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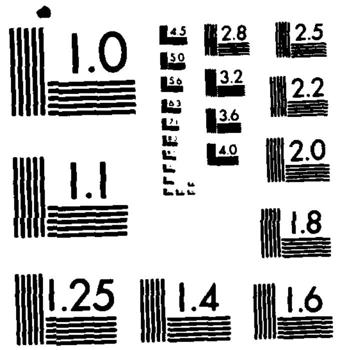
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A SYSTEMS ENGINEERING METHODOLOGY
FOR THE ADVANCED TACTICAL AIRCRAFT

by

Stephen Joseph Kapurch

September 1985

Thesis Advisor: J. W. Creighton

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The increasing specialization of the aerospace industry coupled with the technical complexity of new systems has caused emphasis to be placed on a systematic and logical methodology to design, develop, and produce new products. A systems engineering model to integrate functional management areas with organizational activities in the Advanced Tactical Aircraft program is presented. Special emphasis is placed in applying this systems approach throughout the life cycle of a project. A general methodology

and a synopsis of principles are provided which might be utilized in the development of a systems engineering program. Key words:

A Systems Engineering Methodology For The Advanced Tactical Aircraft

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ABSTRACT

The increasing specialization of the aerospace industry coupled with the technical complexity of new systems has caused emphasis to be placed on a systematic and logical methodology to design, develop, and produce new products. A systems engineering model to integrate functional management areas with organizational activities in the Advanced Tactical Aircraft program is presented. Special emphasis is placed in applying this systems approach throughout the life cycle of a project. A general methodology and a synopsis of principles are provided which might be utilized in the development of a systems engineering program.

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY OF ACRONYMS

AIAS	ADVANCED INTEGRATED ARMAMENT SYSTEM
ATA	ADVANCED TACTTICAL AIRCRAFT
ATF	ADVANCED TACTICAL FIGHTER
DoD	DEPARTMENT of DEFENSE
F2D2	FUNCTIONAL FLOW DIAGRAMS AND DESCRIPTIONS
JAFE	JOINT ADVANCED FIGHTER ENGINE
JPL	JET PROPULSION LABORATORY
JTCG	JOINT TECHNICAL COORDINATING GROUP
LMSC	LOCKHEED MISSILES AND SPACE COMPANY
MIS	MANAGEMENT INFORMATION SYSTEM
NASA	NATIONAL AERONAUTICS AND SPACE ADMINISTRTATION
PHS&T	PACKAGING, HANDLING, STORAGE & TRANSPORTATION
RAM	RELIABILITY, AVAILABILITY AND MAINTAINABILITY
RCS	RADAR CROSS SECTION
RFP	REQUEST FOR PROPOSAL
SEMP	SYSTEM ENGINEERING MANAGEMENT PLAN

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I. INTRODUCTION

A. BACKGROUND

> "The complexity of a modern weapon system requires conscious application of system engineering principles and concepts to ensure producible, operable, and supportable systems that satisfy mission requirements. This concept of technical management is the logical and systematic conduct including planning, organizing, directing, and controlling of the engineering effort required to transform a military requirement into an operational system." [Ref. 1:p. 24]

This statement is an example from one advocate of systems engineering. There are many advocates because systems engineering is not a new concept. However, in this era of technical specialization, systems engineering is one of the most difficult tasks facing program managers because high technology programs require tailored management approaches. Identifying and integrating activities of functional area experts and organizations into a synergistic effort to meet the systems objectives is crucial. This requirement is often overlooked, but even if recognized, is difficult to address because of the complexity of subsystems. The number of functional experts and organizations involved in the acquisition process continues to increase. The responsibilities, tools, techniques, and capabilities of these people must be identified and integrated by the program manager. In addition, the degree to which each should be involved on particular aspects of the program must be determined in a logical and timely manner.

The Advanced Tactical Aircraft (ATA) and its weapon systems will be developed simultanously. In the past a particular weapon was designed to fit an existing aircraft, or an aircraft was designed to incorporate existing weapons. Therefore, the Advanced Tactical Aircraft will create a new and challenging systems engineering approach.

B. PURPOSE OF THESIS

The purpose of this thesis is, first, to develop and present a general qualitative systems engineering model to increase the ability of management to integrate functional areas and organizational activities involved in the ATA program with specific emphasis on the armament subsystem. Second, it will attempt to develop and present a general methodology that can be utilized in the future for other complex programs. Thirdly, it will provide a synopsis of principles which might be utilized in the development of a systems engineering course.

C. SCOPE OF STUDY

Constraints of time and resources limited this investigation to various Department of the Navy organizations and to the Lockheed Missiles and Space Company, Inc. (LMSC).

The scope of this study is confined to:

1. Investigating the validity and need for systems engineering in complex systems,

2. Investigate the general requirements of the ATA,

3. Determine current tools, elements, and models of systems engineering,

4. Synthesize the information found in task three and apply this information to the ATA.

The ATA is currently in the concept exploration phase of its development cycle. Due to the infancy of the ATA program, circumstances are subject to rapid and unpredictable changes. This research effort was undertaken under these environmental considerations. Therefore, 30 July 1985 was used as the cutoff date for information and reference acquisition. Any changes that affect the ATA after that date are not incorporated.

D. RESEARCH METHODOLOGY

The research methodology utilized to achieve the objectives of this thesis is illustrated in Figure 1. Five basic tasks treated in Chapters II - VI were conducted by answering the following research questions:

* Task 1 - Chapter II:

  a) What is systems engineering?

  b) Why systems engineering?

  c) How does it interface with a systems life cycle?

* Task 2 - Chapter III:

  a) What are the tools, elements, and models of systems engineering?

* Task 3 - Chapter IV

  a) What is the ATA?

* Task 4 - Chapter V

  a) What are the advantages and disadvantages of the various systems engineering models in relationship to the ATA?

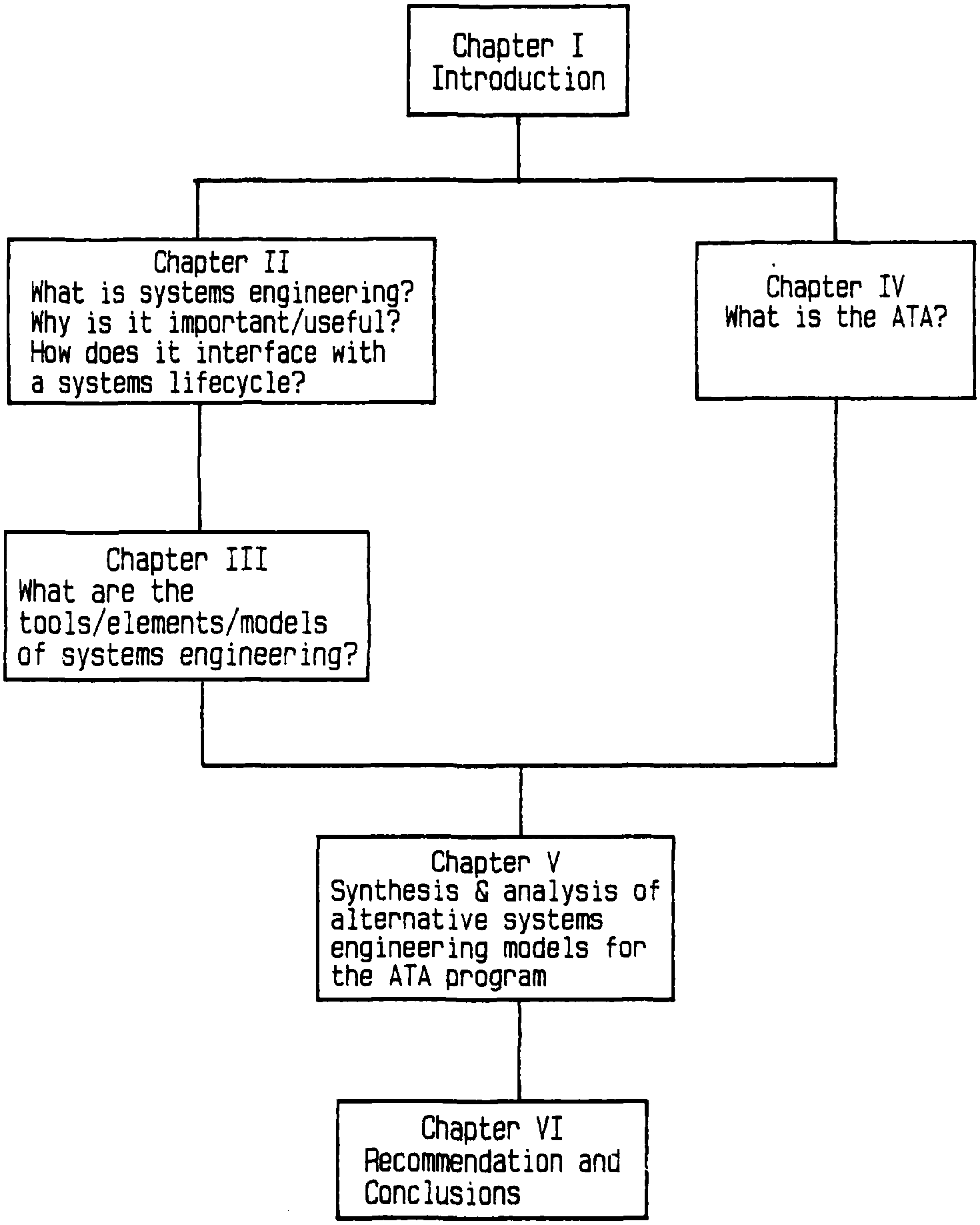


Figure 1 Research Methodology

* Task 5 - Chapter VI

    a) What can be concluded and recommended about systems engineering for the ATA?

A parallel research effort was conducted in Chapters II, III, and Chapter IV. The information from these Chapters was then integrated in Chapter V with the results presented in Chapter VI.

A number of different sources of information were used, including: books and articles in the open literature, Department of Defense (DoD) directives and reports, and discussions with personnel involved in systems engineering and the ATA, both in industry and the Department of the Navy. The list of references cite some of the most important documents utilized. A review of the documents will give readers a more complete understanding of problems facing developers of complex systems and the field of systems engineering.

II. SYSTEMS ENGINEERING

A. BACKGROUND

Systems engineering is not a completely new or revolutionary discipline. As a method, it has been utilized for many years in an informal manner without a specific designation [Ref. 2:p. 19]. Undoubtedly, a rudimentary forerunner of systems engineering was used by the Egyptians to construct the Pyramids and the Chinese to construct the Great Wall. One of the earliest American applications of systems engineering occured during the war of 1812 when the Army commissioned Eli Whitney to provide the first rifles to have interchangeable components and parts [Ref. 3:p. 8].

While the practice is not new, the recognition of systems engineering by name is new. During the past forty-five years the development of large complex systems has given rise to increasing awareness of the field of systems engineering. Within the DoD this has been crucial because of the need to utilize state of the art technology in weapon systems as they are being developed and to control the inherent risks associated with the introduction of new technology.

The difficulties experienced in developing large and complex systems has led to the refinement of specific tools and techniques within the system engineering discipline. The refinements have led to better control and insight into design, development, and production processes.

B. EVOLUTION OF SYSTEMS ENGINEERING

Systems engineering methodology as an effective method for solving the most difficult problems raised by today's complex technological environment has not been developed overnight, but has evolved over a number of years. In 1907, the establishment of an organization in the Bell Laboratories reflected characteristics which, in retrospect, can be identified with the present concept of systems engineering [Ref. 4:p. 35]. In the 1930's RCA recognized the need for a systems approach in the development of a television broadcasting service [Ref. 5:p. 64].

World War II gave the greatest impetus to the extension of the systems engineering approach, largely because of developments in atomic energy, jet propulsion for aircraft, radar, and other electronic devices. For example, the requirements for many types of electronic systems gave rise to a wide variety of components and subassemblies of major systems that became known as "black boxes." The proliferation of these electronic devices caused problems of component interaction and integration. Systems engineering performed the essential task of looking ahead to the ultimate objective, the system, and considering the "Big Picture", of which each component was a part. This approach was then utilized in applying rocket motors to aircraft and other technological improvements. After World War II, the Rand Corporation developed a useful process called "Systems Functional Analysis." This process is often referred to as the first phase of systems engineering. [Ref. 5:p. 64]

Also at this time project engineers started to acquire a staff typically including an assistant project engineer for electronics and another for planning and scheduling. As equipment and life cycle costs became as important to the customer as the initial manufacturing costs, specialists in reliability, maintainability, and producibility were added to traditional design engineering departments and consolidated into systems engineering staffs. The project engineer, whose responsibilities now included life cycle costs and integrated logistics support, became a project or program manager. In the engineering hierarchy, systems engineers represent a new layer of management and technical resources control between the program manager and the detail designer. As a result of these developments the relative growth of engineering departments has been in the systems area. The engineering departments in advanced systems development organizations have grown from about 10 percent of all employees to something over 30 percent. This growth has occured primarily in the systems engineering disciplines. [Ref. 6:p. 140]

C. SYSTEMS ENGINEERING VIEWPOINTS AND DEFINITIONS

A logical first step in understanding the concept of systems engineering is to define the term "system."

> A system is a composite of equipment, skills, and techniques capable of performing and/or supporting an operational role. A complete system includes related facilities, equipment, material, services, software, technical data, and personnel required for its operation and support to the degree that is can be considered a self-sufficient unit in its intended operational and/or support environment. The system is what is employed operationally and supported logistically. [Ref. 7:p. 2-1]

The terms "systems engineering", "systems approach", and "systems management" are used interchangeably, but research has revealed that seldom do two individuals agree to, or understand a definition of these terms [Ref. 2:p. 19]. This condition creates a semantics problem. As a result it is argued that systems engineering is not being practiced effectively.

1. <u>Viewpoints Of Systems Engineering</u>

Since there is controversy regarding the definition of systems engineering, a method to develop a better understanding of the concept is to examine a number of the various ways in which the subject is viewed. A number of the viewpoints were researched and summarized as follows: [Ref. 8:pp. 1-7--1-10]

a. Mathematics

b. Electrical Engineering

c. Engineering Design

d. The Planning of Design

e. The Management of Design

f. Large Scale System Development

g. Design Interface Management

h. An Interdisciplinary Activity

i. The Systems Engineer

Each viewpoint has a degree of validity, and research indicates that each has its advocates.

a. The Mathematics Viewpoint

This viewpoint, which is prevalent in engineering academic circles, considers systems engineering to be a set of mathematical concepts or techniques. These include system theory, simulation techniques, and computational algorithms. In actuality, these are some of the tools and techniques of systems engineering.

b. The Electrical Engineering Viewpoint

This viewpoint is often similar and closely allied to the mathematics viewpoint. It treats systems engineering as being nothing more than control theory, network analysis, information theory, or state-space theory.

c. The Engineering Design Viewpoint

This viewpoint states that systems engineering is nothing more than ordinary design engineering, and therefore "So What's New?" While design is an important major ingredient, the planning phases of system engineering are just as important as design. Further, for complex, interdisciplinary systems, traditional design engineering, as taught and practiced is inadequate.

d. The Planning Of Design Viewpoint

This viewpoint states that there are certain activities which prelude design and that these activities are systems engineering. These are the planning activities which translate needs into system design requirements and specifications. Until recently, such planning activites have not been considered as part of the engineer's responsibility, but the responsibility of systems analysts or operation analysts.

e. The Management Of Design Viewpoint

This viewpoint is that systems engineering is really the management of complex system design and, therefore, is concerned primarily with schedules, costs, personnel assignments, and management controls.

f. Large Scale System Development Viewpoint

This is concerned with the development of large complex systems such as the space shuttle program, transportation systems, communication systems, urban planning and the like. To the extent that such activities include both the planning and design of such systems, they are applications of systems engineering. To the extent that these activities include only system planning and use the decision process, they are partial or incomplete systems engineering.

g. Design Interface Management Viewpoint

In industry and government, systems engineering is often taken to be the coordination or management of the interfaces between different design disciplines. It includes the system engineering effort to define the system and the integrated planning and control of the program efforts of design engineering, system support engineering, production engineering, and test and evaluation engineering. This is one of the functions of primary importance in systems engineering. It is through such interfaces that important design trade-offs and optimizations must be made.

h. The Interdisciplinary Activity Viewpoint

This viewpoint states that systems engineering is the combining of interdisciplinary activities. There is little doubt that systems engineering is concerned with interdisciplinary activities but this is merely a necessary, not a sufficient condition.

i. The Systems Engineering Viewpoint

This viewpoint states systems engineering is more than a knowledge and application of principles of systems design and systems modeling concepts. The heart of the matter lies in the complexity of the system and being able to see the forest without getting lost in the trees. The systems engineer must deal with the various subsystems and component parts in such a way as to optimize the cost effectiveness of the overall system. [Ref. 9:p. 46]

2. <u>Definitions Of Systems Engineering</u>

From the previous paragraphs one realizes that systems engineering cannot be defined within the framework of one viewpoint, but is some combination of all of them. In order to establish a definition which is applicable to this research effort, a number of existing definitions of systems engineering are provided for consideration. These definitions were selected from industry, government, and academic sources.

