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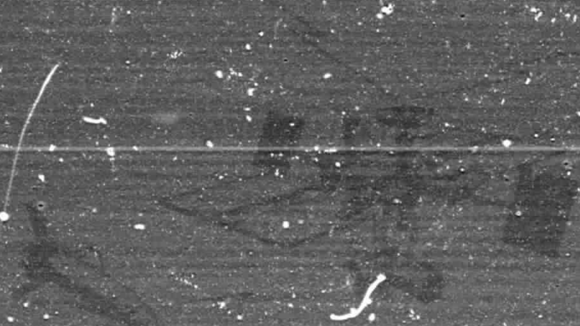

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Space Station Man-Machine Automation Trade-off Analysis

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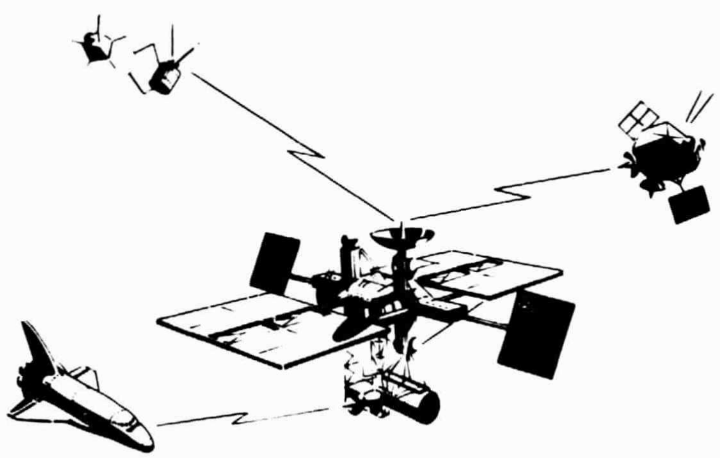

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ABSTRACT

The man-machine automation trade-off methodology presented in this report is one of four research tasks comprising the Autonomous Spacecraft System Technology (ASST) project at the Jet Propulsion Laboratory. ASST, funded under a National Aeronautics and Space Administration (Office of Aeronautics and Space Technology) Research Technology Objectives Plan, was established to identify and study system-level design problems for autonomous spacecraft. Using the Space Station as an example spacecraft system requiring a certain level of autonomous control, a system-level, man-machine automation trade-off methodology is presented that (1) optimizes man-machine mixes for different ground and on-orbit crew functions subject to cost, safety, weight, power, and reliability constraints and (2) plots the best incorporation plan for new, emerging technologies by weighing cost, relative availability, reliability, safety, importance to out-year missions, and ease of retrofit.

While the methodology takes a fairly straightforward approach to valuing human productivity, it is still sensitive to the important subtleties associated with designing a well-integrated, man-machine system. These subtleties include considerations such as crew preference to retain certain spacecraft control functions; or valuing human integration/decision capabilities over equivalent hardware/software where appropriate. Quantitatively, the methodology incorporates these considerations by reflecting a large, and perhaps uneconomical, investment in replacement automation. Rudimentary examples are provided throughout the report to clarify the man-machine and technology trade-off processes. The methodology, representing the results of the first phase of research for the Man-Machine Trade-off Task, is succeeded by recommendations for follow-on research, primarily in the area of database construction for the model.

FOREWORD

This report provides the results of the first phase of development of a Space Station autonomy and automation methodology for (1) identifying optimum man-machine mixes for both on-orbit and ground-crew functions and (2) plotting the best technology growth path for out-year retrofit toward greater autonomy. This study is part of the NASA-funded (Office of Aeronautics and Space Technology) Autonomous Spacecraft System Technology, RTOP 506-64-15.

ACKNOWLEDGMENT

Appreciation is extended to the NASA Johnson Space Center Space Shuttle Operations group for its assistance in defining the extrapolated crew functions for Space Station.

DEFINITION OF TERMS

AAF — Adaptation Adjustment Factor

ADSI — Adapted number of Delivered Source Instructions (this is the original DSI figure)

a_{kt} — identified man-machine alternative, t, for a given subsystem, k

B_{kt} — net benefit from automating subsystem, k, with alternative, t. This net benefit is made up of the benefit from manhours saved, M_{kt}, and other incremental net dollar benefits, c_{kt} [i.e., $(M_{kt} + c_{kt})$]

C — cost of the most expensive man-machine alternative (i.e., that alternative in which all functions are to be automated)

C_F — cost of facilities, such as building space, computers, and ground-crew displays

C_I — initial incremental cost associated with automating subsystem, i

C_{kt} — net subsystem, k, cost not considering the benefit of automating alternative, t

C_{LC} — incremental life-cycle cost associated with automating subsystem, i, for a given man-machine alternative

C_{LSTE} — cost of launch support and test equipment (launch support refers to consideration of launch weight constraints, and test equipment refers to special test, verification, calibration or tooling hardware)

CM — % Code Modified

C_M — cost of maintenance (primarily the recurring retrofit and ground maintenance costs associated with the repair of failed components and associated software)

C_{MP} — cost of on-orbit and ground manpower; on-orbit workforce costs are reduced by the value of crew hours saved, and ground workforce is composed of system-maintenance/support for test and mission-control personnel

C_{OS} — incremental operations and support (recurring) costs associated with automating subsystem, i

C_{RDP} — cost of R&D and production; this cost includes the hardware, software, communication, and additional sensor elements

C_S	cost of initial and follow-on spares
C_{STE}	cost of support and test equipment, exclusive of C_{LSTE}
C_T	cost target for the total system
C_{TD}	cost of supporting technical documentation for training or maintenance
C_{TR}	cost of on-orbit and ground-crew training if subsystem functions not completely automated
$C(x)$	net incremental life-cycle cost for automating function, i
DM	% Design Modified
EDSI	Expected number of Delivered Source Instructions
H_{kt}	incremental hazard exposure time reduction due to automating subsystem, k, with alternative, t
k	master scaling constant that is an algebraic function of the k_i's, scaling u(x) from u = 0.0 to u = 1.0
k_i	scaling constant ranging between 0.0 and 1.0 that determines the "weight" or "importance" of the ith attribute
IM	% Integration required for Modified software
M_{kt}	crew manhour (workhour) savings associated with a given man-machine alternative, t, for a given subsystem, k
n	number of attributes
P	incremental crew hours saved if function i is automated
$\prod$	symbol for the "product" of n expressions
P_{kt}	incremental power impact of automating subsystem, k, with alternative, t
P_T	system-level power constraint
$u_i(x_i)$	attribute utility function of the ith attribute
u(x)	outcome utility function
W_{kt}	incremental weight impact of automating subsystem, k, with alternative, t
W_T	system-level weight constraint
x	automation decision variable for function i having a value of 1 if the function is automated and 0 if the function is not

CONTENTS

Figures

Tables

SECTION I

INTRODUCTION AND SUMMARY

A. OBJECTIVES

The Autonomous Spacecraft System Technology (ASST) effort at the Jet Propulsion Laboratory (JPL) was established to carry out system-level design analysis for unmanned and manned autonomous spacecraft control, with application to Space Station. Although the size and complexity of the Space Station are important design considerations that favor a larger degree of automation and autonomy than current unmanned or manned spacecraft, an even larger design driver is the mission diversity. Present Space Station mission concepts include a large array of scientific experiments, possible manufacturing processes involving pharmaceuticals or alloys, and communications. Therefore, productive crew time will be an extremely important resource. Additionally, the planned long life for Space Station implies (1) an expansion of mission concepts (in both number and sophistication) and (2) long-term involvement of on-orbit and ground-crew resources. A combination of greater demands on both Space Station and ground crews and long-term commitment of manpower and associated ground support suggests a potential for significant cost savings through automation and greater autonomy from ground control. Consequently, the objective of this study was to develop a trade-off methodology that would (1) provide the optimal man-machine mixes for different crew functions and (2) plot the best incorporation plan for new, emerging technologies from the standpoint of both cost and benefits received. Although the study is sensitive to human-factor design considerations (such as the inherent advantages of human integration and decision-making capabilities for certain multi-variable problems), it is outside the scope of this study to explore psychological or motivational dimensions of the man-machine functional allocation problem. Nevertheless, the methodology is designed to allow additional functional selection criteria to be incorporated at a later date. It is anticipated that this methodology will be used as a system design tool by spacecraft (and, specifically, Space Station) project management.

B. TASK BACKGROUND

The JPL involvement in earth-orbiting spacecraft autonomy began in the summer of 1980 with a workshop sponsored by the U.S. Air Force Office of Scientific Research involving industry and members of the academic community. The objective was to define the concepts and technology needed to increase the automation of spacecraft operation and reduce dependence on ground control. This initial effort led to the establishment of the Autonomous Spacecraft Program (ASP) at JPL. Although not linked to the ASST program, ASP provided an excellent knowledge base for the follow-up ASST effort. The JPL ASST effort, funded by the Office of Aeronautics and Space Technology (OAST) at National Aeronautics and Space Administration (NASA) Headquarters, is divided into the following four major research areas:

(1) Architectural concepts for autonomous control.

(2) Man-machine trade-off methodology.

(3) Expert systems-implementation methodology.

(4) Autonomous-control software technology.

For this first research phase, the man-machine trade-off element of the effort was designed primarily to develop a methodology framework for the cost-benefit assessment, provide rudimentary example applications of the methodology, and establish follow-on research priorities.

C. ASSUMPTIONS AND CONSTRAINTS

Although several different types of modeling approaches are used to establish the structure for the automation cost-benefit model, the final rankings of man-machine mixes and technology growth options will be based primarily on cost, crew-productivity impacts, crew safety, and their importance relative to meeting mission requirements. Two of the major underlying assumptions of this approach are that (1) automation and an increasing degree of autonomy are programmatic goals needed to meet anticipated mission demands and (2) extensive total automation and autonomous control of the Space Station, while perhaps technically feasible at this time, may not be economically practical.

