and incorrect timing cannot be tolerated.

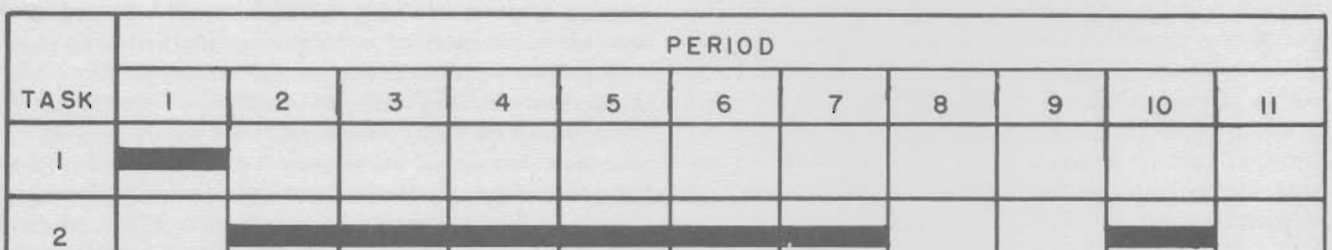

FIG. 6. TIME SEQUENCE CHART

MONEY

The systems engineer should prepare a graph showing the rate at which he expects project funds to be spent. He should also prepare a bar graph showing expected allocation of funds to research, development, testing, and other project activity. The purpose of this is to assist management in internal planning and in coordination with other agencies.

PERSONNEL

A systems engineer should make sure that his management knows his personnel needs. Since it is not always easy to supply personnel with specific capabilities, it is necessary in carrying out the system survey to consider what the personnel requirements will be. These requirements should be listed and submitted to the management as soon as feasible, calling attention to discrepancies between needed and available help.

UNUSUAL REQUIREMENTS

The systems engineer, in preparing the system survey, ought to be on the lookout for things that could eventually create delays in the project activity. This means, among other things, that he should attempt to anticipate unusual requirements in terms of information, supplies, personnel, and equipment. If possible, such unusual requirements should be acted upon very early in the project. If the time sequence chart is thoughtfully prepared, it will do much to cover this situation.

CONSULTING ASSISTANCE

One of the greatest weaknesses of the project-engineering system has been, and seems likely to continue to be, failure on the part of the project engineer to seek consulting assistance when it is needed. Such failure results, usually, from one of two causes:

(1) failure to recognize the need for consulting, and

(2) the human desire to avoid admitting lack of knowledge.

In an effort to solve this problem, several companies list permanent consultants on their staff at various levels of engineering, from the top supervisory level on down through the chain of command. As an example of this, a portion of the organizational chart of a large commercial research facility is shown in figure 7.