> System engineering is the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation; (b) integrate related technical parameters and ensure

compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human, and other such factors into the total engineering effort to meet cost, schedule and technical performance objectives. [Ref. 10]

The systems engineering process is one of translating mission and operational requirements into engineering functional requirements, and subsequently expanding these functional requirements into detailed design requirements. Systems engineering involves the logical sequence of activities leading to a complete and balanced defintion of the design, test, production, operation and support of a system or equipment. Although there are slight variations depending on the system type and program requirements, the general process commences with mission requirement analysis (definition of operational requirements) and continues through system analysis, optimization, synthesis, detailed design, and test and evaluation. This process is a closed loop with the necessary feedback provisions and is iterative in nature. [Ref. 11:p. 18]

The systems engineering method recognizes each system as an integrated whole even though composed of diverse, specialized structures and subfunctions. It further recognizes that any system has a number of objectives and that balance between them may differ widely from system to system. The methods seek to optimize system functions according to the weighted objectives and to achieve maximum compatibility of its parts. [Ref. 12:p. 8]

Systems engineering is the process by which people develop the specification for an optimal system in response to unfulfilled human needs and/or desires. (An "optimal" system is a system which is expected to best satisfy recognized human needs and/or desires according to some specified criterion of "goodness".) System engineering is problem solving which involves the quantitiative application of technology in order to identify and describe a solution. The solution is a model of the system, a set of specifications for the production, installation, and use of an optimal system and its elements. [Ref. 8:p. 1-15]

The major systems engineering and analysis activities include the following:

1. The quantitative analysis and justification of operational needs.
2. The identification and establishment of operational mission requirements and environments.

3. The analysis of these requirements to apportion the performance, design, and test requirements to and through lower system levels down to individual components and elements.
4. The techniques for controlling the design, development, or selection of components to assure that they satisfy requirements (design assurance).
5. The techniques for integrating lower level components into all higher levels of assembly all the way to top system levels. [Ref. 6:p. 141]

Systems engineering is the combination of systems integration and project engineering. Systems integration consisting of the following:

1. Identifying the mission objectives.
2. Identifying the subsystem and component interfaces.
3. Establishing design trade-off and integration criteria.
4. Identifying the system performance testing criteria.

Project engineering consists of project direction, special studies and problem resolution. [Ref. 13]

System engineering refers to the process of translating operational requirements into engineering functional requirements and subsequently expanding these functional requirements into detailed equipment and service end item design requirements. This process involves analyzing system performance requirements, performing system-level trade-offs studies, synthesizing alternative system design solutions by employing various combinations of equipment and service end items, and finally selecting the preferred candidate configuration which best meets system performance and cost effectiveness criteria. [Ref. 14:p. 125]

The system engineering process is the application of the necessary scientific and technical knowledge and skills to the study and planning of the overall system whereby the interrelationships of various parts of the system and the utilization of the various subsystems are fully analyzed and designed in terms of their contribution to the achievement of the specified mission and performance requirements within the given cost and delivery limitations. Documentation of the process provides the common frame of reference and communication media for the "building block" approach to system design which may employ diverse specialists in such subject matter areas as: physics; nucleonics; chemistry; thermodynamics; electronics; mathematics; physiology; medicine; psychology; communications; mechanics; etc. [Ref. 14:p. 7]

The essence of the systems engineering concept is that system performance cannot be determined from the performance of its individual subsystems and components alone. Systems concepts are more the sum of the characteristics of its subsystems derived from the interconnections of the systems objectives and requirements. Each system has its own environment, and is in fact a subsystem of some broader system. [Ref. 15:p. 2]

Systems engineering is an appropriate combination of the mathematical theory of systems and behavorial theory in a useful setting appropriate for the resolution of real world problems. The purpose of systems engineering is to develop policies for the management, direction, and regulation activities relative to the planning, development, production and operation of total systems to maintain overall integrity. [Ref. 16:p. 59]

Upon examination of the preceding definitions, certain key words and phrases emerge. Synthesizing these concepts the following working definition can be developed:

Systems engineering begins with the identification of an operational requirement for a system. The next step is to identify the constraints and environment in which the system will be developed, produced, and operated. At this point scientific and engineering skills can be utilized to transfrom the qualitative operational requirement into quantitative parameters. These parameters will then be taken down level-by-level from system to subsystems to parts and finally to component levels. Then it becomes an iterative process of analyzing the performance parameters, designing a solution, testing, and evaluation. Then trade-offs must be made on the subsystems based on weighted objectives established by the cost, schedule, and performance characteristics of the total system. Then integrate these subsystems into the total system. This relationship is shown schematically in Figure 2.

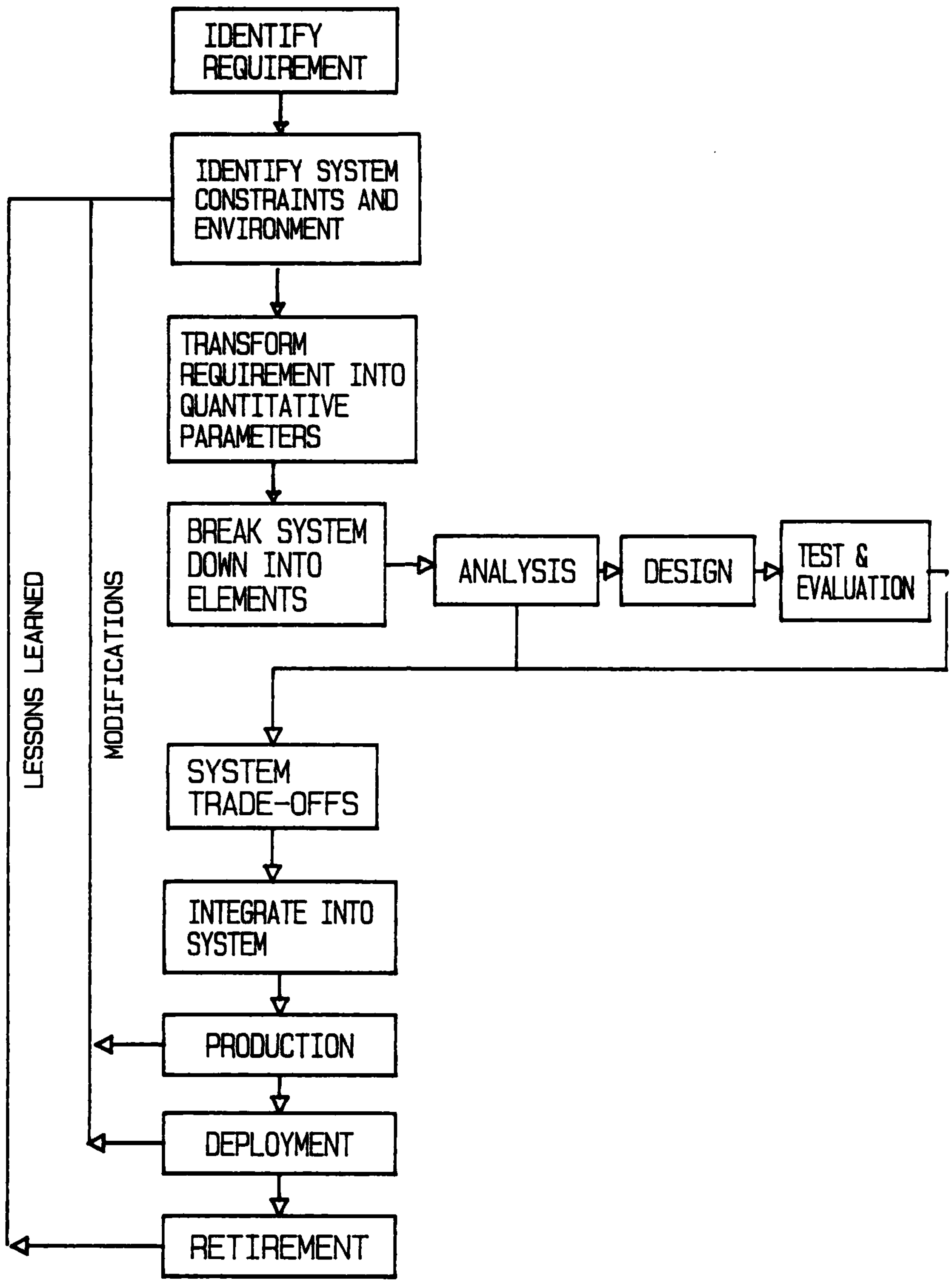


Figure 2 Systems Engineering

D. WHY SYSTEMS ENGINEERING

The preceding sections have traced the origins of the modern concept of systems engineering and provided a working definition. However, this material has not demonstrated to the reader the utility of systems engineering. In order to satisfy this requirement the question "Why Systems Engineering?" should be answered. A two phased approach will be used to accomplish this task:

.1 Detail the importance of systems engineering.

.2 Provide specific examples of the successful implementation of the concept.

1. The Importance Of Systems Engineering

In the development and procurement of a weapon system, the litmus test of the success of that program is based on a number of factors, including: cost, schedule, and design effectiveness. Cost and schedule are readily quantifiable factors which can be judged in relation to other similar programs. Design effectiveness, on the other hand, can only be appraised in terms of the systems requirements. Accordingly, the program manager and his staff must identify specific mission objectives to derive and evaluate design alternatives. A relevant design decision cannot be made without specifying the functions that the total system must perform [Ref. 17:p. 32]. A program that satisfies the functions for which the total system is designed and operates within specified performance and design constraints can be considered an effective system [Ref. 15:p. 9]. This is where systems engineering plays a critical role.

A function is a characteristic action to be accomplished by one of the system elements of hardware, software, facilities, personnel, data, or any combination of these elements [Ref. 7:p. 6-1]. Therefore, the first problem confronting a systems engineer is the identification and classification of all functions to be performed in fulfilling stated mission objectives. For complex systems it is obvious that this task requires orderly and objective problem solving techniques that are logical and consistent. However, even with a simple item it is almost impossible to identify and classify all required functions without applying formal, objective analysis techniques. These formal methods are commonly referred to as system functional analysis [Ref. 4:p. 35]. They follow specific steps that insure the identification of all functions to be performed at the level of detail required for arriving at relevant design decisions.

The functional analysis reduces or decomposes a complete system into individual parts while relating these parts to each other and to the system. A functional breakdown can be accomplished with respect to logical groupings, time ordering, data flow, control flow, or some other criteria. This stepwise breakdown of a system can be viewed as a top-down approach to problem solving. The process results in a hierarchical structure which progressively divides and allocates requirements until the lowest level of the system that fulfills a definable requirement is obtained [Ref. 7:p. 6-21]. A useful example is shown in Figure 3 [Ref. 17:p. 18], a modified version of Corrigan's functional flow with an indenture level of three. A description of the three levels according to Corrigan includes the following:

* "Level I involves the logical gross division of activities into mission phases performed during the total mission. Having identified the seperate mission phases, the system function analyst will identify and classify the functional flow in a functional flow block diagram.

* Level II involves all major operational functions to be performed (independently and in combination) within each mission phase. These functions would be cross-checked for completeness before proceeding to a more detailed analysis.

* Level III involves the most detailed analysis of jobs or tasks that must be performed to succussfully achieve each subfunction (operations) within each mission phase of importance is the deriving of significant performance limits and constraints that must be considered in design." [Ref. 17:p. 19]

The top-down approach is usually applied to a system that is completely new. An opposite approach is a bottom-up method that can be applied to a scenario in which a number of existing subassemblies or parts with known capabilities are integrated to fullfill a requirement. This approach is sometimes difficult to implement due to interface and integration problems. A tailored approach should be utilized for each specific project. [Ref. 7:p. 6-1]

Another factor of great significance is the realization that the system design process is not a one-way street from identification of requirements through functional objectives to

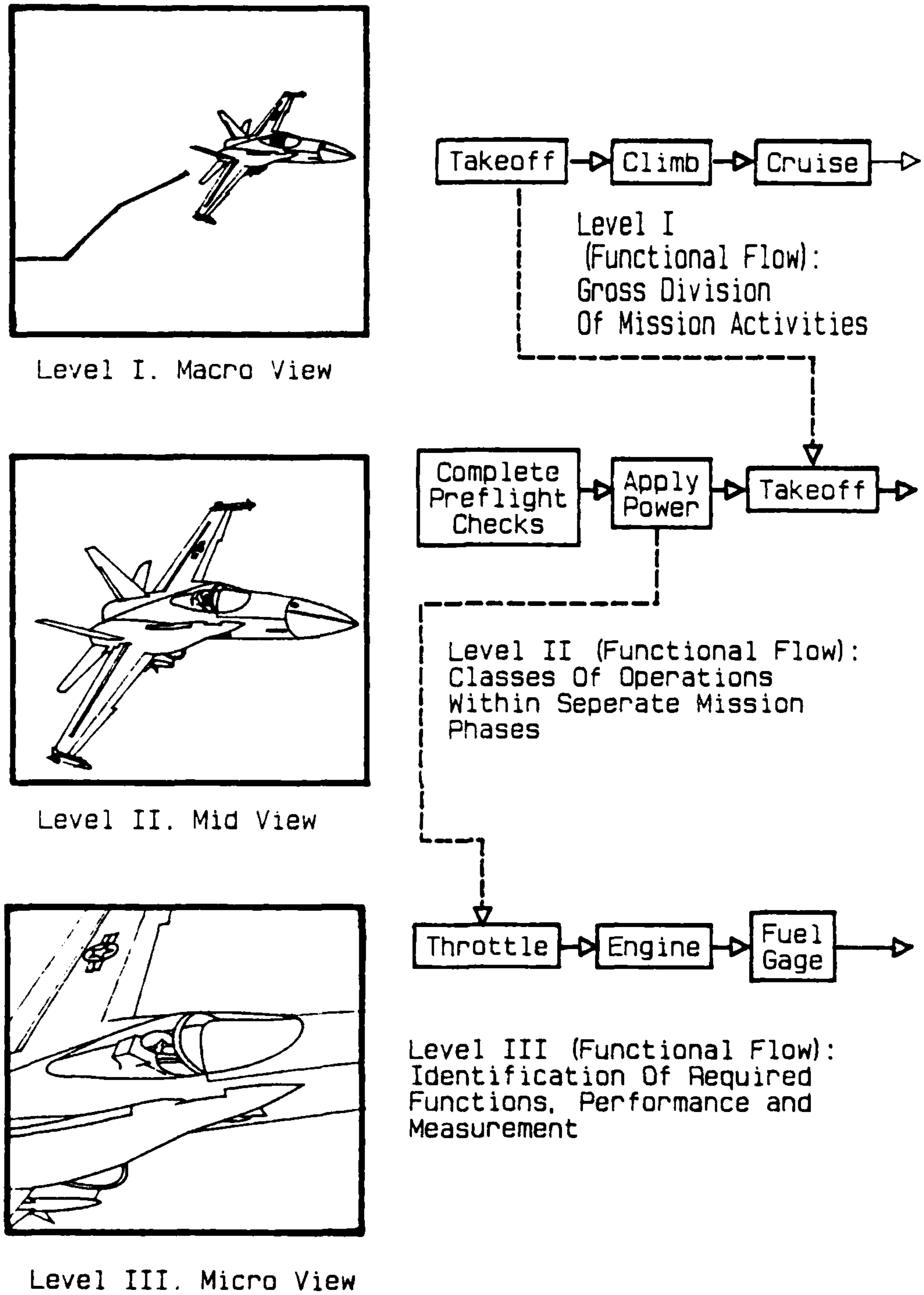


Figure 3 Analysis Phases In Identifying System Functions

final design configuration. In actual practice, the systems engineer goes through a continuous and repeated process of progressive comparison between 1) stated functions 2) performance parameters, and 3) proposed design criteria. This process of checking, comparing and readjusting is system iteration. [Ref. 17:p. 70]

System iteration is a continuous adaptive process as the system designer moves from analysis to synthesis, pulling together parts into an organized system in deriving and completing system design specifications. These specifications are the documents that accurately describe the essential technical requirements to determine if objectives have been satisfied [Ref. 18:p. 4-84]. The process of system iteration becomes critical in completing every phase of systems engineering. From the utilization of system iteration it is clearly shown that system functions control the determination of ultimate design decisions for both design requirements and performance criteria. Therefore, the specific requirement for completing a formal system functions analysis prior to beginning design considerations is critical.