At a more detailed level (within the model framework itself) it was necessary to establish a standard on-orbit operating baseline against which improvements in performance due to automation could be compared. It was assumed that (1) Skylab and Space Shuttle on-orbit operations were representative of the operational baseline and (2) baseline equipment functions, associated crew task/cost data (respectively obtained from operational logs and Shuttle operations planning personnel), as well as Space Station subsystem cost estimates had either a sound historical or theoretical basis. Furthermore, it was assumed that the kinds of on-orbit and ground-crew tasks associated with programs such as Skylab and Shuttle were generic kinds of tasks also required for Space Station. For purposes of costing, a 20-year life cycle was also assumed.

One last aspect of the automation cost-benefit assessment model framework refers to the optimization portions of the methodology. Several different cost and design variables having different values, depending on the man-machine mix or technology selected, must be weighed. As part of the optimization process it was assumed that some variables (such as cost or safety) could be more important design drivers than other variables (such as research and development time). In conjunction with this assumption, it was also assumed that sufficient expertise and experience exists in the government and private sector to allow appropriate weights to be assigned to the variables.

Several constraints generated from Space Station programmatic developments and schedule limitations. Programmatically speaking, the man-machine trade-off task was initiated during the pre-program Space Station Conceptual Design Group (CDG) effort. Although basic design requirements were available at that time, neither the requirements nor the overall configuration was well-defined. Even with the Skylab and Shuttle experience, this lack of definition made it difficult to formulate the system-operating baseline referred to earlier in this section. As a result, the operations and functions (and supporting functional task-time data) were developed at a generic level and designed to allow tailoring as detailed crew operational scenarios become available later in the program. This approach was reasonable in view of the fact that the Space Station program, having just been initiated, requires only approximate cost-benefit estimates. Another programmatic constraint was generated after the task began, and the Johnson Space Center (JSC) Space Station system requirements effort had been started. Once the requirements effort had begun, some reference configurations and mission descriptions became available. In an effort to keep the thrust of the ASST man-machine trade-off study jointly in line with the overall Space Station program, it was decided to deviate slightly from the more general nature of the basic ASST Research Technology Objectives Plan (RTOP) and center on the design and mission scenarios generated by the JSC requirements effort.

The last constraint revolved around meeting the task-deliverable schedule. Originally, the task was structured so that the methodology would be demonstrated on some example conceptual designs. However, other programmatic demands on the conceptual design group caused a delay in the concept generation. Subsequently, it was not feasible to do the concept costing and cost-benefit projections as originally planned. Therefore, the task was restructured to a confirmation that the technique could be developed, coupled with a demonstration of the technique where conceptual design data were available.

D. SUMMARY OF APPROACH AND RESULTS

Several steps are required to identify potential areas for automation, establish strawman conceptual designs for costing, weigh automation cost against other design and system cost attributes, and establish the benefits of automation, namely:

(1) Network analysis (identification and mapping of crew functions).

(2) Conceptual design and costing.

(3) Determination of a most likely set of man-machine alternatives.

(4) Measure of cost, productivity, and safety impacts of design and cost attributes.

(5) Selection of optimal (high-value) man-machine alternatives.

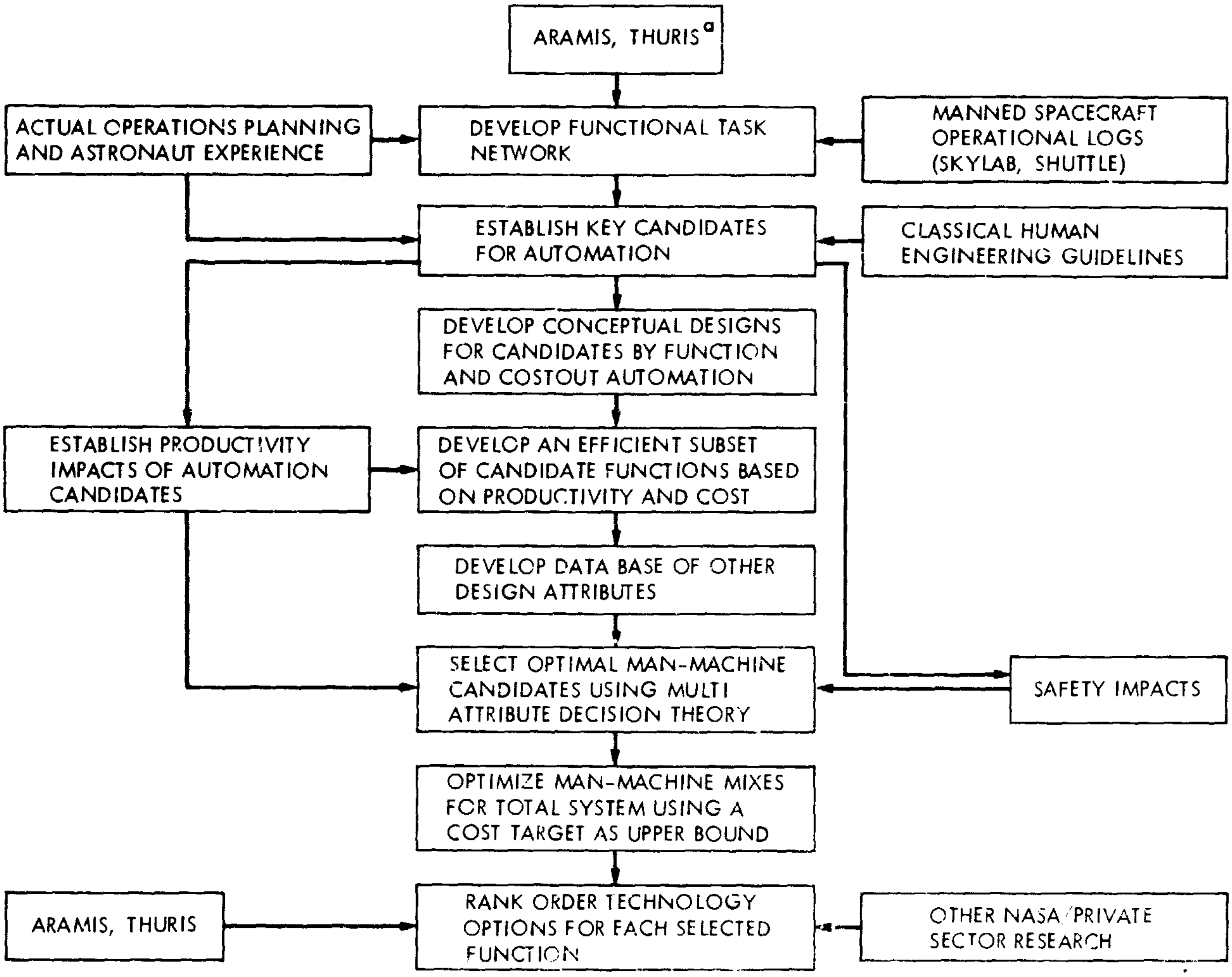
(6) Optimization of man-machine mixes for the complete system.

(7) Rank ordering of technology options.

Figure 1-1 shows an overview of the complete methodology.

1. Network Analysis

As mentioned earlier in this section, Space Station functional task networks were extrapolated from Skylab and Shuttle operational logs and conversations with the Shuttle Operations Group at JSC.



[a]ARAMIS, Automation, Robotics Machine Intelligence Systems (MIT);
THURIS, The Human Role in Space (Marshall Space Flight Center).

Figure 1-1. Man-Machine Trade-Off Methodology Structure

For the purpose of focusing the study effort, it was decided to select two (of the approximate 8 or 10) Space Station modules that represented areas in which major man-machine trade-offs might be required. This was done by interviewing individuals knowledgeable in both the manned-spacecraft and Space Station arenas. Ultimately, the power and command/control modules were selected. Keeping crew productivity as a major design driver in mind, the functional task networks were crucial to understanding (1) the tasks normally performed by the crew; (2) which key tasks, when automated, might have major impacts on streamlining the operation of the spacecraft and freeing the crew to handle more payloads (for example, experiments); and (3) potential exposure to hazards.

2. Conceptual Design and Costing

Once the key automation areas are identified, the next major step is to establish conceptual designs of the automation candidates. The purpose of the conceptual design effort is threefold: (1) identify additional hardware required for automation, (2) identify additional automation software, and (3) estimate the additional cost for automation. One important fallout of the conceptual design step that became apparent from one of the test examples was the identification of economies of scale (that is, the sharing of automation components between subsystems). As the model is refined and the conceptual design database is expanded, it will become easier to understand ways of conserving system costs through economies of scale.

Once the network and conceptual design steps are completed, an initial subset of man-machine mixes can be isolated in terms of the two major design drivers, productivity and cost. This is done by selecting those mixes that have the most favorable increase in productivity for a given cost. Other mixes that give smaller returns for the same, or greater, cost are then considered less desirable alternatives. This process allows a large array of various man-machine alternatives to be trimmed to an "efficient" subset. An example is provided in Section V.

3. Attribute Measures

Clearly, as costs and benefits of automation are examined, the crew productivity and automation cost elements described above are important attributes. Particular attention is paid to identifying not only an economically efficient but well-integrated combination of man-machine resources. Other attributes such as safety, weight, power, reliability, and research and development (R&D) risk are also important design and cost drivers. Because safety is not easily costed and not directly related to productivity, it was decided to apply either a subjective or "reduction in hazard exposure time" measure. The weight and power attributes were basically treated as constraints measured against an allowable deviation above a baseline operating mode. Both have launch cost impacts, while power also has life-cycle cost impacts. Reliability has both productivity and cost impacts. The productivity impact is related to the possible extension in mean time between repair actions while the cost impacts are associated with (1) building in test and verification hardware/software (a launch cost impact); (2) potentially lower operations and maintenance costs caused by lengthening the period between spare stockage (or requiring less in-place redundancy); and (3) developing a more efficient, spare procurement philosophy (a life-cycle impact). Other life-cycle reliability cost aspects include manpower and training. The last attribute, R&D risk, has two facets. From a reliability aspect it can add to the automation cost if it is necessary to spend more money for in-place spares to make up for lower reliability of new, or extensions of existing, technology (both launch and life-cycle cost impacts). In the case of advanced, or future, technology the R&D risk attribute is measured in terms of the amount of time before the technology is qualified and becomes available. This last facet is considered when advanced technologies are factored into the cost-benefit analysis and the design.