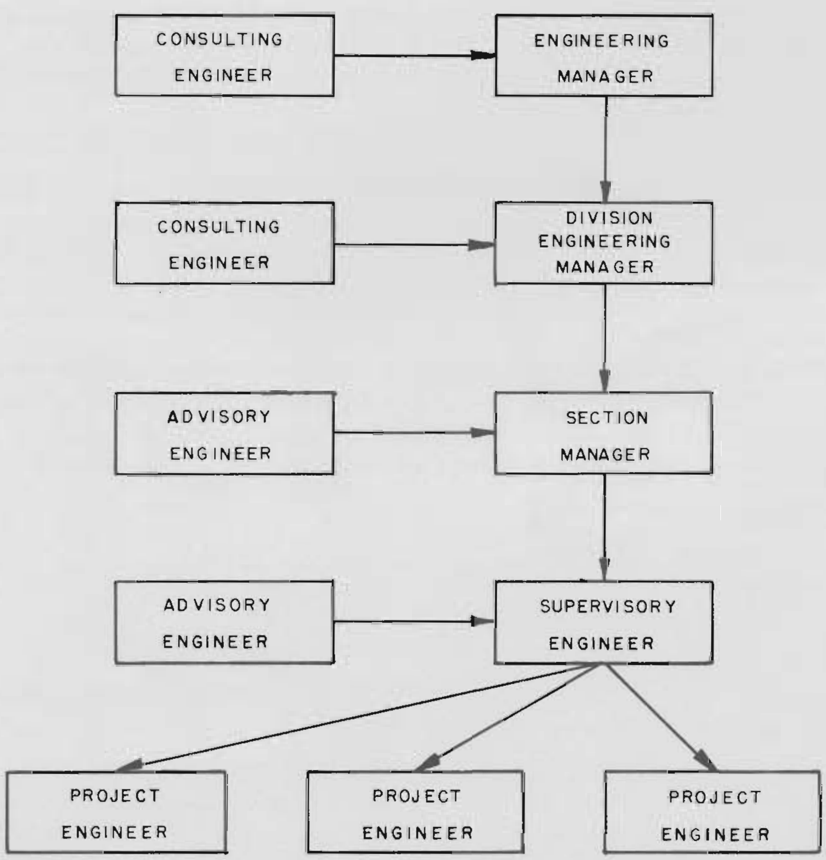

FIG. 7. PORTION OF ORGANIZATIONAL STRUCTURE OF A RESEARCH FACILITY, SHOWING POSITIONS OF ADVISORY AND CONSULTING ENGINEERS

Even though the need for consulting may be acknowledged and management has shown a desire to provide it, the old saying about leading a horse to water is appropriate here. A consultant, generally speaking, is willing to help but does not know what is required of him until he is told explicitly what problem he is expected to help with. He may be an expert in his field, but this does not make him a mind reader. The systems engineer must, therefore, organize his work so that he can formulate or recognize the need for formulating a specific problem, in order to make consulting assistance of maximum value to him. A systems engineer should be prepared to say "I don't know" as the project progresses.

RESPONSIBILITY TO SUPERVISORS

While responsibility for providing many of the needs of the systems engineer rests with the management or supervisor, it cannot be over-emphasized that it is the duty of the systems engineer to demonstrate clearly his needs to his supervisors. Hence, the systems engineer will prepare his system survey with his responsibility to supervisors in mind, as it will be essential to demonstrate why various items are required for the success of the project.

BOTTLENECKS

A systems engineer should try to foresee potential bottlenecks. He should recognize the probability of occurrence of these bottlenecks before they obtain a stranglehold on the project.

Check List for a Good System Survey

A check list for a good system survey is given on page 11. Remember that as yet nothing has been done on the project except that a considerable amount of thought and associated inquiry has been devoted to it by the systems engineer. He has prepared at this point a system survey that shows him what the important factors are in organizing his project. At this point, then, the systems engineer has completed the first phase of his work. He is now ready to turn to the second phase (to be considered in the next section), which involves reorganizing into a final working plan the thoughts that have already occurred to him. To re-emphasize the point, the system survey results in a list showing the factors that enter into the project, together with pertinent information showing how they enter. The organized plan must now combine these individual factors into a final working plan that can be used as a basis for proceeding with the project.

It is suggested that the systems engineer go over the check list in the presence of invited "critics" in order to try to improve the system survey as much as possible.

CHECK LIST FOR SYSTEM SURVEY

1. If the system is part of a larger system, has the relation between it and the larger system been clearly established?

2. Have the project requirements been clearly established in writing?

3. Is there a high probability that the proposed system is physically realizable (on the basis of known information)?

4. Have "pat problems" been identified wherever possible?

5. Have decisions crept into the thinking that rest on old ideas and that may act to deter progressive thinking at a later stage?

6. Has project timing been worked out?

7. Are available funds adequate for the project and is the timing realistic in view of available funds?

8. What personnel are required? How many of these people must be recruited?

9. What supplies and equipment must be ordered at an early date?

10. What consulting assistance is needed in

    a. Formulating the organized plan of procedure?

    b. Carrying out the project development, test, and evaluation?