The resultant product of the functional analysis is the specification of all functions to be performed in a system and the constraints and limitations to be considered by the engineering staff in the design decisions to follow. Expanding these functional steps to include all the subsystems, parts and components in a complex system requires management planning and control which is satisfied by systems engineering.

As the technological complexity of a system increases the number of subsystems, parts, and components increase drastically. Therefore, attempting to trade-off design decisions for thousands upon thousands of parts in terms of synergism of all elements in the total system is beyond the normal capabilities of a single group of designers [Ref. 17:p. 37]. The functional designers of complex technological systems must be specialists in their fields. This specialization does not allow these engineers the generalist outlook which is required to meet the systems mission requirements. In designing an operational system, the individual subassembly or part must be subordinate to the system design objectives. This requirement is imposed by the sheer complexity of the:

* Number of design decisions to be processed and committed
* Number of personnel involved
* Number of speciality skills applied in the design analysis
* Number of seperate system design teams involved
* Number of design trade-offs to be determined between the most practical and most functional design criteria.

Therefore, when designing a complex system the problems of personnel interaction, system communication, and system interfacing must be controlled and directed. This task is solved by systems engineering. But systems engineering is concerned with much more than just design criteria. As mentioned previously, hardware and non-hardware components must be able to perform all functions specified in achieving mission objectives. The subsystems, parts and components must be practical in terms of cost, reliability, availability, maintainability, producibility, and schedule restrictions. Therefore, systems engineering is more than design. It is the technique to produce the total system using the formal analytical and planning model for progressing from mission objectives to achievement of those objectives in an orderly and controlled manner while ensuring that all parts in the total system are integrated and functional. Without utilizing systems engineering in today's complex technological environment a system will not be as efficient and effective if the project succeeds at all.

2. <u>Case Studies Of System Engineering</u>

To further demonstrate the benefits of the systems approach several illustrations were selected to provide examples of the versatile and successful application of systems engineering. The cases were selected based on the following considerations:

* To include an example of an organization, a project, and a service

* To include both small and large programs

* To include both new systems and modifications to existing systems

* To include engineering advances as well as off-the-shelf hardware developments

* To cover the span of years from World War II to present day systems when the modern concept of systems engineering gained its greatest acceptance.

The cases that were selected are the Jet Propulsion Laboratory (JPL), the Appollo Space Program, and the Cheyenne helicopter program.

a. Jet Propulsion Laboratory

The Jet Propulsion Laboratory is an example of an organization that has evolved from a purely research-oriented laboratory into one heavily engaged in the practical application of systems engineering of large and complex projects. In 1940 the JPL was tasked by the Army Air Corps to apply the principles of rocket motor design to aircraft propulsion. The result was the successful development of the Jet-Assisted Take-Off (JATO) principle. However, this project was completed as a functional design engineering problem, basically the design of successful rocket motors, with very little concern for the application of these motors to an airborne mission and the total system. [Ref. 9:p. 124]

At the end of World War II the task of developing an operational missile system was given to JPL. This tasking required an understanding of an integrated system consisting of a rocket motor, fuel tanks, guidance, and payload. This necessitated a group of functional engineers becoming part of a systems engineering team. In the words of the director of the JPL:

> "The system did work, and the military made it work even better, but it was expensive, inefficient, and required large amounts of support equipment. It pointed out the consequences of putting a system together rather than engineering the system." [Ref. 9:p. 126]

In 1958 the JPL sponsorship was transferred to NASA. With this change in sponsorship the laboratory's assignment included unmanned spacecraft missions to the moon and the planets. Again in the words of the director:

"To accomplish these projects with reasonable expectation of optimizing performance or of attaining project objectives within cost and schedule a systems approach was necessary." [Ref. 9:p. 128]

Several valuable lessons were learned from these and other early projects which helped create the environment for the growth of systems engineering at JPL and throughout the aerospace industry. The specific systems engineering techniques that JPL helped promote included:

* The matrix organization
* Integrated management and engineering efforts
* The concept of high reliability in complex systems
* Schedule control
* Application of systems engineering to other activities of national interest

b. The Apollo Program

The Apollo program was the largest and most complex engineering project of its time. Before the project was completed, over $20 billion was expended and more than 200,000 people contributed their efforts to the successful landing of a man on the moon. This program is an example of systems engineering on a large and complex scale. In the words of George Mueller, the associate administrator for manned space flight for NASA from 1963 to 1969,

"The Apollo budget was set at $20 billion. That amount was reviewed annually, and when I arrived in Washington to manage the program, it had been cut for the following year by $1 billion. My first experience with the program, therefore, was the sobering one of searching for things that were not absolutely necessary and cutting them out. This is a most valuable discipline in systems engineering." [Ref. 9:p. 15]

Systems engineering was crucial to the success of the Apollo program. The mission objectives, time schedule, and budget were firmly established. These goals were strictly enforced due to the political nature of the program. The state of the art in technology was pushed to its limits. The task of pulling together all the manpower and resources was an immense task. There were a number of difficult problems to be solved and a number of contingencies to be planned for. The problems included radiation hazard due to solar storms and the Van Allen Belts and the potential of collision with meteoroids which could damage or destroy a then-ordinary space vehicle.

One of the major systems engineering problems was designing the lunar flight. During the design of this critical portion of the flight and the systems to accomplish the mission, a number of trade-offs had to be made regarding weight of the vehicles, thrust requirements, number and location of rendezvous and orbits, and amount and cost of fuel each alternative would require. Another critical systems engineering concern was establishing the reliability of the total system. The Saturn V, with the Apollo spacecraft and support equipment, represented about 15,000,000 parts. A reliability figure of .9999999 for every part would not guarantee a successful mission. Using conventional techniques the probability of a successful Lunar landing was calculated to be about .5. Consequently in planning the Apollo flight new techniques were used to identify the mission's critical events. This method built up the probability of mission success to .9 and a probability of catastrophic failure of less than .01. [Ref. 9:p. 162]

Several valuable skills were acquired and reaffirmed from the Apollo program. A large complex system requires a systematic and logical approach to relate all of the subsystems, parts, and components to the total systems mission objectives.

c. The Cheyenne Helicopter Program

Systems engineering had been applied by other services for more than a decade when the Army acquired its own procurement and engineering functions in the early 1960's. The systems engineering concept was not accepted by the Army in the early 1960's because Army aircraft were tailored to specific missions. In other words, the Army was merely buying existing aircraft. However, avionics and peculiar ground support equipment added to the basic aircraft began to cause problems from a systems standpoint. The Cheyenne Helicopter was a new, complex weapon system employing the latest in automatic gun developments, a full solution computer-directed fire control system with laser ranging, wire-guided air-to-ground missile, a self-contained doppler navigation system, advanced engine and auxiliary power unit, extensive self-test and ground support features, and numerous other innovations. In the early stages of development, systems engineering was not utilized because of existing Army policy. The program was canceled in May 1969 for numerous reasons. However, the program had a new start coincident with the initiation of a formal systems engineering management approach by both the prime contractor and the Army. The complete involvement of systems engineering in every step of the development cycle was formalized and included in the new contract. In the fall of 1970 the Cheyenne did demonstrate its capabilities. [Ref. 3:p. 9]

The Cheyenne program was eventually canceled for a myraid of reasons. However, this program brought systems engineering to the forefront in Army aviation and was utilized on the Cobra Gunship and other programs. Systems engineering management became a way of life for Army aviation.

E. SYSTEMS LIFE CYCLE

The life cycle for a typical weapon system acquisition is well documented. This process is broken down into basically six phases:

1. Mission need determination phase
2. Concept exploration phase
3. Demonstration and validation phase
4. Full scale development phase
5. Production and deployment phase
6. Retirement phase

These phases have been the subject of numerous research efforts. It is not the purpose of this section to reiterate those research efforts. However, just as the definition of systems engineering causes a semantics problem, the requirement for systems engineering in all phases of the systems life cycle is a controversial topic. For example Kline stated:

> "While it might be said that systems engineering is concerned with the complete systems life cycle, in fact systems engineering is concerned primarily with the planning period and with the design phase of the acquisition period. Once the system design has become stabilized (during the early production phase), engineering involvement becomes what is popularly known as "sustaining engineering", and systems engineers turn their attention to the planning and design of new systems." [Ref. 8:p. 2-6]

Chase takes the opposite position.

> ". . . the required system and end item design and development effort must be interrelated with the other system life cycle requirements for fabrication, installation and check-out, test and evaluation, deployment, production, modification, maintenance, logistics support, and phase out (planned obsolescence). Systems engineering is a function which must be exercised throughout all phases of a system life cycle if system integrity is to be ensured. [Ref. 14:p. 126]

In most weapon systems, the environment for which the system was designed is constantly changing. A system must be able to adapt to this changing environment. These factors result in the production of systems which are stable for only a relatively short period of the system's entire life cycle. In order to maximize the utility of systems, the systems engineering approach must be applied throughout the complete life cycle. The following paragraphs outline how systems engineering applies to each phase of the life cycle.

1. <u>Mission Need Determination Phase</u>

This phase starts with an objective. This objective is translated into information about the requirements for which the system is to be designed, resources available, the environment in which the system will operate, and the constraints that affect all of these factors. This input information establishes the bounds of the systems engineering problem. A large percentage of the costs of a program become fixed during this phase so that systems engineering must be utilized from the beginning.

2. Concept Exploration Phase

The systems engineering effort during this phase includes the functional analysis. Effort is directed toward refining mission objectives through analysis that evolve a systems design concept, flowing down and allocating requirements to lower indenture levels, defining major interfaces, and establishing quantitative parameters (how fast, how heavy etc.). Inherent in these analyses are cost and risk assessments.

3. Demonstration And Validation Phase

The systems engineering team concentrates on performing analyses and simulations to completely define all system requirements, prepares upper level specifications, oversees preparation of component level specifications, prepares major interface definition and control documents, and defines a system functional baseline design. A major task is the preparation of the Systems Engineering Management Plan (SEMP), which includes plans for verification, risk alleviation, and supporting areas.

4. Full-Scale Development Phase

The SEMP is implemented at the beginning of this phase. Detailed system simulations and models are developed to predict system performance parameters. Other systems engineering activities include resolving interface problems, auditing engineering documentation, auditing system test activities, configuration control activities, and completion of the verification process.

5. Production And Deployment Phase

During this phase, the greatest amount of effort is in the modification of the system. This is where the controversy lies. However, if systems engineering is not rigorously applied at this juncture, supportability and consequently the ability of the system to meet its mission objectives is an impossible task.

6. Retirement Phase

System engineering efforts in this phase consist mostly of supplying lessons learned from completed projects to new programs early in their life cycles. This phase cannot be overlooked in solving the systems engineering problems of future systems. Just as the concept of systems engineering has evolved, technology continues to evolve, and corporate knowledge is critical to new programs.

III. SYSTEMS ENGINEERING TOOLS, TECHNIQUES, AND MODELS

Systems engineering utilizes many elements to develop, construct and deploy complex systems. It uniquely focuses the application of diverse elements on the system's mission objectives, whereas other methodologies engage these same elements in solving only subsystem and component requirements without considering the entire system.

It is the intent of this chapter to describe in detail the tools, techniques, and models of system engineering. First, several general systems engineering models will be presented. The next two sections will describe a number of the technical and managerial components found in these models. The factors listed in the technical section are more quantitative in nature and are traditionally associated with engineering disciplines. The tools and techniques found in the management section are somewhat qualitative in nature and have been traditionally associated with non-technical disciplines.

A. SYSTEMS ENGINEERING MODELS

In general the utilization of models is an effective and efficient concept because it permits the timely investigation of various entities without actually building and testing the project in question. According to Chestnut:

> "Modeling can be thought of as being a representation of a system or a part of a system in a mathematical or physical form suitable for demonstrating the way the system or operation behaves or may be considered to behave." [Ref. 12:p. 107]

The type of complex systems that have been discussed earlier in this study incorporate a large number of functional activities, subsystems, and components in order to accomplish the system's mission objectives. It has been shown that the integration of these functional activities is accomplished by systems engineering. However, the structure of this method must also be established as pointed out by Mr. Andrew Sage, a well known advocate and practioner or systems engineering:

> "An essential complicating problem in a large-scale system is the need to correctly represent the structure of a system rather than just to accurately reproduce observed data. Thus we want to postulate correctly the forces operating between various subsystems of a complex system. In this way we are able to show how problems are created so that corrective actions may be taken and control policies established, in addition to the simple but important problem of explaining behaviour. Only by obtaining proper system structure can there be a proper understanding of the underlying cause and effect relationships. Selection of a poor structure will complicate system parameter identification and design and inhibit or prohibit proper system operation. Thus techniques such as interpretive structural modeling are of special importance." [Ref. 15:p. 294]

This structure can be realized by the employment of a systems engineering model.

Research has revealed two basic catagories of systems engineering models. The first group contains quantitative models using mathematical representations to describe the system. The second catagory consists of qualitative models. These models utilize words and symbology to portray the interfaces between the elements of a particular system. Due to the nature of this study, it has been determined that qualitative systems engineering models are more applicable to the ATA.

There are a number of excellent qualitative engineering models utilized by various activities and supported by highly regarded researchers and practioners of systems engineering. Five general models are described and presented in the following pages.