4. Cost-Benefit Analysis

For each man-machine alternative identified in the efficient subset, the present-value costs (both costs and savings) are melded together to form a "net cost-benefit." Similarly, the productivity impacts are combined to form a single productivity figure. The safety impact remains independent. The actual cost-benefit analysis encompasses items (4), (5), and (6) listed at the beginning of Section I-D. Even though it is understood that a dollar value could be placed on crew productivity in terms of the cost of having an astronaut in space, it is not clear at this time that this is an appropriate measure. A more appropriate, and perhaps more valuable, measure might be the value of additional experiments, or profits realized, by having more productivity time on orbit. Therefore, until a better measure is obtained, the productivity impacts are assumed to be an independent benefit from the net cost-benefits. However, in so doing, the model structure is left with providing a means of selecting the best man-machine mixes for each subsystem and module, based on all three cost, productivity, and safety attributes. As an intermediate solution, a multi-attribute decision approach was developed. Basically, multi-attribute decision analysis is employed when the outcome of a decision involving a complex system (such as selecting an ideal man-machine mix for Space Station) involves several criteria. Decision makers (experts in the manned-spacecraft arena) are asked to place weights on the various criteria, or attributes. Based on the relative weights obtained from the decision makers, preference values are computed for each attribute so the trade-offs between the various outcomes can be made and the outcomes ranked to express accurately the preferences of the decision makers. In this same manner a small preferred set of man-machine alternatives (outcomes) is selected for each subsystem and module in the Space Station system.

At the completion of the subsystem cost-benefit assessment and selection of optimal man-machine mix, the problem is still only half-solved. The best combination(s) of man-machine alternatives must be chosen across all subsystems and modules. To do this step a standard life-cycle cost algorithm is employed along with a cost target. This calculation determines which set of man-machine mixes reduces the total system cost the most, thereby either meeting or bettering the cost target or minimizing the difference between the actual and target costs.

The last step in the trade-off analysis considers the incorporation of future technologies that may not be available or mature by the intended 1992 Space Station launch date. In this last step various technologies applicable to each automation function are assigned respective quantitative and subjective values for each of ten attributes. Seven of the attributes (IOC and life-cycle cost, safety, power, weight, workhour savings, and reliability) are the same as used earlier for the man-machine mix optimization. Three other attributes (R&D risk, technology importance as related to meeting potential out-year mission requirements, and retrofit amenability) were added because they complete the decision environment in which managers and budget planners will make technology selections. Again, employing multi-attribute decision theory and weighting the relative importance of each attribute, the various technology options are ranked, based on how well each option ultimately compares with others relative to the attribute measures. In this manner an evolutionary improvement program is developed.

5. Summary of Results

Because this initial research effort dealt more with the design structure of the trade-off methodology than with actual design projections, the results to date are more theoretical and qualitative than quantitative. Nevertheless, the results suggest good promise for being able to develop a reasonable, practical, automation/autonomy design tool. The primary result is that an appropriate man-machine automation trade-off methodology was developed. As a measure of the practicality of the methodology, the research strongly indicates that data do exist to support the various analytical steps in the technique. These practical aspects of the research are stated in Table 1-1.

E. REPORT STRUCTURE

In this report the background leading to the study definition is provided in Section II, along with a summary of other recent, associated automation studies. Section III provides an overview of the methodology framework. Sections IV through VII explain each element of the methodology in depth with some examples, where data were available. Finally, Section VIII summarizes the research results to date and defines recommendations for follow-on studies.

Table 1-1. Space Station Man-Machine Automation Trade-off Study Results (Phase I)

Methodology Area	Phase I Study Results in Terms of Data Quality/Availability: Good	Reasonable	Unknown at this Stage
Capability to develop representative on-orbit crew functional task networks	X		
Data to support methodology available	X		
Methodology data input/output accuracy at least equivalent to present conceptual design cost projections	X Input		X Output
Capability to provide reasonable automation conceptual design configurations/cost estimates	X		
Ability to identify and characterize key design attributes	X		
Ability to discretely quantify all design attributes			X
Hierarchical prioritization of man-machine alternatives and technology options		X	
Practical incorporation of existing research data from other related spacecraft automation and costing studies (e.g., ARAMIS, THURIS, PRC cost model)[a]	X		
Demonstration of methodology on actual space station subsystems		X Limited demonstration on storage battery example	X Other subsystems

[a]ARAMIS, Automation, Robotics and Machine Intelligence Systems (MIT); THURIS, The Human Role in Space (Marshall Space Flight Center); and PRC, Planning Research Corporation.

SECTION II

SPACE STATION AUTONOMY/AUTOMATION STUDY DEFINITION

A. OVERVIEW

Section I briefly describes the task background as related to the original Autonomous Spacecraft System Technology program. This discussion also notes that recent developments associated with the JSC Space Station requirements definition were incorporated in the study to keep the thrust of the man-machine trade-off task also in line with the manned spacecraft program. This section (Section II) describes how elements of both programs were combined to define the conceptual foundation for the methodology. Additionally, a brief summary of other associated automation research activities is provided with an explanation of how those activities relate to this study.

B. AUTONOMOUS SPACECRAFT SYSTEM TECHNOLOGY

It is important to understand some of the products of the ASST program (defined in Section I-B) and how they relate to this study.

Early unmanned spacecraft were designed as semi-automated systems. Hardwired sequencers controlled payload functions on the basis of a timer initiated in the launch phase of the mission. Trajectory correction maneuvers that maintained the nominal timeline of the sequencers were ground-initiated and automatically executed by on-board, hardwired controls. Increasing mission complexity with attendant payload and spacecraft control requirements led to the provision of in-flight, programmable sequencing and control that was eventually supplied by on-board digital computers. Additional mission complexity results in increased risk of failure, which may be countered by dedication of some portion of the on-board control resource to fault-protection. The existence of a programmable control resource with access to the engineering data of the spacecraft allows closed-loop control for both fault protection/redundancy management and maintenance of the operating condition of subsystem components.

The preceding description is an example of an automated system evolving into an autonomous system. That is, an <u>automated</u> system functions within a <u>limited</u> and <u>pre-defined scope</u> of circumstances. The addition of <u>fault-tolerance</u> and the ability to <u>adapt control behavior</u> to changing external and internal conditions leads to an <u>autonomous</u> system. This definition allows the "man-in-the-loop" to act as an <u>additional</u> source of information for the control structure. It is exactly this kind of experience that has allowed a better understanding of how to design autonomous systems. The ASST studies have pooled this experience and provided some rules of thumb for designing autonomous and automated systems (Reference 2-1). Basically, autonomy requires a three-step control structure. Those processes that require closed-loop control may cycle from step (3) back to step (1) in the following listing (Reference 2-2):

(1) Sense and analyze the state of internal or external quantities that are inputs to the control process.

(2) Derive and command a response by the system that meets an appropriate objective.

(3) Act to implement the response.

The control process is implemented through control resources that connect command resources with data-management resources. Sensory data required by the command resource may be collected and communicated by data-management resources in a manner typically used for engineering telemetry. As system complexity increases, distribution of separate control resources to the subsystem level and below offers the advantages of (1) reducing the pressure of multiple demands upon a central data-management resource, (2) reducing the interdependence of subsystems, and (3) supporting the flexibility of the system to meet new requirements without major reconfiguration. This type of control structure with the above inherent advantages implies that utilizing a hierarchical functional architecture is an efficient and flexible first step for incorporating automation for system autonomy. The decoupling of functions, where feasible, also simplifies integration testing of the system and evolutionary addition of new capability.

Figure 2-1 demonstrates an example functional control hierarchy for spacecraft core functions (see Reference 2-1). The levels of the hierarchy are numbered, beginning with level 0, representing the executive control functions required for system control and crew/ground interface functions. Traditional functional subsystems have executive control functions at level 1 that allow for direct external control and that interface with the level 0 station executive functions. Level 2 represents the control and execution of internal applications performed by the subsystems. Lower levels are typically provided for control sensors and "smart" sensors, and actuators that implement the functions of the subsystems. A similar hierarchical structure is employed in the methodology. In the case of the functional network analysis the functions and crew tasks are first generically identified (at the system level) and then allocated to modules and subsystems. This was done primarily to simplify automation concept development and eventual programming of the trade-off model. The concept development and costing steps are also hierarchical in nature and, where automated functions are integrated across subsystems, allow economies of scale to surface. The optimization routine at the end of the methodology is essentially a linear programming problem that was able to be easily structured as a result of the hierarchical approach taken in designing the methodology.

C. NASA MANNED SPACE STATION PROJECT

The aims of the NASA Space Station Program are:

(1) To develop a permanently manned Space Station within a decade.

(2) To invite other countries to participate.

(3) To promote private-sector investment in space.