11. Have project details been submitted to supervisors?

12. Have potential bottlenecks been searched for?

13. Have all environmental factors that will influence the product specifications and design been given adequate attention?

14. Is it possible to outline a completion report at this time? If not, why not?

The Organized Plan

Scope of the Plan

THERE is a real problem in determining what the scope of a plan for the project should be. The problem is just where to draw the line. For this reason, it is well that the first attempt at making an organized plan should include more than the engineer expects to eventually constitute the scope of the plan. It is important, then, to have all the factors worthy of being included grouped together so that one may decide which to throw out first, which to throw out second, and so on.

It may occur to the reader that much of the organized planning has been done in the system survey. It is evident that no plan can be settled until all the essential facts have been considered. The system survey has laid the basis for the final working plan.

The Allocation Problem

The scope of the plan being settled, the next factor to be considered is how the facilities to be used can be allocated to the various phases of the plan to achieve maximum benefit. Preliminary decisions on this point should be made at this stage of the planning.

Clairvoyance and Its Practical Benefits

It seems quite likely that if an engineer had all the training of the average systems engineer, and in addition could see into the future, he would have very few problems. From a more practical standpoint, it seems desirable for an engineer to devote as much thought as possible to predicting what his problems are likely to be in the future. This has been mentioned earlier and is now restated because of its influence on the allocation problem. One of the main things one must try to avoid is devoting too much money to the wrong phases of the project. Clearly, this can only be done if thought is given to possible future project developments. This thought leads naturally to the problem of emphasis.

The Emphasis Problem

The emphasis problem is the problem of deciding what phases of the plan are most important. One must decide which is the most important single objective, which is the second most important single objective, and so on. The emphasis problem should be settled as a part of the organized plan. Remember, of course, that the emphasis is not being fixed irrevocably, but that it is being considered for the purpose of establishing "signposts."

For Want of a Horseshoe Nail ...

Everyone knows the old story about the battle that was lost for want of a horseshoe nail. If there is a lesson to be learned from this story, it is that big things may depend on little factors. It is most important to the project engineer to discover early in the project the possibility that the entire project may fail because of an apparently innocuous factor that is easily overlooked. In preparing the organized plan, the systems engineer should be on the lookout for such things. Phrased another way, the systems engineer should establish the rational dependency between the various variables in his project, and he should not be averse to examining the smallest details.

The Indexing Problem

One of the factors that operates against a good plan is the inability of human beings to retain an indefinite amount of material at the tip of their tongues. The success of a project may well depend on having a good filing system. One suggestion for a means of keeping records is to index the project according to relative importance of the subproblems within the project. Hence, if the emphasis problem has been satisfactorily decided, one can make an indexing system consistent with the requirements of emphasis on the project. This sort of thing provides a good opportunity to utilize the pat-problem idea previously discussed.

Check List for Organized Plan

A check list for the organized plan is given on page 14. When the systems engineer has completed his plan, he should employ the check list shown to evaluate it. He should then give the plan to others to evaluate. He should expect criticism and should expect to reorganize his plan before proceeding to the basic design stage. Furthermore, he should be prepared to reorganize his plan as the project continues.

The Definitive Project Meeting

After the system survey is completed, and an organized plan has been prepared, the persons concerned should meet for a single purpose: to agree on the organized plan. At this meeting the systems engineer develops the logical patterns of the project and agreement is reached on the future course of project activity.

CHECK LIST FOR ORGANIZED PLAN

1. Have all essential variables that will affect the final product been established?
2. Have nonessential items been eliminated from the plan?
3. How well does the plan match facilities available for carrying it out?
4. Is the plan written in simple, clear language?
5. Has the plan been evaluated by others?
6. Has expert advice been obtained where needed?
7. Has the project timing been re-evaluated and is it realistic?
8. What factors, if any, cast doubt on the possibility of completing the project as timed?
9. Has a realistic test program been prepared?
10. Will available data-handling apparatus be adequate for product evaluation?
11. Are there spots in the plan where I should say "I don't know" and seek the advice of others?
12. Can a completion report now be outlined? If not, why not?