1. Systems Engineering Model Number 1

The first alternative is an adaptation of a model developed by Arnold and Stepler. In this representation, systems engineering is at the hub of a three tiered wheel as illlustrated in Figure 4 [Ref. 1:p. 25]. The three tiers in this model correspond directly to the three indenture levels of a functional analysis described in Figure 3, page 30. Specifically, the outer tier depicts a number of the tasks that must be executed in the development of a system. These tasks are performed by specialists who can utilize state of the art technology to solve specific problems. Information from this level is provided independently to the basic functional areas of systems, test and evaluation, production, and logistics. Arnold and Stepler incorporated these particular functional areas into their model because thes divisions closely parallel the structure of a typical program office [Ref. 1:p. 24]. The functional managers then provide information to the hub of the wheel, the program manager. The program manager then utilizes his systems engineering staff to make trade-offs and integrate the functional area inputs into a solution which meets the total system's mission objectives.

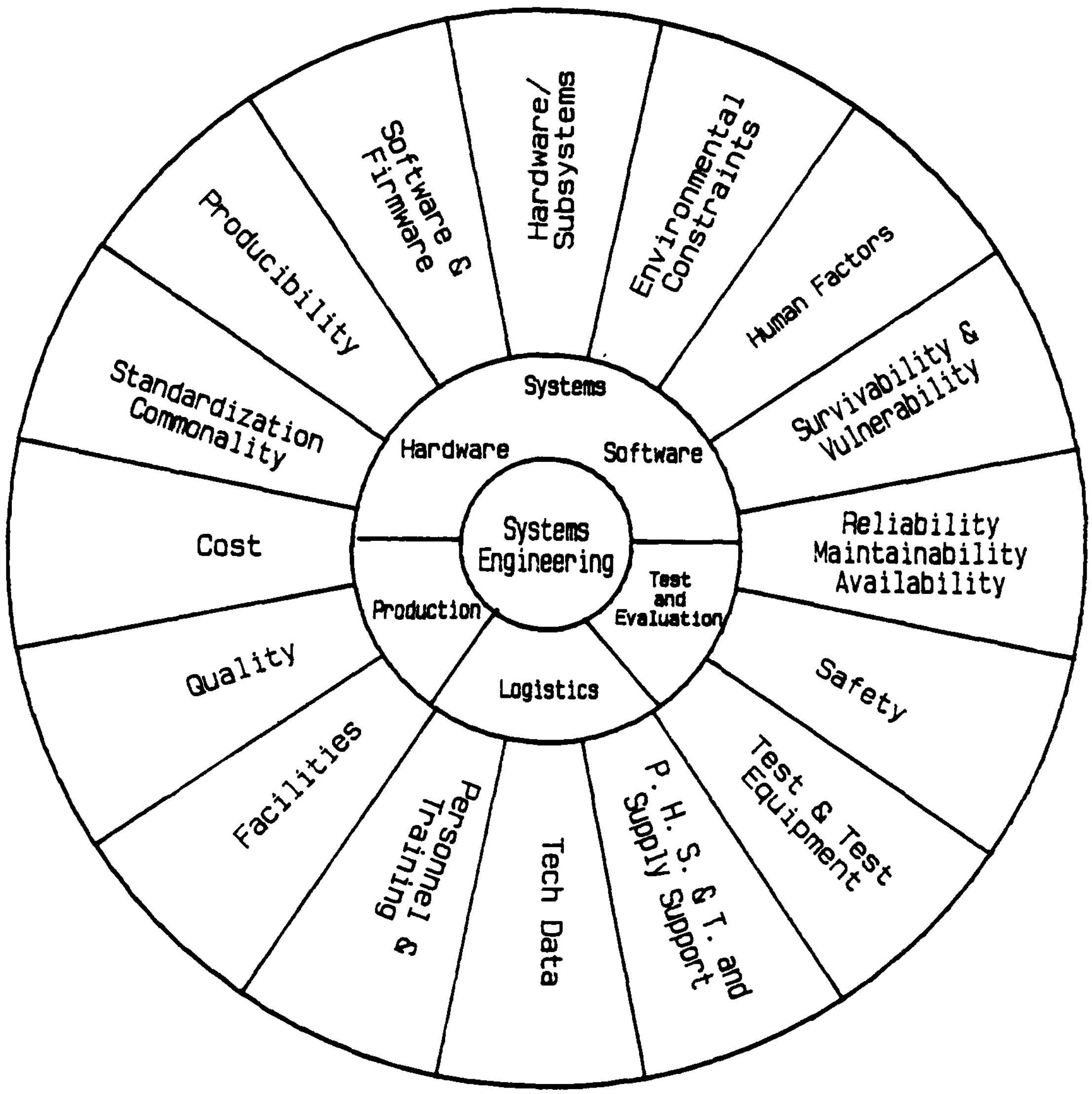


Figure 4. Systems Engineering Model Number 1

2. <u>Systems Engineering Model Number 2</u>

The second model was originally developed as an instructional aide for a systems engineering course offered at the Army Management Training Agency in Rock Island, Illinois. As displayed in Figure 5, this model utilizes a three-phase, two-tier approach to systems engineering. [Ref. 19:p. 8]

The phases correspond to different states in the life cycle of a program. The two tiers in each phase represent the functional elements providing independant technical information to the program manager and systems engineering staff. Each phase emphasizes different functional areas. For example, the conceptual phase accentuates basic technology, whereas the implementation phase stresses hardware requirements. The output of the conceptual and development phases is systems engineering documentation in the form of specifications, manuals, and other data packages. The output of the development phase is production hardware and systems. In addition to this output, information is transmitted from each phase to preceding levels to facilitate the iterations which are paramount to the systems engineering process.

In summary, as stated by the developers of this model:

> "System engineering management encompasses the system engineering process and integration of all engineering activities and technical aspects of the system/project from receipt of a user requirement through delivery to the operational inventory and ultimate disposal. [Ref. 19:p. 8]

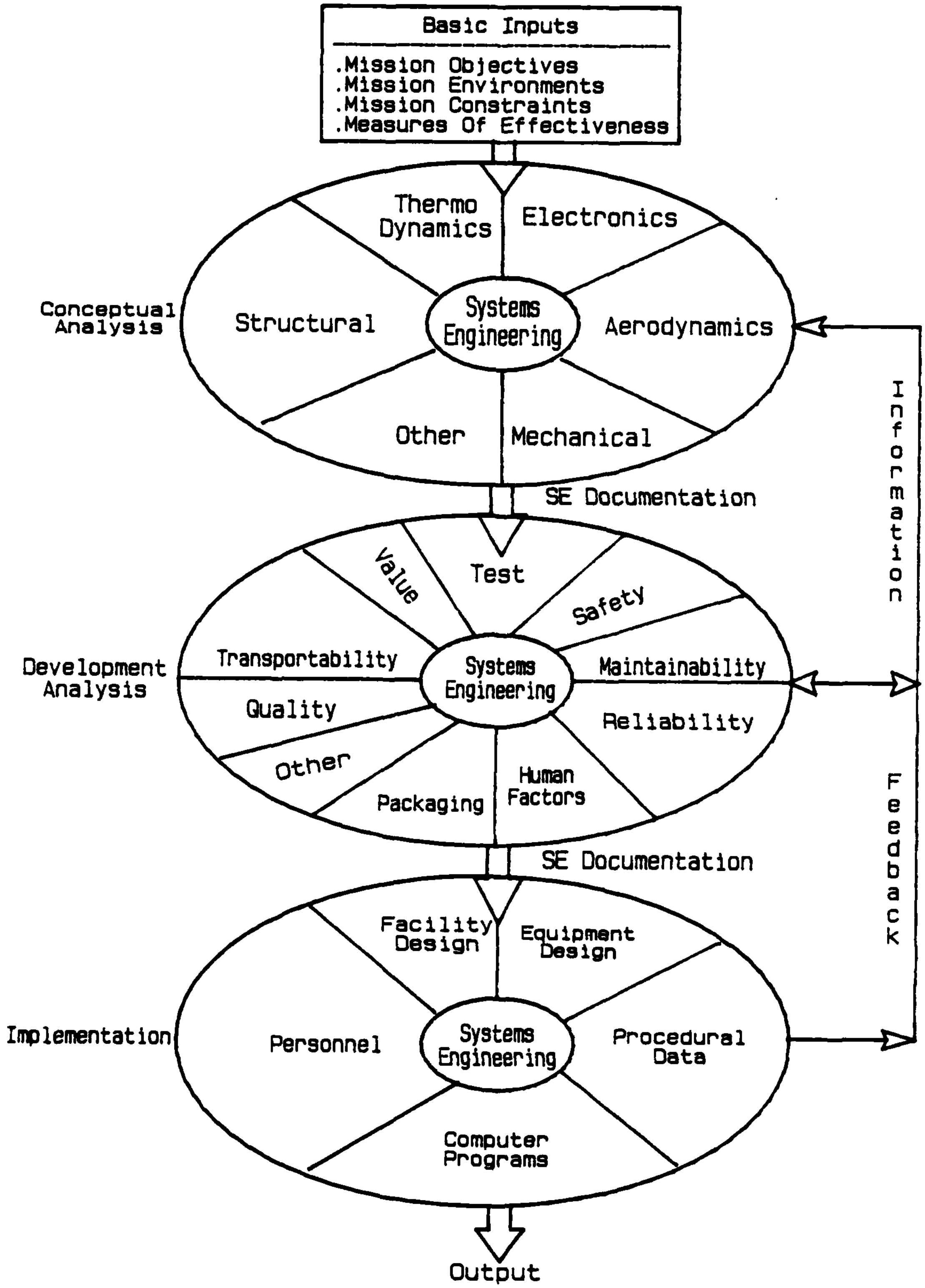


Figure 5. Systems Engineering Model Number 2

3. Systems Engineering Model Number 3

The block diagram displayed in Figure 6 [Ref. 12:p. 32] was developed by Chestnut to represent the interrelationships between three feedback characteristics of systems engineering. The three loops presented are the performance, cost and reliability feedback paths.

In the performance feedback loop, the desired overall system performance is compared to the anticipated overall system performance. The main elements of this closed loop path are the specified overall system requirements, specified function and parameters of the subsystems, determination of the overall system performance equations, and the calculation of the resulting overall system performance. The elements characterizing overall system requirements and specified parameters of the subsystems are also common to the cost and reliability feedback loops. In these closed loops, desired cost is compared to anticipated cost, and desired reliability is compared to anticipated reliability. The elements concerned with the calculation of the overall system relationship due to changes in the system's parameters are also affected by changes in the environment, materials, and the probability of change.

Analysis of this model illustrates that several variables are common to more than one path. Changes in one loop simultaneously create changes in the other loops thereby requiring an integrated, iterative effort. Therefore, according to Chestnut:

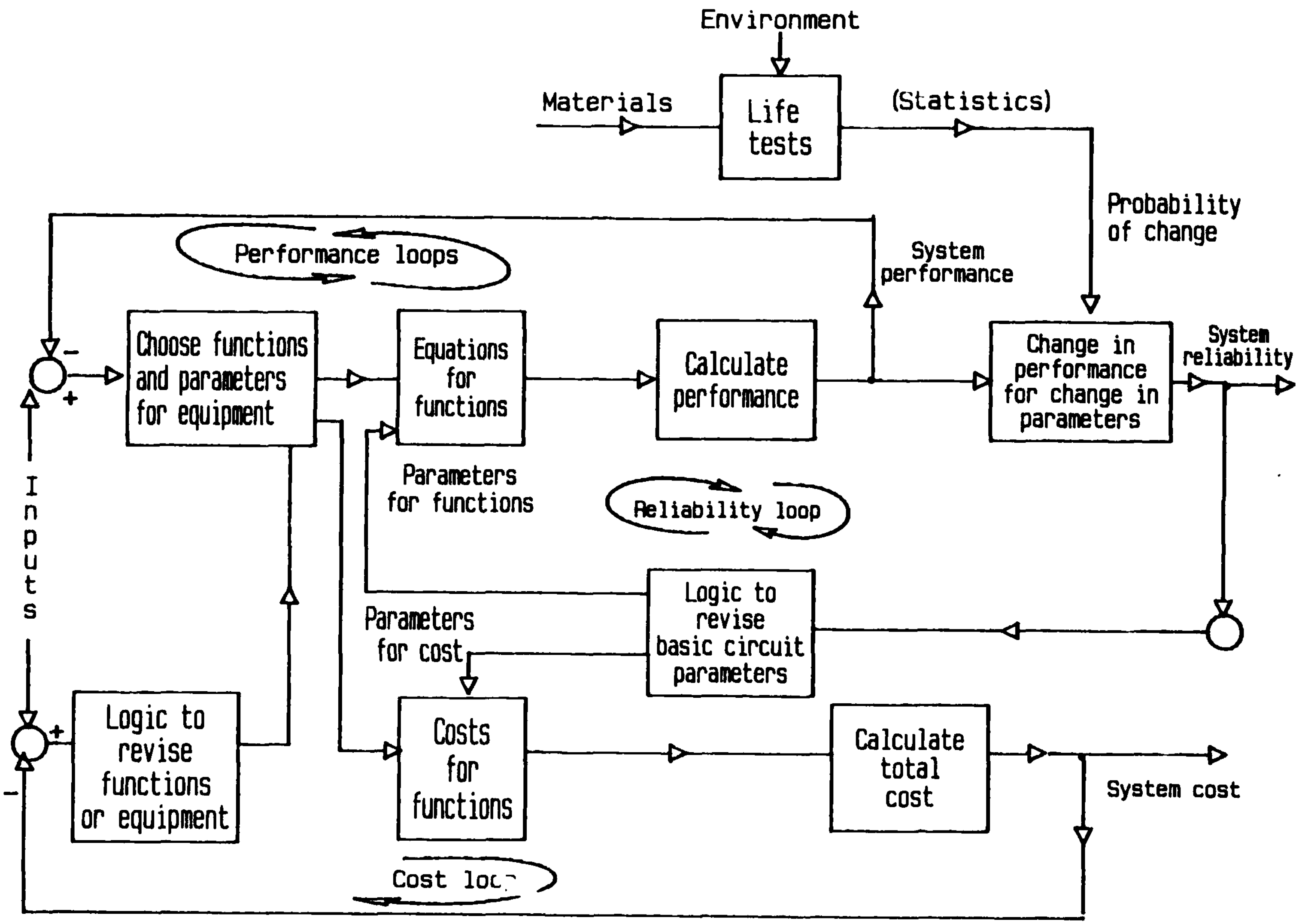


Figure 6. System Engineering Model Number 3

"The existence of many objectives for the systems engineering problem means that the problem is indeed a multi-variable, multi-loop one. System parameters and decisions made on the basis of their effect on one objective also have effects on the other objectives. The systems engineering problem is one of so arranging the treatment of the system that those interactions are minimized or, hopefully, made to be most favorable for each of the systems. [Ref. 12:p. 31]

This model can be expanded further to include maintainability, power requirements, weight, quality and schedule feedback paths.