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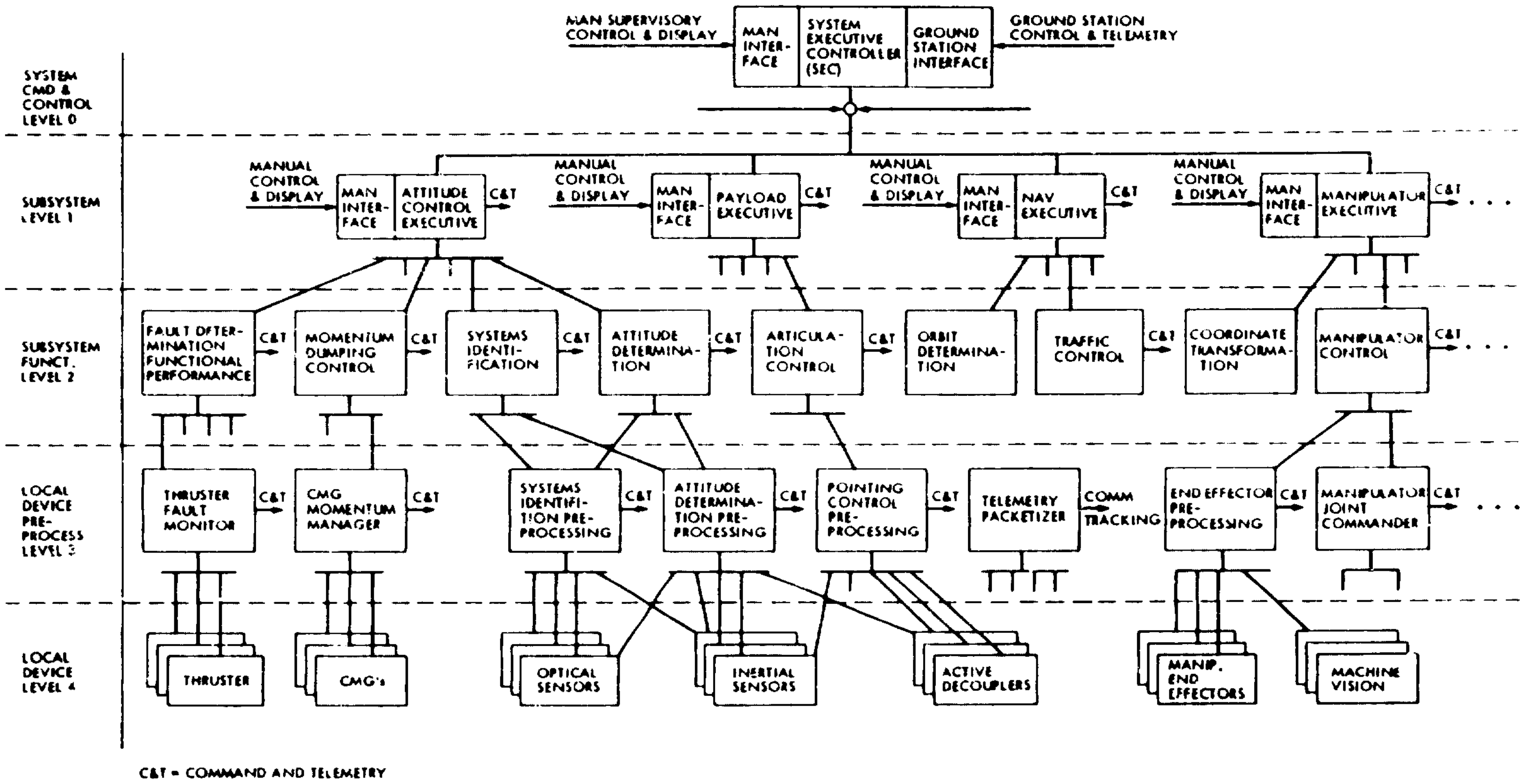

Figure 2-1. Example of Autonomous Spacecraft Command and Control Functional Architecture

In support of these aims, the following long-term Space Station program objectives have been established by NASA (Reference 2-3):

(1) Establish the means for permanent presence of people in space.

(2) Initially enable routine, continuous utilization of space for science applications, technology development, and commercial exploitation.

(3) Develop and exploit the synergism of the man-machine combination in space.

(4) Provide essential system elements and operational practices for an integrated national space capability.

(5) Reduce the cost and complexity of working and living in space while also assuring a high level of safety and reliability.

The engineering guidelines for Space Station include provisions for continuous habitation; Shuttle usage for initial launch, resupply, and crew rotation; cost reduction by maximizing commonality; evolutionary growth through maintainable and restorable systems; manned and unmanned elements; and autonomous operation with the ability to upgrade systems as new technologies become available. The entire system is planned to be customer-oriented for flexibility and simplicity of customer interfaces.

The NASA (JSC) system requirements effort, which resulted in the detailed engineering guidelines, provided key information for constructing the methodology framework. First, the requirements provided some reference configurations that assisted in understanding the overall modular design and in determining where major subsystems might be located in relation to pressurized versus unpressurized volumes. The reference configuration selected as the most preferable, based on cost and design flexibility, is the strawman example employed in this study. Second, the requirements effort provided operational information essential to developing the functional task networks (specifically related to crew task descriptions, rendezvous and docking activities, and payloads). Finally, the requirements activity provided some useful component failure data which, again, was essential to understanding crew interactions with system failures as part of the functional-task networks.

D. SUMMARY OF OTHER RELATED AUTONOMY/AUTOMATION STUDIES

1. THURIS

The most encompassing man-machine automation assessment presently being conducted is The Human Role In Space (THURIS) effort sponsored by the Marshall Space Flight Center. The THURIS study is a 1-year effort designed to (1) investigate the role and the required degree of direct involvement of humans in future space missions, (2) establish criteria for the allocation of functional activities between humans and machines, and (3) provide insight into technology requirements, economics, and benefits of the human presence in space (Reference 2-4). Although the THURIS effort primarily addresses tasks as independent, unrelated elements, the overall effort has provided an excellent bank of information consisting of activity definitions, component costs, cost versus activity-level plots, and technology projections. All of the THURIS results are extremely useful data inputs to the network portion of the methodology developed in this study.

2. ARAMIS

One vital precursor to the THURIS program has been the Massachusetts Institute of Technology (MIT) Automation, Robotics, and Machine Intelligence Systems (ARAMIS) study (Reference 2-5). The study first identifies tasks that may potentially be required by future space programs, based on projects such as Geostationary Platform (GSP) and the Teleoperator Maneuvering System (TMS), and defines ARAMIS possibilities that represent candidates for the generic tasks. The study then subjectively evaluates the relative merits of the possibilities. Finally, the study identifies promising applications of ARAMIS and recommends specific areas for further research. Again, the foundation for the functional network analysis developed in this study draws largely on the ARAMIS space activities study as well as historical task data from Skylab and Space Shuttle.

3. Other Space Station Automation Studies

A brief mention is made here of some private-sector studies which, although not as broad as THURIS or ARAMIS, provided useful conceptual design, task, and ergonomics data for the extra vehicular activity (EVA) activity (e.g., on-orbit EVA assembly, maintenance, and remote manipulator activities).

The MATRA study, prepared for the European Space Agency, assesses the role of humans in space in a similar fashion as THURIS (Reference 2-6). A qualitative review of major functions in space, which can be automated or performed by humans, is made with emphasis on assembly and servicing or repair. In an effort to demonstrate the practical nature of potential man and machine roles, two mission scenarios (assembly and servicing) are used to demonstrate possible man-machine combinations. The Essex Corporation study (Reference 2-7) provides an excellent bank of information on a whole series of EVA tasks. The study progresses from manual (with tool assist), through remote, to fully automated operations. Additionally, useful cost information is provided for the various kinds of augmenting or totally automated equipment. Last, the Loughead, Pruett study, also of ESSEX origin, provides an in-depth study of the EVA function as related to manipulation and assembly of large space structure columns (Reference 2-8). The major thrust of this study is to examine assembly procedures, tools, and hardware configurations for the prediction of assembly times of large, complex structures in space.

4. Foundation for Man-Machine Trade-off Structure

Having summarized other contributing literature, it is appropriate to recap briefly the one study that provided the framework for the man-machine trade-off methodology presented in this report. The U.S. Department of Energy (DOE) and Bureau of Mines have long been concerned about the extremely high fatality and disabling injury rates in underground coal mining. Consequently, DOE funded JPL to develop a design plan for automating underground mining machinery (Reference 2-9). This plan had to be sensitive to industry's needs, as well as to cost and the worker.

Several steps were required to identify potential areas for automation, establish the appropriate sensor, guidance, and control technology, and determine productivity impacts and cost benefits. The first step was the identification of automation opportunities. The assessment consisted of developing functional descriptions for each major component in the mining system, followed by conducting an industry survey of equipment manufacturers and designers, mine managers, and miners. The functional description provided information on mining operations, the present degree of system mechanization, and operations potentially amenable to automation. The survey confirmed the system operational and functional descriptions and provided valuable information on problem areas for which automation could enhance productivity or improve miner health and safety. These findings largely formed the basis for determining the automation opportunities.

The second step was to assemble the functional descriptions into a network. A detailed underground mining operational network was assembled, based on the functional descriptions, industry inputs, and additional industrial engineering data obtained from mining studies. The industrial engineering data were crucial to understanding system delays that detracted from production time but had potential to be streamlined with automation. Once the automation opportunities (developed from the considerations summarized above) were reflected in the form of appropriate delays in the network, an estimate of potential increase in productivity was obtained.

The third step was to perform an automation technology assessment. The technologies required to implement each automation opportunity were identified. This effort included an investigation of appropriate sensor technology, development of mathematical models for each affected system component to establish the location and data feedback for each sensor, and conceptual design of guidance and control systems. The technology assessment included preliminary cost estimates and schedules for developing the various automation candidates. Mitigation of potential health and safety hazards was also part of the technology assessment.

The last step was a comparison of costs and benefits, which were established for each automation opportunity by comparing the projected productivity improvements against capital and operating costs. Other variables derived from health and safety impacts, market-potential, and market-penetration rates were also factored into the final cost-benefit calculation. The automation opportunities were then prioritized to allow formulation of a development plan. Overall, when reviewed by the mining industry, the final results were considered to be reasonably correct, based on independent private-sector research in automation. Additionally, one of the larger mining companies ultimately adopted the proposed automation development plan.

Although similar to the mining problem, the methodology developed for assessing Space Station man-machine trade-offs had to be tailored to consider the different working environment, a much larger array of worker activities and man-machine combinations, consideration of a greater number of cost-benefit attributes, and a much broader advanced technology scope. In comparison to the THURIS and ARAMIS studies, this methodology provides more depth in the conceptual design and costing areas, a more comprehensive approach to identifying and linking crew tasks with Space Station functions/modules, and a complete structure for melding together a large amount of data from different studies into a comprehensive man-machine design trade-off tool. Additionally, a man-machine and technology optimization approach is provided that considers the system as a whole. Overall, this study serves to enhance and increase the scope of the THURIS and ARAMIS efforts. The revised methodology framework is presented in Section III of this report.

SECTION III

GENERAL METHODOLOGY FRAMEWORK

A. OVERVIEW

Section II indicates that the methodology presented in this report represents another building block to the THURIS and ARAMIS research. The basic framework for the man-machine trade-off technique is summarized in Section 1 and is discussed in greater depth in this section. Specifically, areas are highlighted in which distinct differences occur between this methodology and THURIS or ARAMIS.