Ideal Systems and Optimum Systems

Use of the Word "Ideal"

THE FIRST reaction of many when confronted with the word "ideal" is that it is just too ideal a term to be of much use. They seem to feel that when a thing is ideal, it is too far removed from the practical. This need not be true. Every engineer who develops something visualizes, to a certain extent at least, the kind of performance he would like to get from the object he develops. Because of his background of training and experience, however, he is conditioned to temper his desires and to fit them to what he has learned to expect as a realistic kind of behavior from the end product.

Persons without engineering background, on the other hand, are prone to desire certain things and to disregard through ignorance the practical limitations imposed by nature. For this reason, such persons have been known to inspire engineers to produce devices which they would never have believed could be produced. In such situations, it appears that the engineer has not succeeded in learning to separate the desirable from the physically realizable and, in a case involving both, is inclined to weigh the latter too heavily in his considerations.

The word ideal, it is believed, can grow fruitfully into the engineering vocabulary, if it is construed in functional terms and is removed just far enough from the physically realizable aspects of a situation to permit discussion of the situation on its own merits. For example, if one visualizes the ideal door operating mechanism as one which opens a door at a touch with a definite constant velocity and closes it after a prescribed time delay provided no one is passing through it, a variety of ways of realizing such a device may occur to the individual. If, on the other hand, he visualizes a door operating mechanism as a human being propelling the door in both directions, there is little stimulus to the imagination.

What is suggested is that the "ideal" be used to convey the functional sense in which a device or a system is supposed to be used, and that, in using it, certain physical factors such as time, space, weight, and so on, enter into the description. If it is desirable, for example, that a certain event occur in a prescribed minimum time, let the time be set at the absolute minimum consistent with satisfactory performance. If this time happens to be zero, let this define the ideal behavior.

Used in this way, the word ideal can serve as a means of defining goals as divorced from the physical ways of arriving at these goals. Let's try to shoot at a target.

Use of the Word "Optimum"

In system design terminology, the word "optimum" has strings attached. In any system design problem, there are certain limitations that preclude the attainment of the ideal. These limitations may be physical, economic, or technical. Physical limitations are those limitations imposed by nature. Economic limitations are those limitations imposed at the administrative level for well known reasons. Technical limitations involve limitations on quantity and quality of personnel.

Now, suppose that a system design problem has been assigned. It is true that there are any number of systems that might be selected to accomplish the desired end. Among this group of possible systems, there is one that most nearly approaches the ideal and that is attainable within the set of limitations mentioned previously. It is this one that is considered to be the optimum system.

The question of choosing the optimum system from the set of possible systems is sometimes settled by reviewing the physical limitations, and disregarding the other two types of limitations. On other occasions, economic limitations are advanced as the major limiting factor. A sound decision as to what constitutes the optimum system in a given case should involve all three types of limitations.

The three types of limitations mentioned above may or may not be subject to adjustment. For example, physical limitations may be such that the systems engineer can do nothing to overcome them. On the other hand, by use of much ingenuity, the systems engineer may recognize that what appeared to be a physical limitation may be circumvented by a new approach, and hence was not really a physical limitation, but only appeared to be. Economic and technical limitations may often be adjusted by strong action on the part of the systems engineer.

Since a proper selection of the optimum system involves these three types of limitations, it can be seen that the person in the best position to make the decision is the systems engineer. It can also be seen that with this decision goes responsibility for it. Hence, it follows that the systems engineer should have a clear picture of what the limitations are and should seek to adjust them, whenever possible, to enable him to upgrade his concept of what the optimum system would be. In order to do this effectively, the concept of the ideal system as discussed in the first part of this section should be kept well in mind.

Alternate Definition of Systems Engineer

On the basis of these distinctions, an alternate definition of systems engineer can be phrased. A systems engineer conceives the ideal system to perform a given task, and supervises the physical realization of the optimum system to perform that task.