4. Systems Engineering Model Number 4

Model number 4 is a modification of the representation in the previous section. As illustrated in Figure 7 [Ref. 20:p. 33], Chestnut developed this model to emphasize equipment production, test, and quality control. In his own words:

"In complex programs such as are now involved in supplying military equipment, there is normally not time or money to build a complete prototype for design evaluation before delivering equipment to the customer. Instead, evaluation will take place on the first few systems to ensure adequacy of the design. From this point, then, a gradual transition is made from a systems design evaluation to a more quality-control type of testing, which then ensures that the manufacturing process is producing equipment in accordance with the established design." [Ref. 20:p. 34]

Another important facet of this model is the recognition of the importance of equipment and component change on the system configuration. Personal experience and information obtained by senior personnel at Lockheed Missile and Space Company underscored the fact that any change, no matter how small and seemingly insignificant, has an effect on other characteristics of the system. A minor modification has the potential to drastically upset the design configuration and

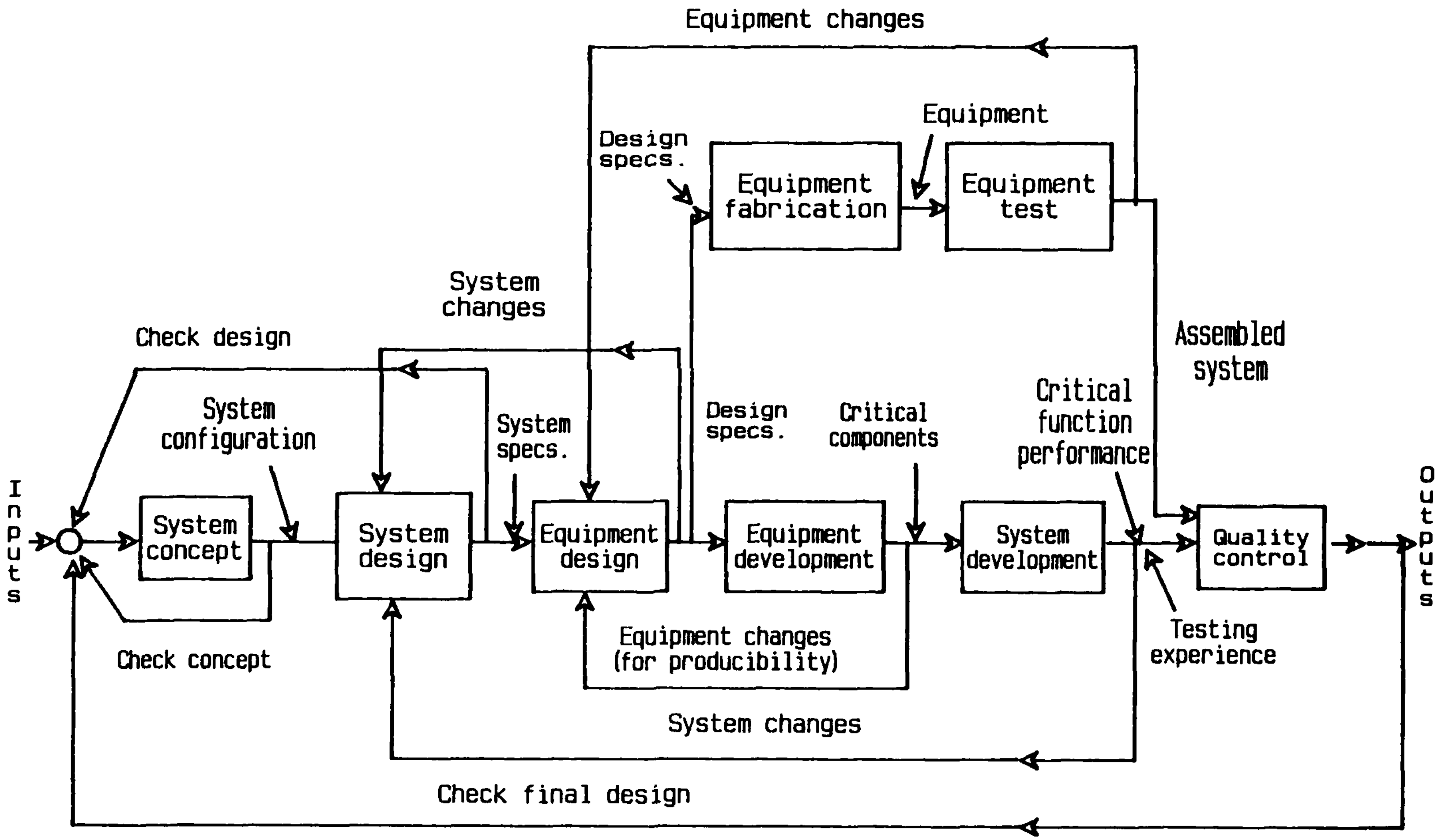


Figure 7. Systems Engineering Model Number 4

ultimate performance of the system resulting in hidden project costs. Therefore, each change must be analyzed so as to determine its total effects on the system. This analysis becomes more important as the system progresses through its life cycle as illustrated by Figure 8. [Ref. 21:p. 72]

5. Systems Engineering Model Number 5

The final alternative was developed as a composite of all the interviews conducted for this research effort and past personal experience in the field of systems engineering, coupled with the basic structure of a model developed by Kerzner.

The systems engineering model, as shown in Figure 9, [Ref. 21:p. 81] begins with the needs of the operational user translated into an objective. This objective is tempered by constraints in technology, funding, schedule, and socio-political conditions. A functional analysis is performed by specialists in aerodynamics, electronics, and other basic technologies to develop requirements that satisfy the customer's objective. From these requirements, a number of alternatives are generated by prospective manufacturers. The alternatives are then compared on the basis of predetermined selection criteria. This selection process utilizes cost/benefit analysis, performance, schedule, and other techniques to make trade-offs between alternatives. The loop is then completed using feedback and testing to determine if the system meets its assigned goals.

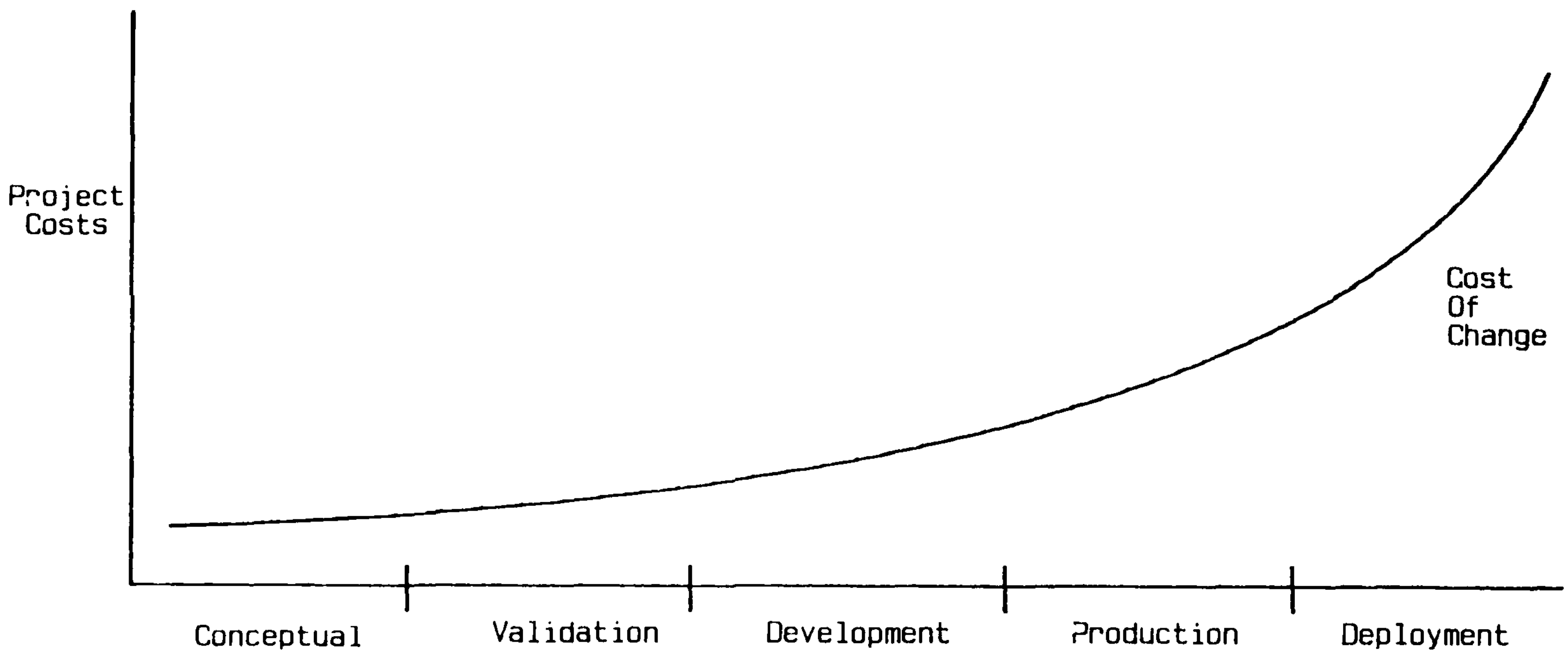


Figure 8. Cost Of Change

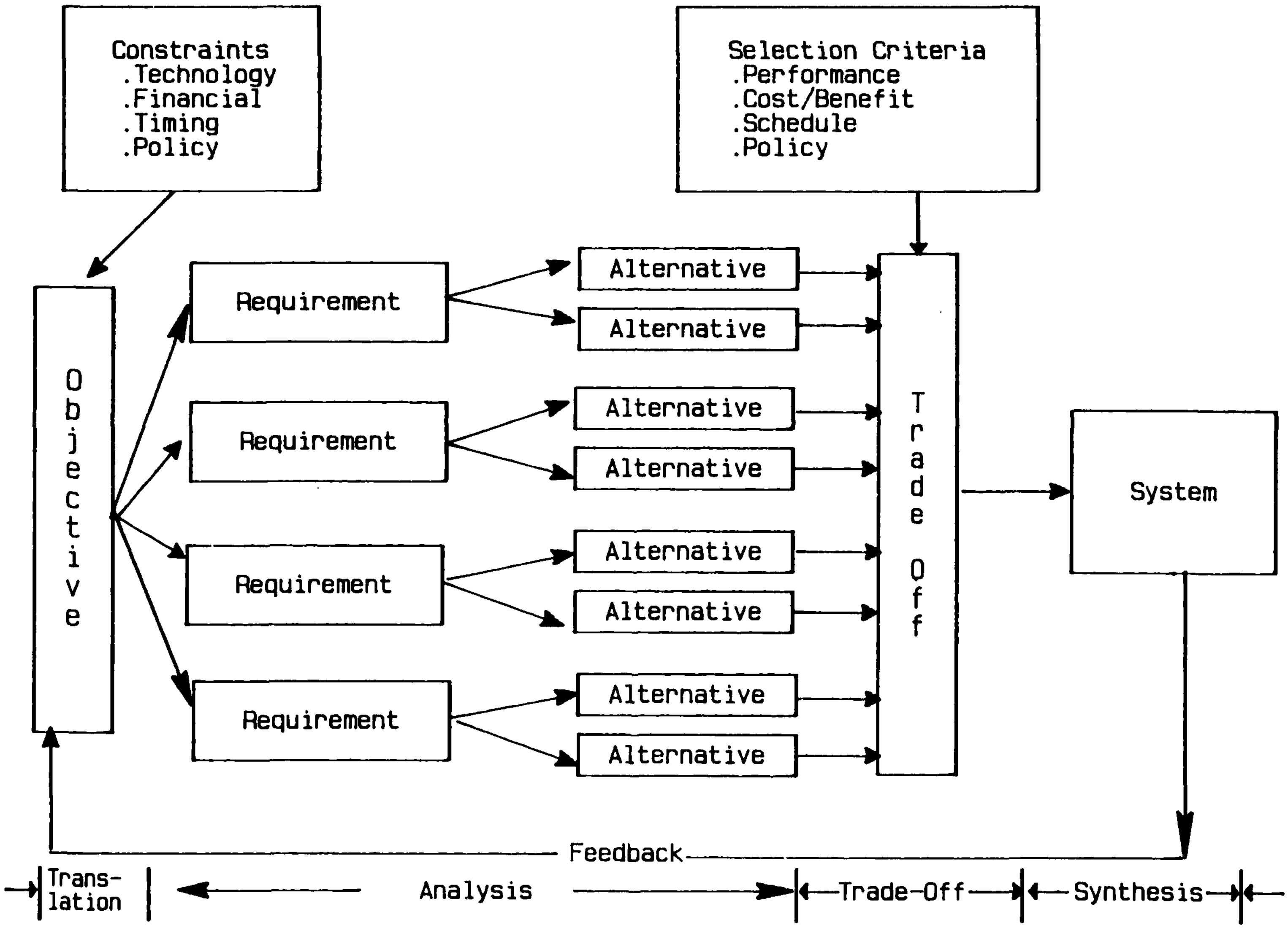


Figure 9. Systems Engineering Model Number 5

At this point the process becomes iterative in nature as the system is modified due to a dynamic environment of changing technology and customer objectives.

B. TECHNICAL ELEMENTS

In the next paragraphs several technical tools and techniques will be described. They are derived from the models presented in the previous section. Even though they may not have been alluded to directly in each model, they are key components found in a majority of systems engineering models.

1. Reliability, Availability, And Maintainability

The requirement for Reliability, Availability, and Maintainability (RAM) in complex military systems has been recognized since the late 1940's [Ref. 22:p. 3]. However, recent developments have initiated a renewed interest in them, as evidenced by a recent article in Military Electronics Design:

> "Reliability and maintainability--long-term quality and the ability to find and fix system failures--are two critical concerns for military electronics. Many of today's sophisticated military-electronics systems have rather short mean times between failures and rather long mean times to repairs. As a result, a staggering 25% of the defense department's budget is spent on scheduled preventive maintenance." [Ref. 23:p. 37]

Another similar view by Mr. Welko Gasich, the senior vice president for advanced projects at Northrop Corporation amplifies the importance of RAM as applied to new aircraft:

> "Reliability and maintainability are key requirements in the fighter force of the future to meet the need for high levels of availability. . . . In the 1980's, we see emphasis on

cost, not just fly away cost but total life cycle cost and operability. Reliability by design, not by chance, is now a proven technology and will be demanded by our customers." [Ref. 24:p. 59]

The traditional definitions of RAM are:

"Reliability is the probability that the system will perform satisfactorily for at least a given period of time when used under stated conditions." [Ref. 25:p. 1-7]

"Availability is the probability that the system is operating satisfactorly at any point in time when used under stated conditions, where the total time considered includes operating time, active repair time, administrative time, and logistics time." [Ref. 25:p. 1-8]

"Maintainability is a characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when maintenance is performed in accordance with prescribed procedures and resources." [Ref. 11:p. 10]

2. Quality

There are a myriad of factors that affect a system as it progresses through the life cycle from concept exploration to retirement and disposal. Quality is one element that is required in every phase of a system's life cycle. As defined by one of the leaders in the field of quality engineering, J. M. Juran:

"The quality function is the entire collection of activities through which we achieve fitness for use, no matter where the activities are performed." [Ref. 26:p. 2-11]

Quality has traditionally been thought of as a technical element that can be regulated through improvements in technology, effective planning and inspection, and exhaustive design procedures. However, this notion has been adjusted recently as evidenced by Peters and Waterman's study of excellence in American industry [Ref. 27:p. 172]. This study indicates quality is an attitude that starts at the top of the organization. For example, the corporate philosphy of Digital Electronics states:

> "Growth is not our principal goal. Our goal is to be a quality organization and do a quality job, which means that we will be proud of our work and our products for years to come." [Ref. 27:p. 174]

With this type of corporate attitude, an environment is created for the organization that enhances quality. This technique is different from the policy of expending large amounts of resources to fix the symptoms and results of problems instead of the cause of the discrepancy. Quality is still a technical field due to the complexity of systems, but it encompasses more than pure technical characteristics.

3. Performance Testing

Performance testing of a complex system is one of the most important aspects of the overall systems approach. The test and evaluation program provides the proof (or negation) of all of the theoretical calculations, models and simulations.

Testing is the source of all relevant data from the inception of the project throughout the entire life cycle of the system. These data inagurate all corrective actions on design, manufacture, and operation of the system as well as the basis for all logistics planning. In addition, testing provides the program manager with the most vital information on the technical progress of the system. The results of this test and evaluation program signal the approval for service use of the system. If the program does not pass, the program may face major modifications or termination. Follow-on test and evaluation programs continue throughout the life cycle of the system to monitor wear and latent defects.