As stated earlier, the methodology is divided into four major elements:

(1) Network Analysis.

(2) Conceptual Design and Costing.

(3) Attribute Measures.

(4) Cost-Benefit Analysis.

Each element is made up of specific analytical procedures that act as building blocks and that provide data inputs for the next step. The major elements and some key procedures are displayed in Figure 1-1. Each element and analytical procedure is discussed in the following paragraphs.

B. NETWORK ANALYSIS

Crew productivity is one of the high design priorities. Figure 3-1 demonstrates the importance of the crew's available productive time for both initial operational capability (IOC) and out-year growth configurations. The curves shown in Figure 3-1 qualitatively represent the variables shown on the y axes. For example, the level of assembly activity is expected to be very high around IOC and then taper off in out-years. Similarly, the system failure curve is the standard "bathtub" function in which there is an early "shake-out" period, followed by a period of stabilization, and last by aging accompanied by failure creep. Finally, the Space Station will be expected to handle an increasing number of experiments and other payloads (such as manufacturing processes, etc.) with time. Two important potential time drivers early in the station's life are clearly the assembly and shake-out activities. These activities will probably consume a large portion of both the on-orbit and ground crews' time, regardless of the amount of automation incorporated. Around the middle and later portions of the station's life the experiments, payloads, and failure-creep time drivers comprise the bulk of demand on crew time. Of specific concern will be the following variables:

(1) There may be a large number of non-routine tasks associated with tending experiments or manufacturing processes.

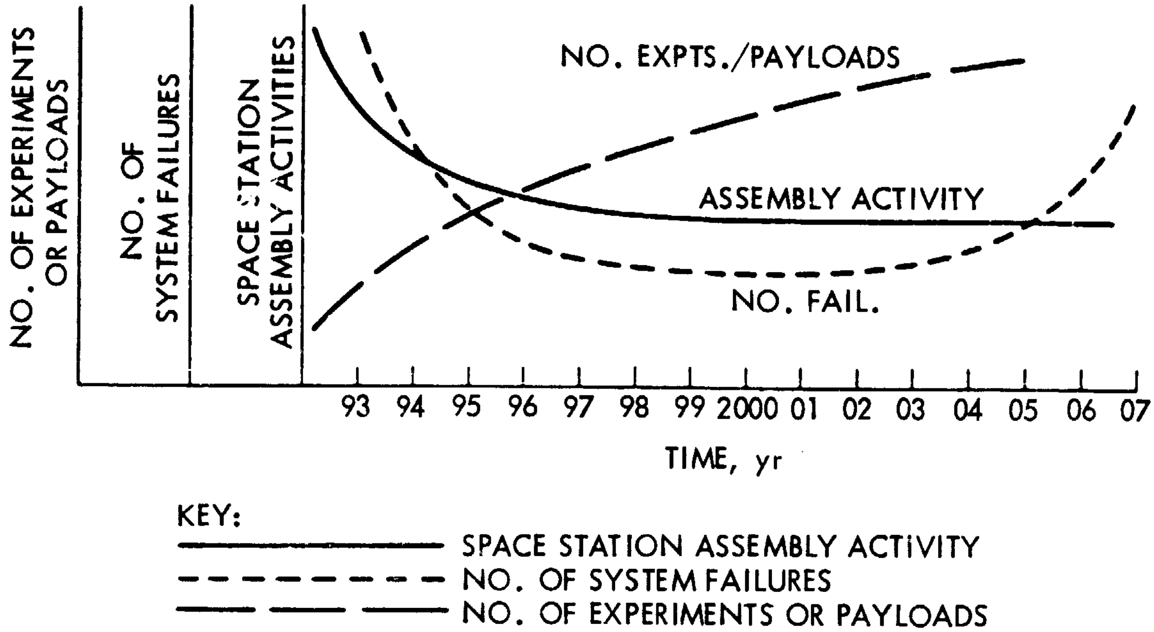

Figure 3-1. Major Factors Affecting the Demand for Crew Productive Time During Initial Operational Capability and Out-Year Operation

(2) Station/payload interface problems may occur with having to monitor, collect (or segregate), and compare vast arrays of different experimental control parameters.

(3) There may be a constantly changing variety of experiments that may require a large number of non-routine handling procedures.

The major thrust of these considerations is that both the Space Station and ground crews must be free to perform those tasks that (1) allow the station to be assembled and operating as soon as possible and (2) maximize the utilization of the station. To these ends, the first facet of the cost-benefit framework, the network analysis, identifies those tasks that are prime candidates for automation. Network analysis provides an operational map of equipment functions and crew tasks that must be performed both in parallel and series. Specific attention is paid to the crew tasks because it is here that benefits of automation are fully realized. The Space Station network analysis recently completed drew upon results of ARAMIS, THURIS, and operational experience from Skylab and Shuttle to develop a baseline network. Once the networks were assembled, they were reviewed by the Shuttle Operations Support Group (JSC) to ensure that the various functions or tasks, although extrapolated to fit the Space Station concept, were reasonably representative of actual on-orbit operations. Besides providing insight into potential time and operational savings, the network analysis (in addition to the previous Skylab and Shuttle experience) provided an understanding of task areas where the crew could be exposed to major hazards. Table 3-1 summarizes those top-level functions or tasks which, if automated, would have major impacts for

Table 3-1. Key Automation Candidates Impacting Crew Productivity and/or Safety

Key Automation Candidates	Area Most Affected by Automation			
	Space Station Crew		Ground Crew	
	IOC[a]	Growth	IOC[a]	Growth
System/subsystem state change[b]	X	X	X	
System assembly/on-orbit structural manufacturing	X		X	
Monitoring	X	X	X	X
Verification/calibration	X	X	X	X
Fault isolation/management	X	X	X	X
Extra vehicular activity	X	X		
Mission planning		X	X	X
Rendezvous/docking		X	X	X

[a]Initial Operational Capability.
[b]Refers to initiation of control functions as a planned activity.

enhancing crew productivity and/or safety. For example, automation of structural manufacturing processes (such as truss structures) and system assembly will probably have the greatest impact on station-crew productivity and safety during the period when assembly activity is the highest, which is around IOC. During this same period, automation of these activities will also greatly enhance supervision and control by the ground crew. Similarly, because ground crew involvement will be the major source of mission planning and docking control around IOC, Table 3-1 shows the greatest impact of automation occurring with the ground crew, followed by a shift to the station crew in the out-year growth. Of course, automation of EVA activities will greatly enhance the station crew's available payload tending time and safety during both IOC and growth. For purposes of this initial research activity, only on-orbit, steady-state crew functions were examined.

In summary, with the exception of system assembly and EVA, the remaining candidates in Table 3-1 historically have consumed in excess of 40% of a mission day. For example, on-orbit monitoring, verification/calibration, and planning have consumed slightly more than 40% of a 9- to 10-h work period. Fault isolation and repair have consumed anywhere from 5 min to several hours per day. Rendezvous and docking maneuvers, although only requiring active crew involvement for the last half hour before docking, have required fairly constant monitoring for 4 to 6 hours before the actual dock. Finally, EVA, although an important asset, has required 3 to 4 hours of preparation and de-preparation time, usually involving two to three people. Both EVA and docking are important network variables because of the potential high frequencies of activity reflected in present station operating plans.

Although actual on-orbit task experience is discussed in much greater depth in Section IV, the preceding discussion serves to illustrate the importance of network analysis in identifying potential areas for automation based primarily on how redundant, time-consuming, or safety-endangering the crew tasks are. Other automation selection criteria are discussed in Section IV. The major difference between the approach used in this methodology and ARAMIS/THURIS is that generic tasks are linked together into an operational network for each Space Station module, as opposed to merely identifying tasks as independent functions.

C. CONCEPTUAL DESIGN AND COSTING

Having identified the prime automation candidates as a first step, the next step in the cost-benefit framework is to develop a conceptual design for each candidate automated function. Ultimately, each conceptual design is life-cycle costed to establish the cost side of the cost-benefit algorithm. The conceptual design approach is hierarchical in nature; that is, not only must a function be managed at the subsystem level but also at the system level, specifically because many subsystem control variables, being integrated with other subsystems, have system-level control impacts (see Reference 2-1). The following estimates are extracted from the conceptual designs and provide the basis for the costing effort:

(1) The number of dedicated microprocessors and integrating networks.

(2) Number of both dedicated communication links and integrating communication links.

(3) Software requirements.

(4) Software complexity.

(5) Number of additional sensors and suggested number of backup microprocessors and other necessary components for fault management.

Figure 3-2 isolates the generic automation elements of any function/subsystem. An interesting aspect of this figure is that, whether a function is automated or not, existing manned spacecraft design usually dictates that the sensors, comparators, servos/actuators, data management, and communication components already be in place to enable crew control. Therefore, the only additional components are generally those shown in the inside box.