Product Development

The Development Cycle

AT THIS point, if the previous planning has been properly carried out, and agreement has been reached on the project details, the systems engineer is ready to enter the development sequence. This sequence, which is diagrammed in figure 8,* should be a part of every systems engineer's being. One may observe that the sequence consists of a basic design inserted into a closed-loop feedback system, the output being the approved prototype. Since the basic design is fundamental to this development sequence, the importance of a good basic design should be apparent. The systems engineer carries the project from the basic-design stage through the construction stage, the test stage, the data handling, the evaluation stage, to the improved design, the new construction, the new test, the new data reduction, the new evaluation, the new improved design, and so on, until out of the construction stage one arrives at an approved prototype. Naturally, the emphasis given to the various steps of this development sequence will depend considerably on the nature of the product. Yet each of the steps is normally to be found as a part of the development sequence for a product. From this figure, one can well imagine the difficulties that will result, the huge wastes of time and effort and money, if the basic design is not well thought out and carefully planned. However, sound evaluation is equally important to the efficiency of the development sequence, and it may not be possible to provide this unless sound tests can be carried out and unless appropriate data-reduction means are available.

In addition to good planning and sound evaluation, good communication between various portions of the personnel involved in the development sequence is essential. Furthermore, consistent monitoring must be carried out to make sure that the development cycle operates efficiently. Otherwise, how can one be sure that the improved design is really better than the first design?

*This figure is based on a discussion in Erwin Donath's paper "Automatic Data Reduction," presented before the Bumblebee Guidance Panel at Princeton, N. J., December 6, 1951.

Another important question is one which involves the efficiency of the systems engineer. How many times must the feedback loop be traversed before the approved prototype emerges? Here is a real measure of sound planning. This is the essence of systems engineering.

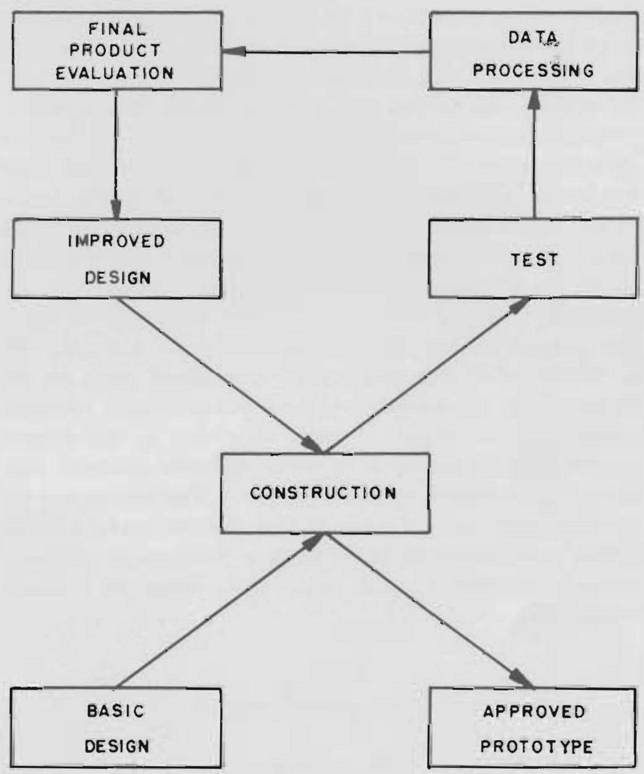

FIG. 8. DEVELOPMENT SEQUENCE

System Requirements

The systems engineer must keep the requirements of the system well in mind. These requirements may often permit the use of certain components that are not exceptionally good components in their own right, but that will satisfactorily fulfill their functions in the system. For example, a systems engineer who knows the requirements of his system will not spend project time and funds in building a high-gain, high-fidelity amplifier when a low-gain, low-fidelity amplifier will suffice. Often in such cases an inexpensive, purchased component can save much development effort.