There are many types of testing techniques. They include the use of automatic test equipment to check key system parameters and non-destructive tests such as magnetic particle and x-ray analysis to verify structural integrety and wear. However, the most effective test is an operational test which exercises the system in a realistic scenario.

4. Logistics

Logistics, as an element of systems engineering, is a controversial topic. Webster's dictionary defines logistics as:

> "The aspect of military science dealing with the procurement, maintenance, and transportation of military material, facilities, and personnel." [Ref. 28:p. 702]

However, design engineers consider the field as "sustaining effort" after the difficult tasks have been completed. On the other hand, personnel involved in logistics consider their task one of making a system work with inherent shortcomings. Just as systems engineering continues past the design phase to the development and production phase of a system, it continues on through the deployment phase to retirement. Therefore, logistics factors such as manpower, training, support and test equipment, facilities, spares, technical data, and Packaging/Handling/Storage/Transportation (P.H.S. & T.) must be considered in the systems engineering efforts conducted in the preliminary design stages. Information acquired during the deployment phase on RAM, latent defects, and other problems must be fed back into the system to incorporate in future design, development, and production.

5. Design

It is intuitively obvious that the design of a system is critical to the systems approach. As illustrated by Figure 8, the costs of a system increase drastically as projects progress through the life cycle. Steps must be taken in the early stages of a program to insure that the design is flexible, yet thorough enough to satisfy the stated goals and provide for expansion or modification. Design of a complex system is a difficult task, but many elements must be taken into consideration.

C. MANAGEMENT ELEMENTS

System engineering traditionally has been looked upon exclusively as a technical field. As discussed in the preceding chapters of this study, the concept has evolved to incorporate a myriad of elements both technical and non-technical in nature. This section will focus on the managerial aspects of the systems approach.

1. Organization

There are three basic organizational structures. They are the traditional or line structure, the project structure, and the most recently developed of the three structures, the matrix organization. These structures are presented in Figures 10, 11 and 12, respectively [Ref. 21:pp. 97, 107 and 110]. Different activities may have slight variations or combinations of these organizations.

The traditional structure is commonly found in military organizations and large corporations with only one or two products. It has also found wide acceptance in job shop or speciality product organizations where only one or two units of a product are manufactured. The advantages to this form of organization are:

* Vertical well established lines of communication,

* Flexibility in the use of manpower,

* Fast surge capability to react to emergencies, and

* Economics of scale for mass production for two or three high volume items.

The disadvantages include:

* No single point of contact for a project throughout the systems life cycle,

* Organization is functionally oriented rather than project oriented, and

* Decisions tend to be made by time consuming committees.

The program oriented structure is commonly found at manufacturing facilities that have several mass produced systems. The advantages of this system are:

* A single, well defined point of contact for each project,

* System-oriented personnel,

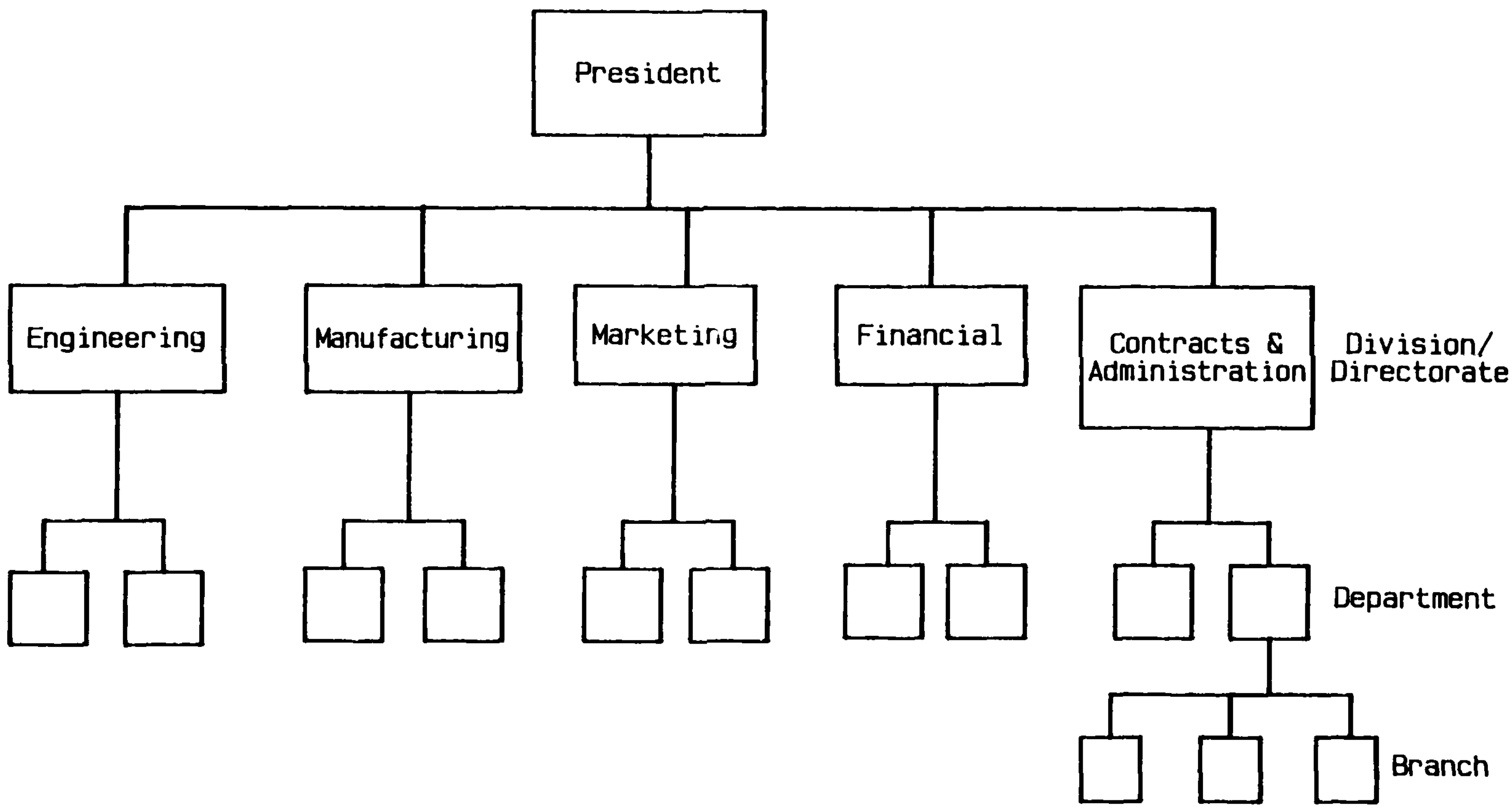


Figure 10. Traditional Organizational Structure

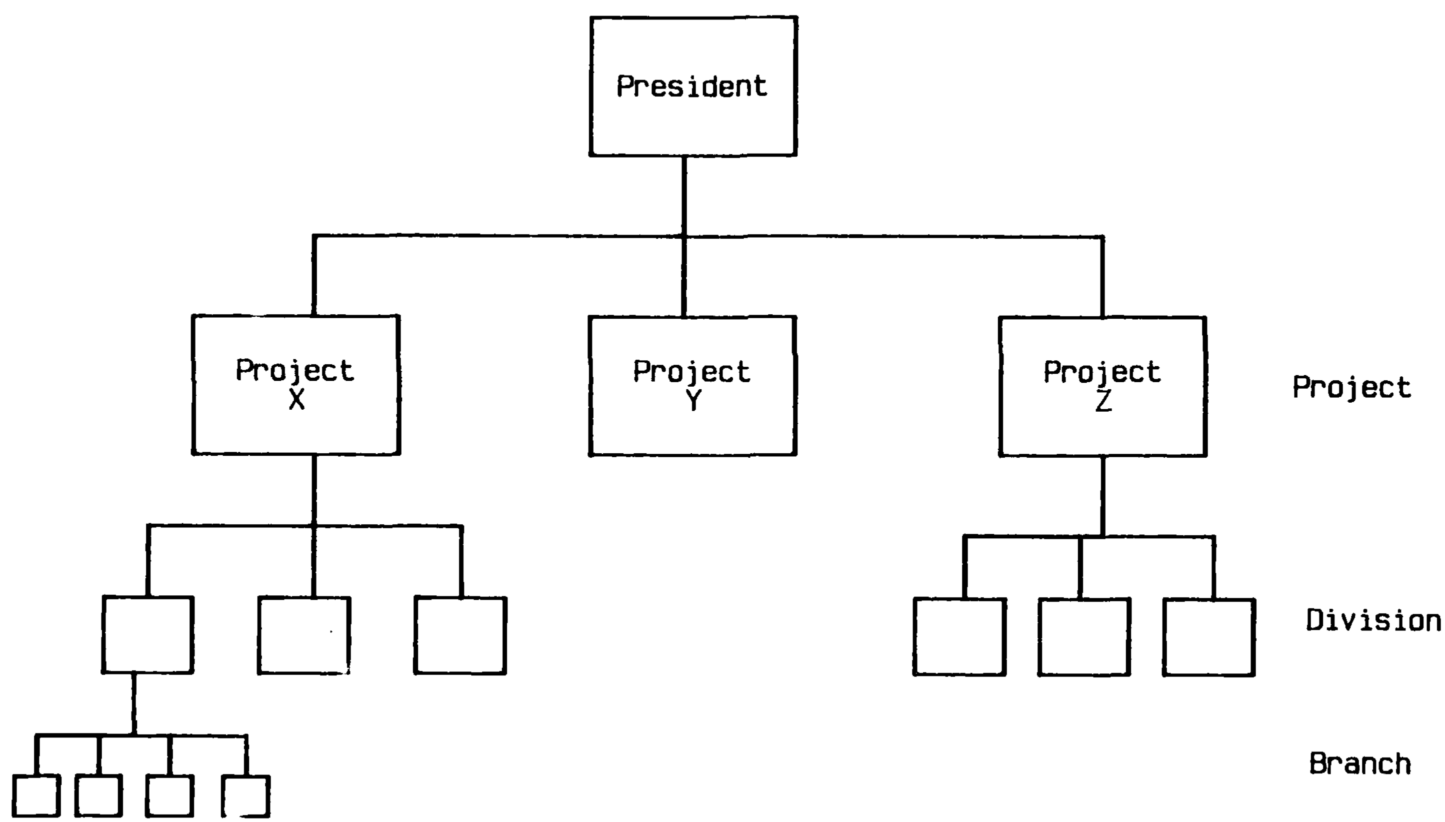


Figure 11. Project Oriented Organization

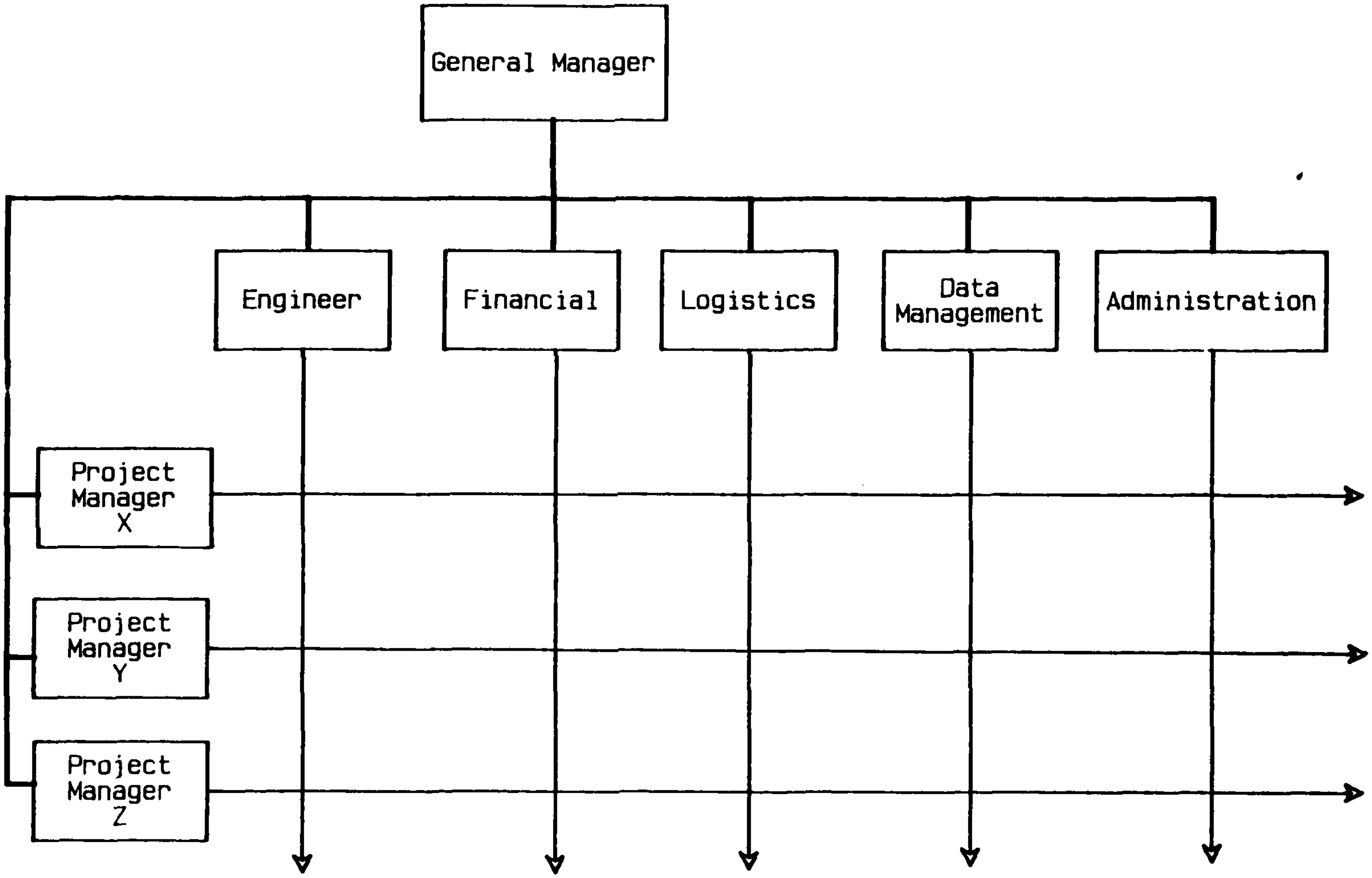


Figure 12. Matrix Organization

* Strong lines of communication, and

* Flexibility in determining cost, schedule, and performance [Ref. 21:p. 109].

However, the disadvantages include:

* Large manpower requirements,

* Functional expertise is not promoted, and

* Lack of technical interchange between projects which results duplication of effort.

Matrix organizations are established in order to combine the attributes of the traditional organization and the product structure. They provide both product and functional outlook, but add the expense of increased layers of management.

2. Management Information System

Management Information System or MIS has gained popularity with the advent of the micro and mini computer. However, an MIS does not have to be automated to be effective and efficient. Although, with the reduction in cost and the breakthroughs in computer technology, cost and complexity should no longer be a deterrent to automation. As McLeod states:

> "The manager is responsible for gathering raw data and processing it into usable information. He must assure that appropriate individuals within the organization receive the information in the proper form at the proper time so that it can assist in the management process. And finally, the manager must discard out-of-date, incomplete, or erroneous information and replace it with information that is usable." [Ref. 29:p.4]

Therefore, for a complex project the program manager and his staff must have a MIS that can handle any needed quantity of information. The key to establishing an effective and efficient system is to know which personnel need what type of information.

3. Interface Techniques

One of the major problems in the successful application of the systems approach is coordinating between system engineering, program management, and functional specialists.