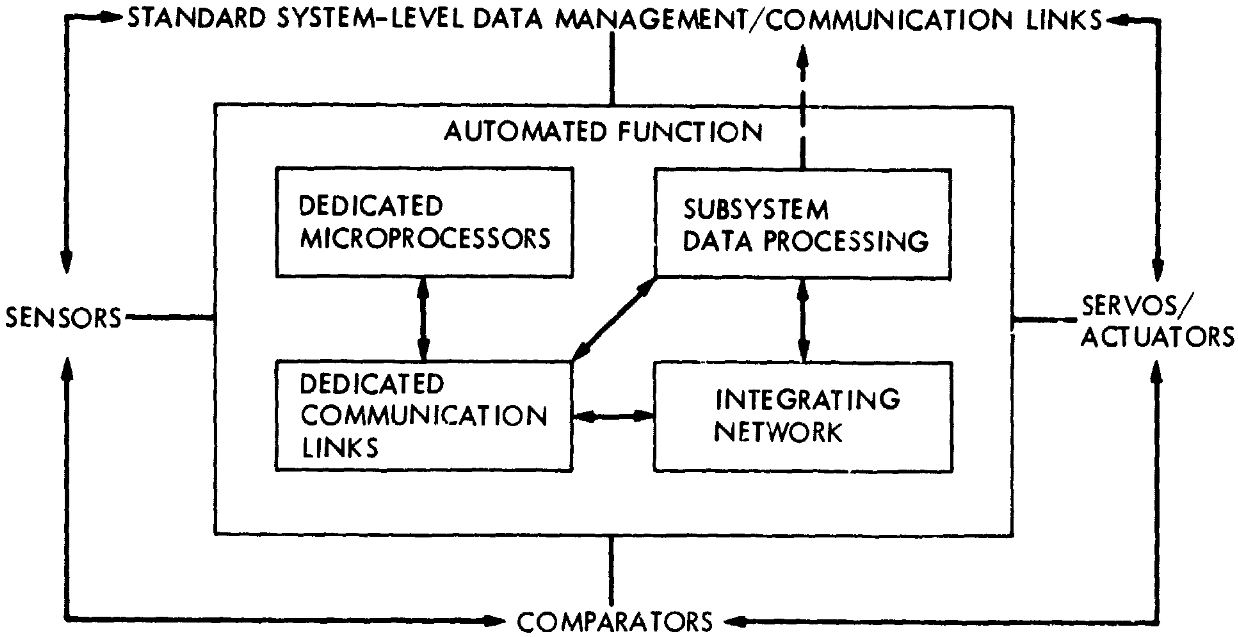

Figure 3-2. Major Components of a Generic Automated Subsystem

The conceptual design and costing step is explored in greater depth in Section V, along with a supporting example. It is important to state here that the basic difference between the THURIS effort and this study is that the conceptual designs for automation are carried to a greater level of detail. Additionally, as the automation concepts are developed, this level of detail allows a clearer understanding of areas in which subsystems can share common processors and thus contribute to economies of scale.

The last analytical procedure associated with the conceptual-design step is a determination of an "efficient" subset of man-machine mixes. For example, Table 3-1 shows that the crew can be involved in monitoring, verification or calibration, anomaly troubleshooting, and repair. One possible alternative is to allow the system to operate without any additional automation. This would mean that the on-orbit and ground crews would basically perform all three of these tasks as presently performed on Shuttle. Another alternative might be to let the crews do the monitoring and verification tasks but allow switch-over to automated fault management when an anomaly or failure is detected. As yet another alternative, all three tasks could be automated. Indeed, not all alternatives offer the same payoff on crew productivity time. Furthermore, because cost and productivity time are major design drivers, it is essential to select alternatives that predict the best productivity results for a given cost. This initial sorting process is important because control of a specific subsystem within a module might involve a rather large array of man-machine alternatives. The sorting routine merely selects those mixes that have the best increase in productivity for a given cost. Other alternatives that offer lower returns for the same, or greater, cost fall into a sub-optimal cost productivity region and are discarded. The net result is an efficient subset of man-machine alternatives. In addition to trimming the size of the alternative array, this step also makes the data-gathering process less unwieldy when considering the other cost-benefit attributes and station modules.

D. AUTOMATION ATTRIBUTE MEASURES

The third facet of the cost-benefit framework involves the determination of measures for the attributes of automation. The total list of the attributes (not prioritized) includes the following:

(1) Crew safety (hazard exposure in h/mission day).

(2) Crew/ground operational efficiency (workhours/mission day).

(3) IOC automation hardware/software costs (1984$).

(4) Life-cycle automation hardware/software costs (1984$).

(5) Weight limitations (launch cost, 1984$).

(6) Power consumption (additional power hardware, 1984$).

(7) System/subsystem reliability (maintenance and spares costs, 1984$).

(8) Research and development risk (dollars required to make technology available by IOC, 1984$).

(9) Importance to future missions (subjective value).

(10) Amenability to retrofit (subjective value).

It should be noted that, although the preceding variables are termed "attributes," the model is being designed so that each of these variables can be reflected as either a cost "saver" or a cost "driver."

The first item listed (safety) is a difficult attribute to quantify, especially because there is very little accident/injury history to which some type of "value-of-life" costing technique can be applied. However, the network analysis can identify functions that have crew safety impacts. Therefore, a qualitative weight can be assigned to the final cost-benefit calculation on those functions that jointly reduce exposure to hazards.

Crew and ground operational efficiency (or productivity) improvement due to automation may be approximated by a corresponding reduction in labor costs if such reduction takes place. However, if, for example, on-orbit crew time is saved due to automation, the value of such savings would be more properly measured in terms of the present values of additional future experiments in which crew members can engage. Such values may be estimated by the attractiveness of increased experimentation or on-orbit manufacturing capacity per mission (in terms of profit per additional mission day).

Because the cost of automation is covered in the preceding subsection, it will not be discussed here.

The value of weight reduction due to automation depends crucially upon whether or not the weight is a limiting constraint. For example, if the weight reduction is not accompanied with any changes in configuration of other payloads, lower frequency of launches, reduced size of launch vehicle, or any other factors, then the value of such weight reduction is zero. However, if the weight reduction enables additional payloads to be carried or increases the weight allocated to other payloads or subsystems (such as substitution of heavier but less costly materials), then the value of the weight reduction would be measured by the value of these modifications.

The power attribute can be quantified in terms of the net power savings or increase caused by automating subsystem functions. The value placed on power usage is measured in terms of either the cost of generating additional power or the cost of reducing the power requirements in other ways. On the other hand, the dollar value of power savings is measured in terms of either the cost savings of not generating additional power, or the value of additional experiments that are made feasible due to the power addition.

The reliability attribute has several cost aspects. The first aspect is the early consideration of component/subsystem functional self-test for test and verification both before Design, Development, Test, and Evaluation (DDT&E) and during IOC. The dollar value placed on this reliability aspect is measured primarily through the net dollars saved by using the same DDT&E test/verification hardware and software in the actual IOC station. This includes using a common communication and control language across all subsystems that facilitates the operator-system interface.

The other aspects of reliability have to do with measuring the benefits of using fault isolation and fault management. The benefits are measurable primarily through the previously stated productivity and safety attributes, as well as hardware and software component reductions due to commonality across subsystems. For example, fault isolation is a critical network function because it often takes considerable crew time to track down an anomaly or component failure. Historical failure data from Skylab and Shuttle indicate that the fault-isolation function occurs on a daily basis. Therefore, the on-orbit and ground-crew time savings are potentially significant. Similarly, resolving anomalies or failures can also be extremely time-consuming. Again, crew productivity and segregation from safety-endangering tasks such as EVA and maintenance (e.g., electrical troubleshooting, handling components) are priorities. Another measurable benefit comes from the different ways automation can handle component failures (see Reference 2-1):

(1) The design can incorporate automated component redundancy and switching.

(2) The design can incorporate a means of automatically managing the key variables controlled by the component (e.g., reduce rev/min or power input), prioritize activity demands, and shed low-priority demands.

(3) As a subset of (2) above, the design may automatically indicate that no component change or fault-management decision is necessary (e.g., knowing that only a malfunction indicator light has failed).

(4) The design can incorporate a means of automatically locating and switching to another component/software routine in an integrated subsystem that can assume the same controlling function (i.e., functional redundancy).

The net dollar benefit is measured in the value of the components saved by not requiring complete redundancy in all subsystems. Secondary cost-benefits are measurable through the dollars saved by being able to schedule maintenance and establish subsequent spare component procurement/stock levels more efficiently (i.e., ordering long-lead-time items in advance reduces the problem of paying a premium price for crisis production).

The last attribute, R&D risk, is an important cost-benefit consideration because it provides a measure of the costs associated with (1) spending more money for in-place spares to make up for reduced reliability in newer technologies and (2) spending more money to make newer technologies available sooner.

E. COST-BENEFIT ANALYSIS

The last facet of the cost-benefit framework is the actual cost-benefit calculation itself. The basic approach is to convert all costs and cost savings to present values and calculate the IOC and net cost-benefits over the station life cycle (20 years). This approach is necessary because some benefits are not evident until several years after IOC (e.g., on-orbit crew productivity savings or industry profits). This overall cost-benefit modeling approach is unique because it provides a means of considering trade-offs between varying degrees of automation/autonomy (as related primarily to greater or lesser crew involvement) and/or different technologies. The varying degrees of automation are considered primarily through changes in the operations efficiency, cost savings, and safety attributes. The selection of different technologies is considered by examining the preceding three attributes plus R&D time, safety, reliability, weight and power savings, technology importance relative to mission, and amenability to retrofit. Each man-machine alternative within the efficient subset is ultimately ranked, based on multi-attribute decision analysis. The multi-attribute technique is used when the outcome of a decision involving a complex system (such as selecting an ideal man-machine mix for Space Station) involves several criteria. Decision makers (experts in the given system arena) are asked to place values on the various criteria, or attributes. Based on the relative values obtained from the decision makers, weights are placed on each attribute so the trade-offs between the various outcomes can be made and the outcomes ranked to express the preferences of the decision makers. In this same manner a small, attractive set of man-machine alternatives (outcomes) is selected for each subsystem and module in the Space Station system. As a simple subjective demonstration, consider the example in which the experts are asked to estimate the relative utility of the net benefits, crew productivity, and safety as related to automating a specific function on Space Station. The experts might report the following:

(1) An improvement in safety is preferred, but conformance with existing levels of safety is acceptable; degradation in safety is absolutely unacceptable.

(2) A specific man-machine alternative must demonstrate a positive net cost-benefit to prevent the R&D program for the associated subsystem exceeding a hard-cost ceiling. Therefore, the net cost-benefit attribute is weighted heavily.

(3) A large productivity improvement is preferred. However, a small-to-medium improvement in productivity is acceptable as long as it is accompanied by a positive cost-benefit. No improvement in crew productivity is counter-productive to future programmatic demands and is, therefore, unacceptable.

The final optimal subgroup of alternatives would be those man-machine mixes that jointly exhibit a positive net cost savings, demonstrate a productivity improvement, and maintain safety at present levels. An example "preferred" alternative might be one in which all subsystem monitoring is done by the crew until an anomaly surfaces, at which time the crew allows the subsystem to verify itself and proceeds to fault isolate and manage the anomaly or failure, followed by some type of status-report feedback. A more concrete example is provided later in Section VII.