However, system requirements should be phrased so that hardware does not appear in the phraseology at any point. One should be prepared to say in simple English what the system is to do, what it is to work with, what it is to work from, what it is to work into, and what the properties are of the device or devices with which the system is to work. Is the system a part of a larger system? If so, the system requirements are in some ways independent of the additional outside elements and in other ways dependent on them. This distinction should be clear in the mind of the systems engineer.

A system which, in itself, is exceptionally good, when required to fit into a larger system may be exceptionally poor simply because it will not meet the requirements of interconnection. In effect, we may say that to know the system requirements one must know (1) what will be put into the system, (2) the nature of the device that feeds the system, (3) what will go out of the system, (4) the nature of the device into which the system is to feed, and (5) what the system is required to do to relate the input and the output. When input and output are used in this sense, one need not visualize any particular physical things. In a battlefield, for example, the input may be an order from the colonel, the output may be a private going out on a patrol and shooting a machine-gunner. The factors in between the colonel and the private make up the system. The system will be optimum in this case if the task is carried out in the minimum of time with a minimum of personnel involved and with the desired result achieved.

Old Chestnuts

The term "old chestnuts" is often applied to devices or means of doing things which have been around for a long time and with which general familiarity is assumed. Since progress depends on better ways of doing things, a systems engineer will always accept old chestnuts with a certain amount of caution. If a device or a way of doing things has been around for a long time, the odds are very great, in view of the rapid pace of engineering progress, that such a device or system can be improved. At any rate, a systems engineer should never assume that the desirability of a method or device is obvious* merely because it has been around for a long time. He should always be prepared to question the fundamental aspects of a device or a means of doing something before incorporating it in his project. On the other hand, of course, there is no justification for new developments unless improvements are made over the previous results.

Help Wanted

On the typical type of project that systems engineers are being called upon to handle, it is usually impossible for the systems engineer to have acquired all of the background knowledge essential to carrying out the project successfully. This being true, the systems engineer has two alternatives: he can either proceed to learn personally all the facts that he needs to know to successfully complete the project (which may sometimes take many years), or he can call upon persons who are well trained in the areas where he is lacking. Probably one of the best indications of a man's real suitability for systems engineering is his willingness to admit to himself and others that he does not know everything there is to know about the project and that he needs technical advice in certain areas.

Probably the best type of background to have for systems engineering is a mixture of basic engineering, basic physics, and advanced mathematics. If a systems engineer has a background of advanced mathematics, the chances are he can recognize the need for mathematical assistance; this is often one of the most difficult things to do in a project since, by its very nature, mathematical assistance is intangible and the need for it is not manifested in a tangible way. An engineer can be a success as a systems engineer without advanced mathematical training only if he is willing to request qualified mathematical personnel to go over his planning and suggest possible ways in which mathematics or analysis can be of aid in his project. It is not uncommon, at present, to see mathematicians in systems-engineering posts, in spite of the fact that their training and background may not be adequate from the standpoint of basic-design principles. This is probably a direct outgrowth of the fact that engineers have failed to qualify themselves mathematically for systems engineering.

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*The word obvious has been defined as (a) not understood, (b) impossible to explain, and, often, (c) incorrect.

The Role of the Aspirin Tablet in Systems Engineering

While a systems engineer will have many problems in the prosecution of his project, there is one whose satisfactory solution will merit any amount of effort and aspirin tablets. That is the problem of getting along with people. If there is one quality that is more essential in systems engineering than any other, it is the ability of the systems engineer to get along with people. The success of a systems project depends on many people. The responsibility for the systems project rests with the systems engineer. It is, then, of the utmost importance to the systems engineer that the persons who work for and with him do an effective job. If system planning has been sound, much of the battle has been won. Nevertheless, the systems engineer must occasionally subjugate his personal feelings and beliefs in order to achieve advances in the project.