An effective concept has been developed by Mr. Lurcott at the RCA facility in Morestown New Jersey. The technique is currently employed by RCA on the Aegis Ship Combat System [Ref. 30:p. 19]. This process is characterized by functional flow diagrams and descriptions (F2D2). The technique defines and integrates the tasks of functional areas and personnel required by a particular project. As described by Lurcott:

> "The F2D2 translates the missions, goals and requirements of the specifications into functional diagrams and functional descriptions for every level of system operation. As a tool for system definition, F2D2 provides the baseline from which all functions are quantified and allocated. As an auditing tool, it provides the visibility required to ensure that all functions have been incorporated in the design and that the design is in accordance with the system specification. Design control is supported through the combined use of definition, audit, and the functional descriptions." [Ref. 30:p. 28]

Another successful technique is to minimize the layers of management. By keeping the number of interfaces to a realistic number, systems engineers and other technical experts can work together to solve integration and trade-off problems in a timely and efficient manner, if not impeded by red tape. [Ref. 27:pp. 306-308]

IV ADVANCED TACTICAL AIRCRAFT

The evolution and application of systems engineering as an effective method for complex technological systems has been discussed in the previous chapters of this study. Many of the advocates of the application of this concept have contrasting viewpoints. First, they cannot come to a universally accepted definition for systems engineering. Second, they cannot agree to utilize the technique in all phases of the life cycle of a program. All of the advocates agree, however, that the first step in the systems approach begins with a statement of the project's overall mission objectives.

This chapter will first investigate the development of the ATA program as the solution to a projected requirement. It then describes a major subsystem which makes this complex program a prime candidate for the systems approach. Thirdly, a number of problems that affected a weapon system with a similar development background are studied to provide valuable examples.

A. BACKGROUND

Through mid-1983 the Navy and the Air Force were teamed on an advanced technology aircraft program designated the VFMX. The aircraft was to be the successor to the Air Force's F-15 air superiority fighter as well as the Navy's single successor for both the F-14 air superiority fighter and the A-6 medium attack aircraft. In order to reduce costs and improve reliability and maintainability, the aircraft were to have as much commonalty as possible; particularly, in airframe and engine design. To facilitate the cost effective development of a new, sophisticated powerplant, the Joint Advanced Fighter Engine (JAFE) program was also established by the two services. These combined ventures, however, were short lived. With the approval of the F-14D upgrade program, the requirements for the Navy's air superiority fighter were satisfied until approximately the year 2005. The Navy continued to pursue various options for the follow-on aircraft to satisfy the A-6's current mission and to meet the predicted threat for the late 1990's. These options included a derivative of the VFMX, an upgraded A-6E, and a modified A-18. Following a great deal of discussion and subsequent trade-off studies conducted by the Navy and prospective contractors, Navy planners decided on a two phased approach to satisfy the requirement for the next generation medium attack aircraft. [Ref. 31:p. 161]

.1 A number of existing and new production A-6E aircraft will be modified with improved avionics, and propulsion systems. This upgraded aircraft will be designated the A-6F.

.2 The planned FY86 new start of the ATA was moved up to FY85. The ATA will be the successor to the A-6 aircraft.

The A-6 aircraft has been in the fleet since the early 1960's and has undergone several modifications. Deliveries of the A-6F are scheduled to begin in 1989. Therefore, upgrading the A-6E to the A-6F configuration is expected to relieve pressures for an earlier development and procurement of the ATA. [Ref. 31:p. 162]

The A-6/ATA decision combined with the F-14D improvement program precipitated the Navy's withdrawl from the VFMX program. The Air Force, however, continued the development of a new air superiority fighter which was designated the Advanced Tactical Fighter (ATF).

The Navy initially continued the joint development effort on the JAFE program anticipating use of the new powerplant on the ATA. As the ATA and ATF programs developed it became apparent that they were substantially different. Although the configuration of the ATA had not been finalized, it was envisioned that this aircraft will be a relatively low cost, all-weather, low observable day/night deep interdiction aircraft that would have improved performance and survivability operating at low altitudes and high subsonic speeds. The ATF on the other hand will be a supersonic air superiority fighter which will require an engine that is efficent in a different flight regime than the ATA. With these factors in mind the Navy withdrew from the JAFE program in late 1984. [Ref. 32:p. 28]

On the surface, dual service development programs for new technology aircraft appear to be an ineffective technique. In the early 1960's the TFX (F-111) program, and now in the 1980's the VFMX and JAFE programs have failed to produce an aircraft or engine that was to be utilized by both services. This is only a partially accurate assessment of these joint ventures. The lessons learned from the TFX were applied in the later programs.

Specifically, when it became apparent that the objectives of the two services were diverging and a common airframe and engine were not practical the Navy withdrew early in the concept exploration phase. This early departure from the development team prevented a negative impact on the ATF or ATA program. On the other hand, by working together, key personnel from both services have acquired valuable information on new developments in technology. Although it has been concluded that the requirements of the ATA and ATF are too divergent for a common airframe or engine, major subsystems such as avionics and new technology such as reduction of radar cross section can be utilized by both programs. [Ref. 32:p. 28]

The ATA development schedule lags the ATF program by approximately three years. This time differential will allow the Navy to capitalize on technological developments that are applicable to both programs. For example, the schedule for the ATF program is shown in Figure 13 [Ref. 33:p. 143]. The ATA program can expect to proceed in much the same manner with inputs from the ATF program as illustrated by Figure 14 [Ref. 34]. The major subsystem with the greatest potential for a substantial transfer of technology is the armament system.

B. ARMAMENT SYSTEM

In the past the typical design methodology was to develop an aircraft to incorporate existing weapons, or develop new weapons for existing aircraft. The ATA will be a departure from this long standing technique. In order to enhance mission

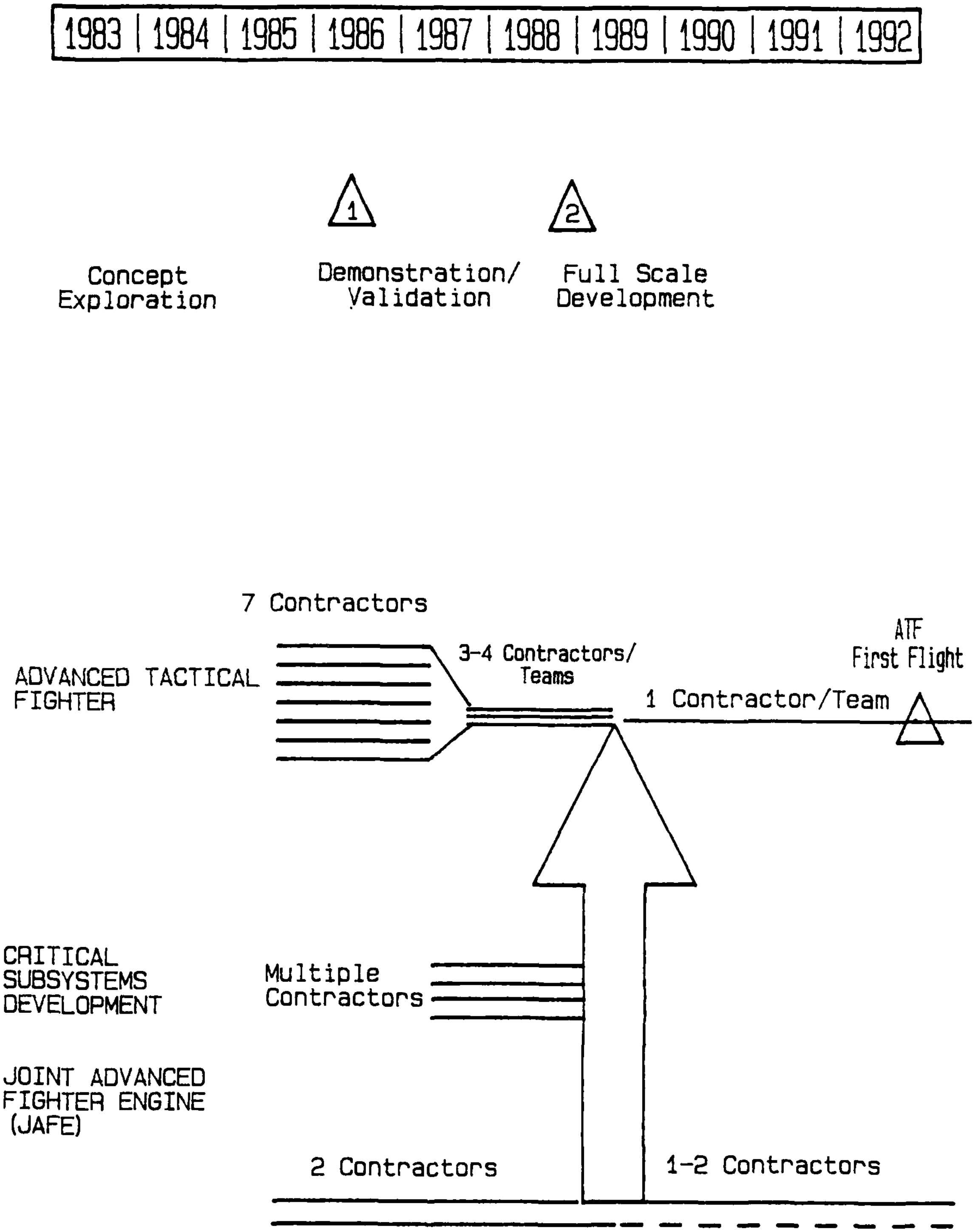


Figure 13. ATF Schedule

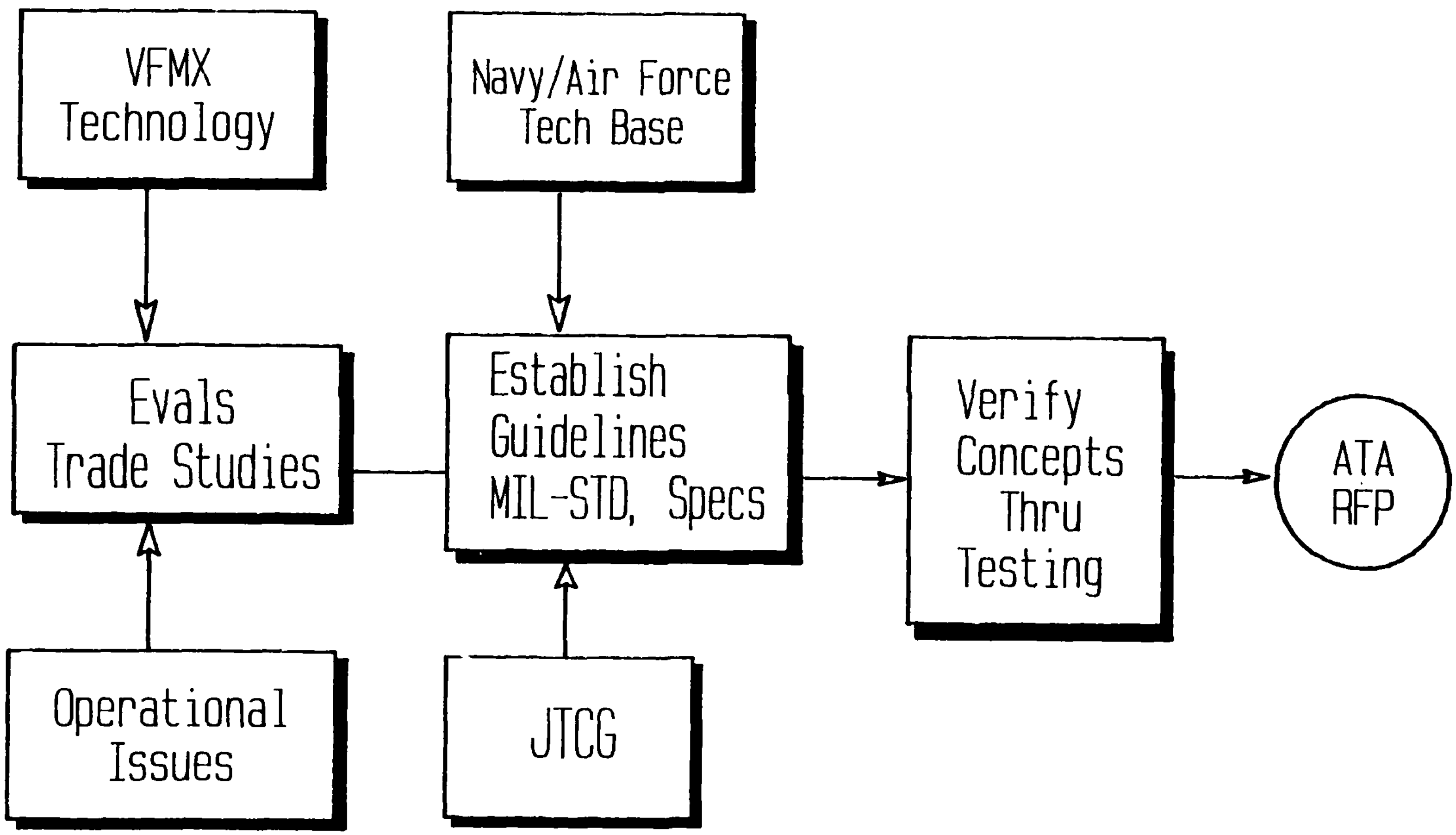


Figure 14. ATA Process

effectiveness and survivability of the ATA, a new arament suite must be developed in parallel with the airframe and powerplant.

As mentioned in a previous section, the configuration of this aircraft has not been finalized. However, as a successor to the A-6 its mission objectives include increased combat radius, reduced radar cross section, and increased airspeed [Ref. 32:p. 28].

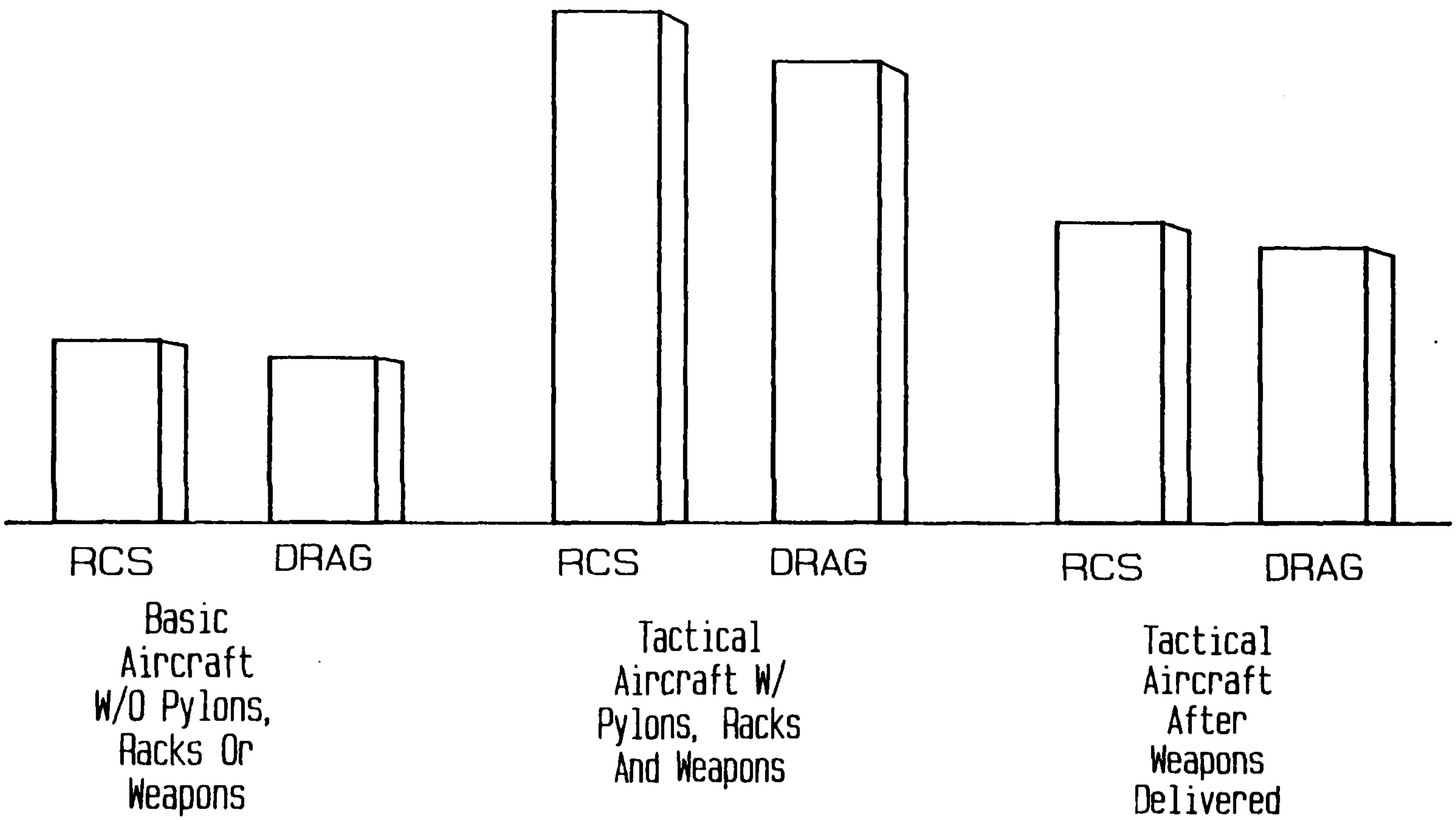
A tactical aircraft with weapons on standard pylons has a larger radar cross section and pays a substantially higher drag penalty than an aircraft in a clean aerodynamic configuration. These facts are graphically portrayed in Figure 15 [Ref. 34]. Therefore, to achieve its mission objectives the ATA must incorporate internal or conformal carriage of the air-to-air and air-to-ground weapons.