System Tests

Reasons for Running Tests

SOME ENGINEERS give the impression that the reason for running a test is to acquire a great mass of data which cannot be analyzed or, if analyzed, would mean nothing. Since tests usually consume much of the time and energy available on a project, it is desirable, as has been stated previously, that the systems engineer plan his testing program early in the course of the project. This does not mean that he should decide what voltmeter or what kind of oscilloscope he will use, or anything of the sort. It means that he should try to decide early what quantities he will measure in order to make possible an evaluation of system performance. He should decide early whether these quantities are measurable with existing equipment and whether the quantities desired can be measured to an accuracy necessary to give conclusive results. Certainly, it is ridiculous to attempt to meet test specifications with a completed system if one could have seen before the system design began that the required tests would be impossible.

In setting up tests, the systems engineer faces a problem that should not be taken lightly. This is the problem of obtaining a test plan that will yield objective and unbiased results. It is suggested that the problem of setting up tests might well be referred to an individual with very little connection in other respects with the project. This individual will be free of any love for the equipment or obsessions regarding it, such as the engineer who conceived it might have. In this way he can set up a test as an "unbiased testing organization." If tests are really to mean anything, they should not depend on who sets them up or who takes the data; in other words, results of tests should be reproducible. Therefore, it is suggested that, if at all possible, system tests should be planned early in the project by the project engineer and referred to an unbiased observer at that stage before proceeding with the development cycle; and that this dual test planning arrangement should be renewed at the time when tests are carried out.

Scientific Experiments

The theory of carrying out tests (which properly should be thought of as scientific experiments) can be quite a science in itself. A systems engineer can usually find someone who is well versed in the design of experiments. If so, such an individual should be called upon to evaluate the system test plan.

Interpretation of Data

The best rule to follow in interpretation of data is this: Do not take a single piece of data until you know beforehand what you will do with it. Most data are hard to interpret simply because the planning and test procedures, which produced them, are open to question. It cannot be emphasized too strongly that data are only as good as the people and devices that produce them. They are also only as good as the form in which they are taken. The points stated previously apply to data interpretation - careful planning of the experiment is essential if the data are to mean anything.

Check List for System Tests

A check list for system tests is given on page 22. This check list should be applied to the system-test planning early in the planning stages of the project. It should be applied again at the time the tests are being set up to make sure that conditions have not changed since the early planning stage, making revisions of the tests necessary. If these steps are taken, the data processing, which is usually carried out by a group not previously concerned with the project, will probably be carried out effectively, since the person bringing the data to the data analysis group will be able to explain to them what the data are and what they show. It might be well to show the system-test plan to someone in the data analysis group before the test is run. Since the reason for running the test is to obtain data that can be analyzed, it may be possible that, by simply reading another variable, the data analysis problem will be greatly simplified.

The possibility of analyzing the data simultaneously with the system tests should be considered. Modern developments in computing devices have made this often possible, and it may save a substantial amount of project time. This is a question that may call for technical assistance. It should be considered in almost any project test where a considerable amount of data is involved.

CHECK LIST FOR SYSTEM TESTS

1. What quantities must be measured for system evaluation?

2. Can the quantities be measured?

   a. What data can be taken to check other data?

   b. What precision is required for meaningful results?

3. Can additional facilities be requested at an early date, if required?

4. Estimate the volume of data to be processed.

5. How will the data be processed?

6. What will the test results reveal about the system?

7. How can test results be checked?

   a. How can test results be used to improve the design?

   b. Can a preliminary evaluation of test results be made before the entire test program is completed?

8. Can an instrument be purchased, leased, or devised for data handling?

9. Has the test program been reviewed by an unbiased observer?

Project Completion

When Is a Project Completed?

A PROJECT is completed when the minimum objectives that the systems engineer has set have been achieved.

The Need for Project Completion

There was, for a time, a standing joke in the electronic computer field that an electronic computer is never completed; it is continuously being revised and brought up to date. It is probably true to say that even now this is as much of a reality as it is a joke in noncommercial computing machines. Still, this is not a good way to look at product development. Product development, as illustrated by the development cycle, should

(1) terminate,

(2) be reinstigated, if necessary, after product review.