Faced with these factors, the requirement for internal or conformal carriage of existing weapons employed by existing armament systems was investigated by cognizant technical personnel [Ref. 35:p. 51]. Among the problems revealed by these studies are:

.1 Current armament system:
- not designed for internal or conformal carriage;
- not designed to minimize rcs; and
- limited high speed capability

.2 Current weapons:
- not designed for efficient use of volume;
- not designed to minimize rcs;
- unable to lock on targets while submerged; and
- not designed for high speed operations.

Therefore, the ATA requires a new armament system to be developed for the control, carriage, interface, and release of



(All Values Are Illustrative Only---Not Based On Actual Data)

Figure 15. RCS/DRAG Measurements

new and existing ordnance. This new armament system has been designated the Advanced Integrated Armament Systems (AIAS). Elements which must be addressed in the development of the AIAS are weapon size, and shape and interface requirements, because these factors will impact the structural configuration of the aircraft. [Ref. 34]

C. PROBLEM AREAS

The development of the F-14/Phoenix weapon system can provide valuable corporate knowledge to the ATA development program. The F-14A and Phoenix missile system were designed and developed to provide long range air defense for the Navy's carrier battle group. However, the missile design and development preceded the design and development of the aircraft. Specifically, the Phoenix missile fire control and physical envelope had been developed for the TFX; however, when it became apparent that this aircraft was not compatable with Navy requirements, a new platform was required. This integration and development effort resulted in the recognition of the following design principles: [Ref. 36]

.1 When incorporating a sophisticated subsystem, electric power requirements and weight must be considered for each subsystem and the total system.

.2 Configuration management is crucial because of physical interface and control requirements.

.3 A change in any major piece of equipment, no matter how small, must be evaluated from a systems standpoint.

.4 Logistics elements such as the maintenance concept and supply support must be considered from the beginning of the development program.

V. SYNTHESIS, ANALYSIS AND EVALUATION OF ALTERNATIVE SYSTEMS ENGINEERING MODELS FOR THE ATA

In Chapter IV, a description of the ATA program was presented, and potential problem areas were discussed. It was determined that the requirements for a new, state of the art armament system would make the development of the ATA a unique and difficult systems engineering problem. However, by upgrading existing A-6 aircraft, schedule pressures have been relaxed. In addition, the potential for transfer of advanced technology between the ATF and ATA programs has been enhanced by the collaborative efforts on the VFMX and JAFE projects.

In this chapter the general system engineering models presented in Chapter III will be integrated with the information developed in Chapter IV to tailor a qualitative systems engineering model for the ATA.

A. SYNTHESIS OF ATA REQUIREMENTS

The ATA's program objectives include:

1. Improvements in performance over the A-6 that include;
   * Increased combat radius,
   * Increased employment air speed,
   * Increased survivability,
   * High reliability, and
   * Reduced RCS.

2. Relatively low cost so that sufficient numbers of aircraft can be purchased to satisfy fleet requirements.

3. A reasonable measure of commonality built into new systems so that these systems are not unique to the ATA.

Under these objectives, the following requirements have evolved:

1. A new state of the art armament system compatable with conformal or internally mounted weapons.

2. New weapons which are compatable with conformal or internal carriage.

3. A high efficiency power plant.

B. SYNTHESIS OF ALTERNATIVES

The second phase in the development of a system model is a synthesis of alternative solutions. A number of excellent general systems engineering models are available for application to the ATA problem. Chapter III presented and described in detail five of these models. These models are summarized in the following paragraphs.

1. Model Number 1

In this model a three tiered wheel is utilized to denote the indenture levels of a functional analysis. The outer tier represents the specific functional areas which must be executed in the development of a system. The second level represents the typical program office's organizational structure. Finally, this model has at its hub, the program manager and systems engineering staff.

2. Model Number 2

In this representation, the basic inputs are translated through various stages of the development cycle of a project. As the system progresses through its development cycle, the emphasis changes from basic technology in the conceptual analysis phase, to prototype hardware in the design phase, and finally operational hardware and support equipment in the implementation phase.

3. Model Number 3

The third model emphasizes the interrelationships of various functional areas. Specifically as one key element such as cost is modified, the other functional elements are directly affected. This model also emphasizes the iterative nature of systems engineering.

4. Model Number 4

This next model presents a variation of the theme which is found in the previous model; even small changes have drastic effects on other functional areas. The emphasis in this alternative is placed on modifications to subsystems and equipment and the requirement for quality control.

5. Model Number 5

The final model is the most general of the five. This is not necessarily negative, because it is flexible and thorough. It is flexible in organizational structure, with emphasis on functions, yet iterative in nature with appropriate feedback loops.

C. ANALYSIS OF ALTERNATIVE SOLUTIONS

Each systems engineering model has advantages and disadvantages. The following analysis is based on the requirements of the ATA as discussed in Chapter IV and summarized in section A of this chapter.

1. <u>Model Number 1</u>

a. Advantages

* Comprehensive coverage of key functional areas.

* Functional areas have a great deal of flexibility. Therefore, there will be minimal restriction to developing new technology and new approaches.

* Organizational structure is compatable with the typical program office.

* The program office and systems engineering staff are at the center of activity, so that the total systems objectives can be emphasized during key design reviews.

b. Disadvantages

* There is a middle layer of management that could limit lines of communication between functional areas and the appropriate personnel in the program office. This layer could create miscommunication problems or slow the rate of information exchange, thereby inhibiting goal congruence.

* The emphasis of this model is on specific functional areas. Functional requirements evolve, to some degree, as the project progresses through its life cycle. For example, quality should be a key element throughout the life cycle, however, in the products initial stages, quality is mostly a planning function. In mid to later stages of a system's life cycle, the personnel and resource requirements for quality increase. On the other hand, raw technological areas such as aerodynamics or electronics have an opposite requirements profile. This model does not take this evolving characteristic into consideration.

* The effects of change on one parameter are not emphasized in other areas.

* Even though independence of functional areas is benefical for developmental reasons, resulting duplication of effort can be detrimental to goal congruence for subsystems.

* Large resource requirements result in high cost.

2. <u>Model Number 2</u>

a. Advantages

* Evolving emphasis of functional areas.

* Good lines of communication between functional and systems personnel.

* Information feedback to preceding stages to transmit lessons learned and forward transmission of data to follow-on phases so that production and operational personnel know what to expect.

* Cost is low because personnel move from project to project as requirements evolve.

b. Disadvantages

* Continuity suffers because functional people move from one project to another and corporate knowledge may be lost.

* The effects of changes on subsystems are not applied to other functional areas.

3. Model Number 3

a. Advantages

* Emphasizes interdependence between functional areas and effects of the environment.

* Emphasizes iterative nature of systems approach.

* Advocates both informal and formal communication between functional groups.

* Advocates compatibility of subsystem outputs.

b. Disadvantages

* It is a complex system which becomes almost unmanageable when all key functional elements are included.

* Complexity and personnel requirements cause high cost.

* It is difficult to stop the iterative cycle and establish a configuration baseline so that production can commence.

4. Model Number 4

a. Advantages

* The interrelationships between subsystems and the total system mission objectives are emphasized.

* Promotes both formal and informal communication between functional areas.

* Promotes a team atmosphere which is better for quality control and goal congruence.

* Flexibility.

* Information provides feedback to insure desired performance.

* Personnel within the organization's functional groups have the opportunity to move laterally into different positions thus providing training for future systems engineers.

b. Disadvantages

* It is complex and difficult to implement.

* Non-recurring costs are high.

* It is difficult to stop the interative change process and establish a configuration baseline so that production can begin.

5. <u>Model Number 5</u>

a. Advantages

* It is simple and easy to implement.

* Cost is low.

* A number of alternatives to choose from are presented.

* Functional groups may be independent.

* Flexibility.

b. Disadvantages

* Communication and feedback between functional groups is limited.

* Does not take into consideration changes in requirements due to progression of the system through the life cycle.

D. EVALUATION

If the implementation problems of model number 4 can be simplifed, a modified version of this alternative will satisfy the ATA requirements. This modified version is illustrated in

Figure 16. The reason for this decision is the emphasis on the importance of a parallel effort of the major subsystem and the aircraft. If the implementation problems can not be resolved, model number 5 provides the next best alternative.

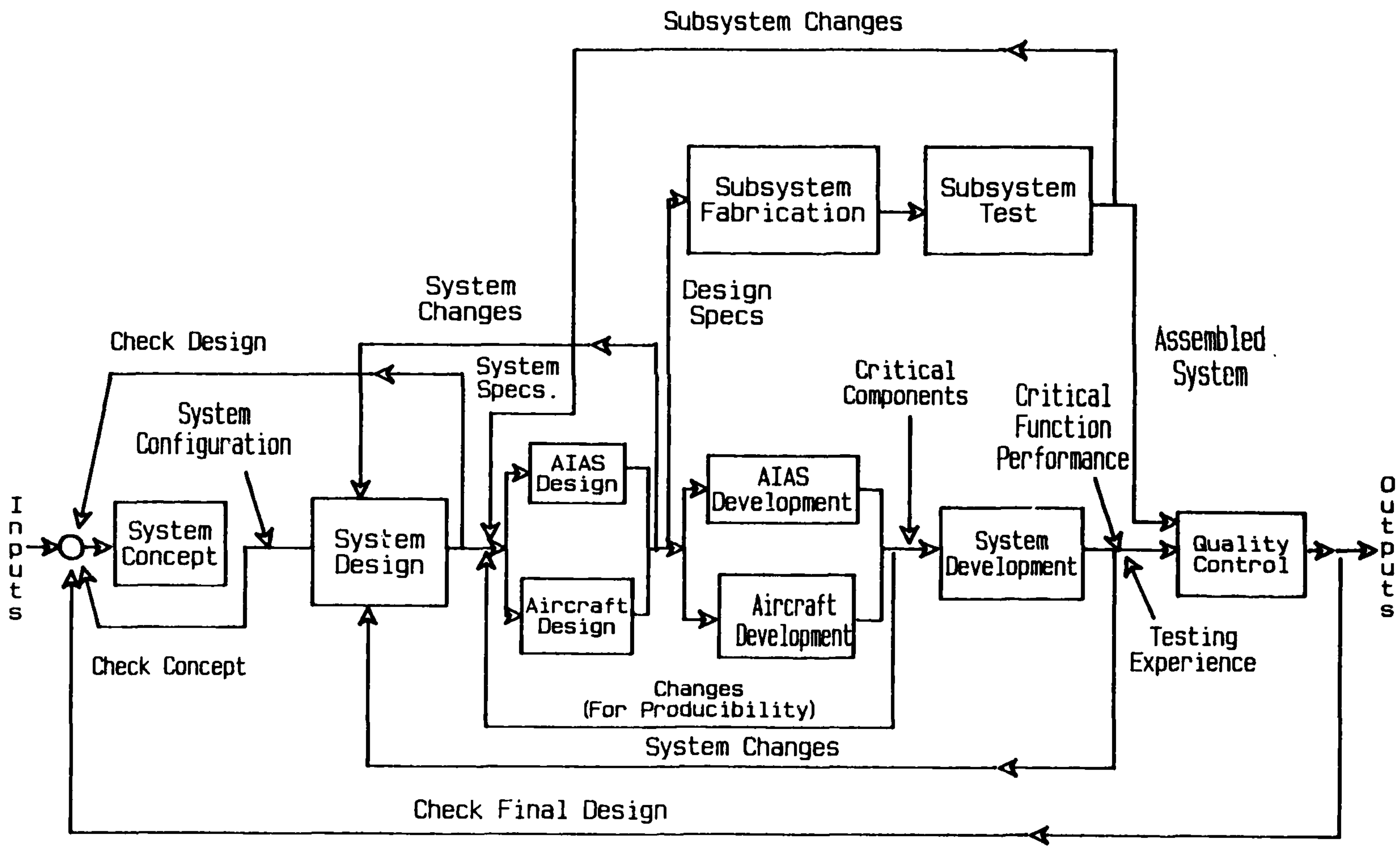


Figure 16. Recommended Alternative Model

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The increasing complexity of weapon systems, coupled with technical specialization requires a tailored management approach. This tailored approach requires orderly and objective problem solving techniques that are logical and consistent. Systems engineering provides the methodology to provide better control and insight into the design, development, and production process.

The Advanced Tactical Aircraft and its weapon systems will be developed simultanously. In the past a particualar weapon was designed to fit an existing aircraft, or an aircraft was designed to incorporate existing weapons. Therefore, the Advanced Tactical Aircraft presents a new and challenging systems engineering problem.

B. CONCLUSIONS

Following is a summarized list of the major conclusions in this thesis:

* Large complex systems must employ systems engineering to ensure success.

* The systems approach offers a methodology for decision-making for the ATA, whereby all relevant information is considered.

* The systems engineering model is a flexible tool which can be tailored to the specific requirements of a particular program.

* It is critical to utilize systems engineering during each and every phase of the system's life cycle.

* The interfaces between subsystems are extremely important. If these are not taken into consideration integration of the subsystems may be impossible, especially on the ATA where a number of major subsystems will be developed simultaneously.

* Any change in a subsystem, no matter how insignificant it may seem, must be evaluated from a total systems perspective.

* Both the Navy and the Air Force have benefitted from collaborative efforts on the UFMX and JAFE programs.

C. RECOMMENDATIONS

The following recommendations are made:

* Introduce a systems engineering model for the ATA similar to the model presented in Figure 16.

* Broaden the systems perspective of all functional groups so they can see the impact of their efforts on the total system and other subsystems.

* Establish a parallel design and development effort for both the AIAS and the aircraft subsystems. However, ensure frequent exchanges between the two groups to insure goal congruence of these two systems.

* Monitor the development of the AFT so that compatable advanced technology can be transferred to the ATA.

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