The vague region in between these two stages is no place for the systems engineer. The systems engineer should attempt, in the early planning stage, to set the objectives at such a level that the project can be terminated within a certain amount of time. He should have a target date set for each individual portion of his project, as outlined earlier in connection with the plan of organization. The goal of a systems engineer should be to terminate the project in the minimum amount of time consistent with the product objectives set at the beginning of the project. One of the factors that may cause a project to drag out too long is that the responsible engineer may be reluctant to delegate authority in sufficient quantity and at appropriate levels to those working with him. This is an understandable fault, but one that the systems engineer should try to overcome. If, during the course of the project, new problems arise, these problems should be identified as such and suggested as possible new projects, unless it is absolutely essential to carry out these tasks as part of the project at hand.

If some particular problem in the project is delaying the project, the systems engineer should recognize this as a symptom of trouble in the early stages and should immediately seek technical assistance. While there may be a short-term advantage to the systems engineer in denying himself needed technical help and thus (for the moment, perhaps) appearing more efficient in the eyes of management, in the long run his accomplishments will be considerably less than they would have been had he requested such help when needed, and thus completed his project sooner. In this connection, the systems engineer should never be afraid to face the fact that a certain task may not be possible to accomplish. He should be willing to admit to himself that some of the problems may not be solvable. Having done this, he is in a position to demand proof that such is not the case. Contrast this with the assumption that a certain problem is solvable if one merely works at it long enough. The adoption of the attitude that the problem may not be solvable permits the systems engineer to try to place the burden of proof of solvability on technical advisors or other individuals on the project.

The Advantage of Project Completion

Aside from the evident advantage to the contracting agency of having a project terminated with the development of a suitable product, there should be a great deal of personal satisfaction for the systems engineer in realizing that he has coordinated his attack on the problem so effectively that he has been able to complete the project. If the systems engineer is the kind of fellow who looks forward to new experiences and enjoys increasing the breadth of his experience, he will welcome the completion of one project in order that he may be assigned to another. The good systems engineer will recognize this advantage to himself and will attempt to terminate his project as soon as possible, consistent with good results. It is thus the mark of a man with limited interests and little systems-engineering ability to be responsible for a project which drags on and on. There are often, of course, extenuating circumstances and this criticism is not meant to apply to these cases. However, too often such circumstances are not justified in fact, but are a result of poor planning on the part of the engineer. Such circumstances may arise, for example, when an engineer permits the continuation of the work to depend upon the activity of an outside organization to the extent that he cannot control the effective progress of the project. Such arrangements should be avoided whenever possible.

When Should a Project Be Reinstigated?

A project in which minimum objectives have been met should be regarded as complete. A question which then may arise is: Should the work of the project be reinstigated? This should be done if

(a) minimum objectives have been obtained within a reasonable time;

(b) the need for upgrading the objectives is evident;

(c) facts have been developed, in the process of attaining minimum objectives, which provide reasonable assurance that a higher level of objectives may be achieved;

(d) there is no more important or effective way to utilize available manpower and facilities.

Since members of the administrative staff will have cognizance of item (d), clearly the decision for project reinstigation should rest with them.

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Dr. G. C. Quarles, Director
Ordnance Research Laboratory
The Pennsylvania State University
University Park, Pa.

Dear Gil:

I have read with considerable interest Warfield's report on SYSTEMS ENGINEERING (Report No. 307). Although I have read many related reports, they usually cover only a portion of the concepts covered by Warfield. This report is concise enough to be used, and contains some sensible check lists for ready reference.

I do not know whether I can get all my Systems Engineers to follow the recommendations exactly and, in all probability, it would not be desirable for them to do so. However, I would like to give them an opportunity to consider what is in the SYSTEMS ENGINEERING report when they are making their plans. Accordingly, if you have about 20 to 30 extra copies of the report, I would appreciate your sending them to me.

Sincerely,

Gerry

G. G. GOULD
Technical Director