At the completion of the subsystem cost-benefit assessment and selection of optimal man-machine mix, the problem is still only half-solved. The best combination(s) of man-machine alternatives must be chosen across all subsystems and modules. To do this analytical procedure, a standard life-cycle cost algorithm is used along with a cost target. The calculation basically determines which set of man-machine mixes reduces the total system cost the most, thereby either meeting or bettering the cost target, or minimizing the difference between the actual and target costs. In comparison with the THURIS effort, this approach provides a more comprehensive means of optimizing the man-machine mix for the complete system.

The last step in the trade-off analysis considers the incorporation of future technologies that may not be available or mature by the intended 1992 initial operational capability. In this last analytical procedure various technologies applicable to each automation function are assigned respective quantitative and subjective values for each of the ten attributes. Seven of the attributes (IOC and life-cycle costs, safety, reliability, productivity time, weight, and power) are the same as used earlier for the man-machine mix optimization. Three other attributes, R&D time (as related to the investment necessary to make technology available), technology importance (as related to meeting potential evolutionary mission requirements), and retrofit amenability were added to describe the Program Manager's decision environment more fully. Again, using multi-attribute decision theory in a manner similar to the above example, the various technology options are ranked, based on how well each option ultimately compares with others relative to the attribute measures. In this manner a future retrofit program can be developed. Although somewhat similar to THURIS, this approach provides a more quantitative means of weighing advanced technologies.

SECTION IV

NETWORK ANALYSIS

A. OVERVIEW

Enhancement of crew productive time is an important Space Station design attribute. It is anticipated that automation of various functions will streamline station operations to allow the station crew more on-orbit time for payloads while at the same time reducing ground-crew involvement. The tool used to measure productivity impacts is a network that describes each function and activity in the system by increments of time elements. Time savings through automation are then identified to identify the potential productivity impacts. Consideration is given to crew preferences on various man-machine mixes. The following sections of the report provide the early results of the network analysis using ARAMIS, THURIS, Skylab, and Shuttle operational experience superimposed on one of the Space Station reference configurations developed during the recent JSC design requirements activity.

B. STRAWMAN CONCEPTUAL SPACE STATION DESIGN

The ARAMIS and THURIS studies identified generic spacecraft functions and crew activities. It is important to recognize that, whenever concepts are developed that either extend or require new technology, there is usually not a one-to-one correspondence between the old and new functional modes of operation. Therefore, extremely useful preparatory steps to the functional network analysis are (1) to establish a strawman conceptual design and (2) to superimpose the known activities onto the design as a baseline functional, or operational, description. By using this approach, generic functions in the new system can be identified and located (e.g., functions delineated by unpressurized or pressurized areas). There are also more payloads on the Space Station located in unpressurized areas than on Skylab or Shuttle. This reconfiguration could, therefore, require greater extra vehicular activity (EVA) if present methods are used for maintenance. The strawman design used for this study is shown in Figure 4-1 (Reference 4-1), which highlights the four basic modules:

(1) Resource, or Power.

(2) Laboratory.

(3) Command/Control and Habitat.

(4) Logistics.

The resource module primarily contains the solar arrays, radiators, storage batteries, fuel cells, and supporting structures (which includes mechanisms such as motors, gimbals, etc.). The command/control and habitat modules are basically the centers where the guidance, navigation, station-control, data-management, and communication functions take place. These modules are also where the crew sleeping quarters, galley, and support systems are located. The support systems include components such as medical

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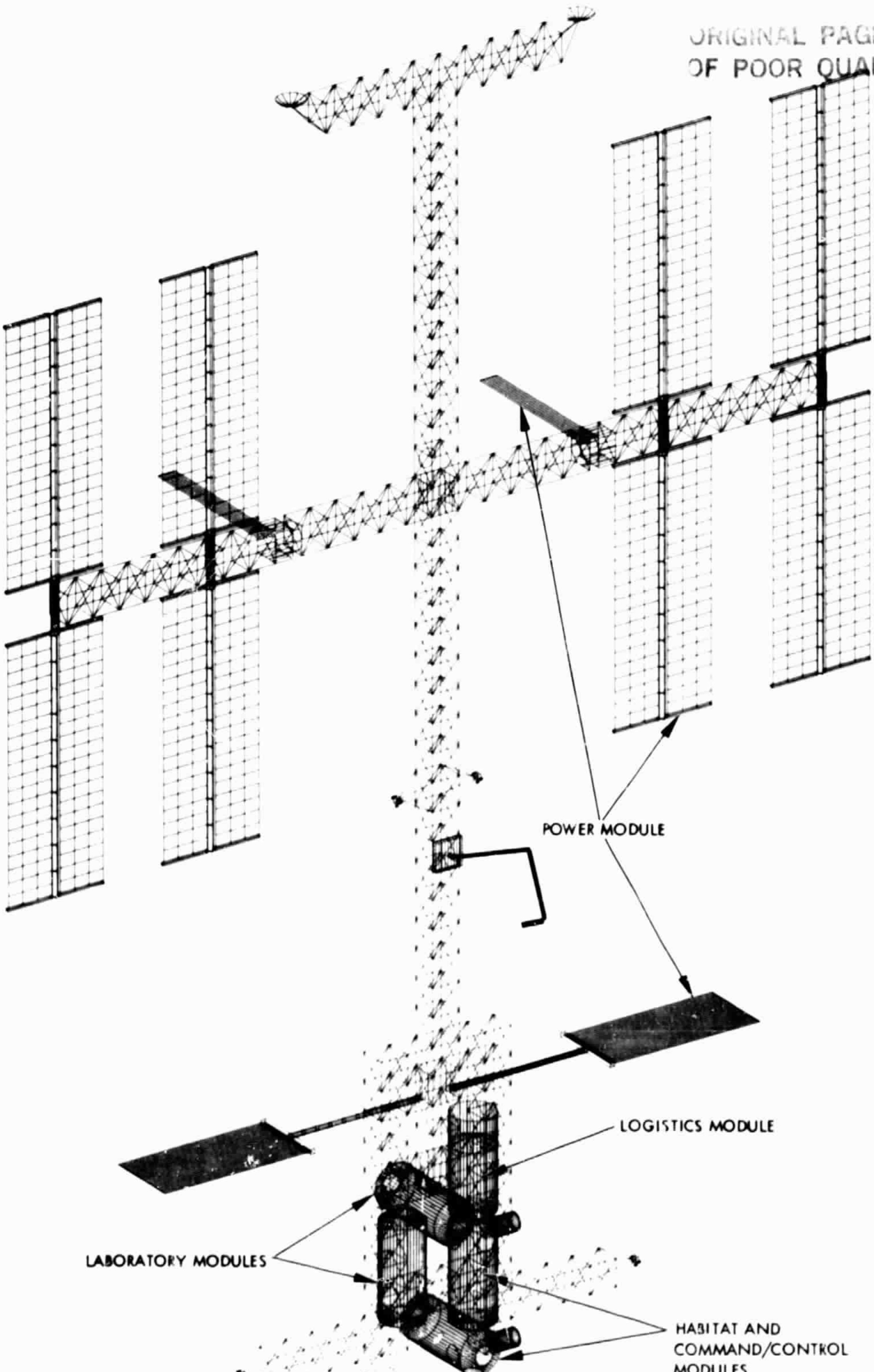


Figure 4-1. Strawman Space Station Design

facilities, EVA equipment or manned maneuvering units (MMUs). The laboratory module is where the internal payloads (or experiments) are controlled. Last, the logistics module contains spare supplies and might act as a workplace for component repairs. Figure 4-2 displays the corresponding Space Station system hierarchy used in this methodology for modeling the crew functions and interactions with each subsystem and module.

Each module contains many subsystems, which in turn have several crew and/or machine activities associated with the control of the subsystems, modules, and system as a whole. Some modules share many of the subsystems (e.g., data management). The Figure 4-2 system hierarchy serves three important functions in the methodology:

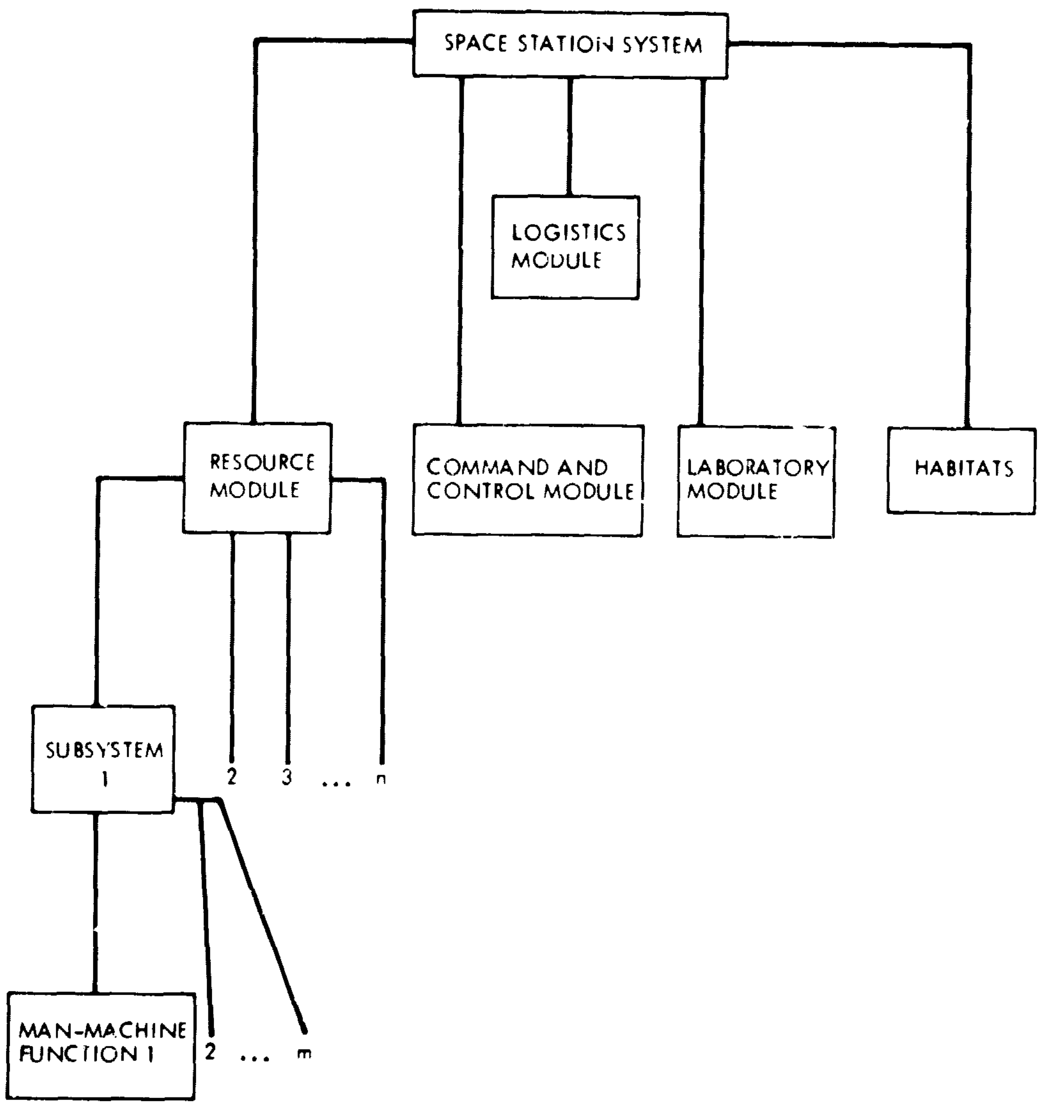


Figure 4-2. Space Station System Modeling Hierarchy

(1) It provides a basis for identifying extrapolated crew functions with the appropriate subsystem, module, and system operations. which in turn provides a conceptual basis for applying automation technology.

(2) Once automation technology is applied to various crew functions, it provides a theoretical structure for assessing automation costs and savings (discussed in greater detail in Section VII).

(3) It provides a simple means of examining abbreviated forms of the Space Station design if funding is not available for the complete configuration shown in Figure 4-1.

It should be noted that there is another hierarchical level below the "man-machine functional" level shown in Figure 4-2. For example, the fault-management function and its associated task time might vary from a simple switching procedure to an actual troubleshooting and repair procedure, depending on the component and nature of the failure. The ability to differentiate between these tasks is directly related to the granularity of the historical task-time data. Although outside the scope of this study, it is expected that a better determination of the actual granularity of task-time experience will be established in follow-on research phases. An approach to obtain the varying task times for fault management is provided later in this section.

Once a strawman conceptual design and associated system hierarchy is developed, the next step is to develop the functional task network for the station and ground crews and to identify the automation candidates.

C. FUNCTIONAL-TASK NETWORK DEVELOPMENT

The scope of this study prevented the complete chain of Space Station functional-task networks from being developed. Therefore, to demonstrate the network process it was decided to concentrate on two modules that posed key man-machine interface issues. To select the appropriate modules, key individuals at each NASA center who were members of the original station conceptual design group (CDG) were contacted (Reference 4-2). The results of the interviews suggested that the resource (power) and command/control modules were two "high" human interface areas. The power module was considered important because, unlike Shuttle, the Space Station power subsystems could be largely exterior to the pressurized modules (see Figure 4-1). Therefore, major man-machine trade-off issues arose concerning (1) subsystems that should be brought inside pressurized areas for operation and control purposes and (2) potential EVA maintainance activities. The command/control module is important because it represents the hub of command and control activities, especially guidance, navigation, reboost, and docking. This selection of modules was especially advantageous because it provided two extreme cases: (1) examination of a fairly straightforward power subsystem within the resource module (the storage batteries) and (2) examination of a much more complicated subsytem within the command/control module (navigation, guidance, and control for rendezvous and docking). High-level networks were developed for all the functions in the power and command/control modules so that the example cases could be isolated while clearly showing the connection with the other subsystems and system as a whole.

1. Network Foundation

The classical tool used in developing functional-task networks is the PERT diagram (References 4-3 and 4-4). PERT diagrams are useful for separating a large, complicated process into activities and delays to identify the major variables necessary to complete a project or process. Activities and delays (called events) are networked as shown in Figure 4-3. Events that occur in a straight line (Events 1 and 2 above) are in series because Event 1 must occur before Event 2. Event 3 is in parallel with Events 1 and 2 because it can occur while these two events are happening. In a similar manner, the complete process is diagrammed from beginning to end.

The complete application of the PERT approach usually requires that best, worst, and desired event completion times be used. Multiplying the probability of an event being completed (based on historical experience) by the three completion-time estimates results in the expected value for finishing a specific task. When all the best estimates of task completion have been placed in the network, the minimum time to complete the whole process can be determined. This is called the critical path and is an important baseline to establish ways of streamlining the process.

The use of the network approach implies that a series of events has a beginning and an end, or some definable cycle. In the case of Space Station, a reasonable cycle seems to be the period between Space Shuttle resupply and crew changes (i.e., approximately every three to six months). For this initial feasibility study a more deterministic approach was taken by using mean task times for major crew activities. Task areas requiring more definition are displayed as ranges (e.g., fault management). It is anticipated that more detailed task definitions and time ranges can be obtained eventually through examination of the THURIS task time-line data and

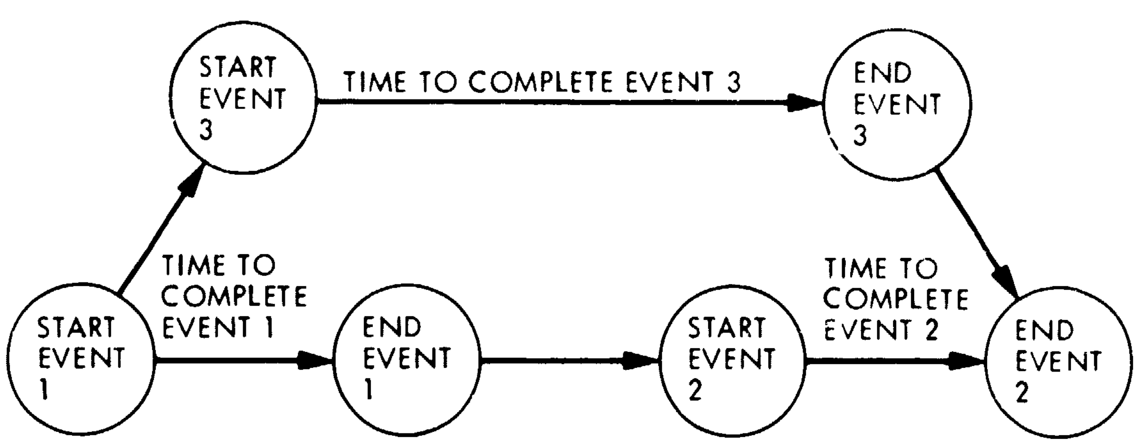


Figure 4-3. Example Network

closer scrutiny of Shuttle operational logs. The emphasis placed on this initial network study was fourfold:

(1) Identify major activities and activity sequences.

(2) Establish network structures that eventually can be programmed for critical-path analysis.

(3) Identify major man-machine tasks that represent reasonable initial candidates for automation.

(4) Use the network framework and initial candidates to help structure the rest of the man-machine trade-off model.

2. Network Analysis

Based on Skylab and Shuttle (References 4-5 and 4-6) experience, the top-level primary Space Station functions are as follows (not necessarily in order of priority):

(1) Housekeeping.

(2) Command/control.

(a) Change in station state as part of a planned mission scenario.

(b) Monitoring.

(c) Verifying/calibrating control variables.

(d) Fault investigating, adjusting, or repairing.

(3) Mission planning.

(4) Extra vehicular activity.

(5) Experimenting.

(6) Rendezvous and docking.

For purposes of this study only Functions (2) through (6) are directly associated with the power and command/control modules. Because housekeeping is basically an overhead function, it was decided to remove housekeeping from the list of functions and to establish a "mission essential" timeline in which to examine operational impacts of automation. Table 4-1 displays the approximate amount of time required for housekeeping functions, as well as the time remaining for other mission-essential functions.

Table 4-1 shows that the individual productive time available is about 10 h per mission day. Once the mission overhead was removed, the next step was to establish the in-flight schedule loading characteristics of the various resource and command/control man-machine functions. The resource

Table 4-1. Approximate On-Orbit Time Available for Command/Control Types of Functions (Hours/Person/Day)

Housekeeping Functions	Hours/Person/Day
Pre-sleep activities	0.7
Sleep	6 to 8
Post-sleep activities	0.7
Meal preparation	0.3
Meal	1.0 (3 meals/day)
Post-meal clean-up/biocide application	0.3
Waste-water dump	0.3
Supply-water dump	0.3
CO_2 absorber replacement	0.1 (about 3/day)
Fuel-cell purge	0.1 (about 2/day)
Check safety devices	0.3 (about 2/day)
Crew free time	1.0
Subtotal	13.7
Productive Time Available	24 - 13.7 = 10.3

module, which was the easiest, was investigated first. Figure 4-1 illustrates the resource module (power components/structural support) as being completely exterior to the pressurized components. Although the resource module must perform many functions, the only human interfaces that occur seem to be at initial checkout of the power components both before and after they are deployed by the Shuttle and during maintenance. Present designs suggest that the actual command and control of the power components will be accomplished from the pressurized command/control module(s). Figure 4-4 provides the high-level functional network for the resource module. A more detailed functional breakdown is shown in Appendix A. Each function (or event) for each set of nodes is labeled in the figure. The characteristic times are explained in the following paragraphs.

a. Power Module Network. Figure 4-4 shows that, after system checkout, the control of power-related subsystems is done in parallel. This is because of the interaction between subsystems. Any reboost capability, although possibly related to load management, is usually associated with maintaining earth orbit and is, therefore, not part of the power-control portion of the network. The power-conditioning function occurs after power is generated by one of the three (or all three) power subsystems. Load management and data storage (for calculating the next power state or assessing failures) occur in parallel. Once the data are received and stored, anomalies or faults can be assessed. With the exception of system checkout and fault management, all the preceding deployment, control, conditioning, and load-management functions are already largely automated in existing manned and unmanned spacecraft and, therefore, only consume seconds or minutes (i.e., the

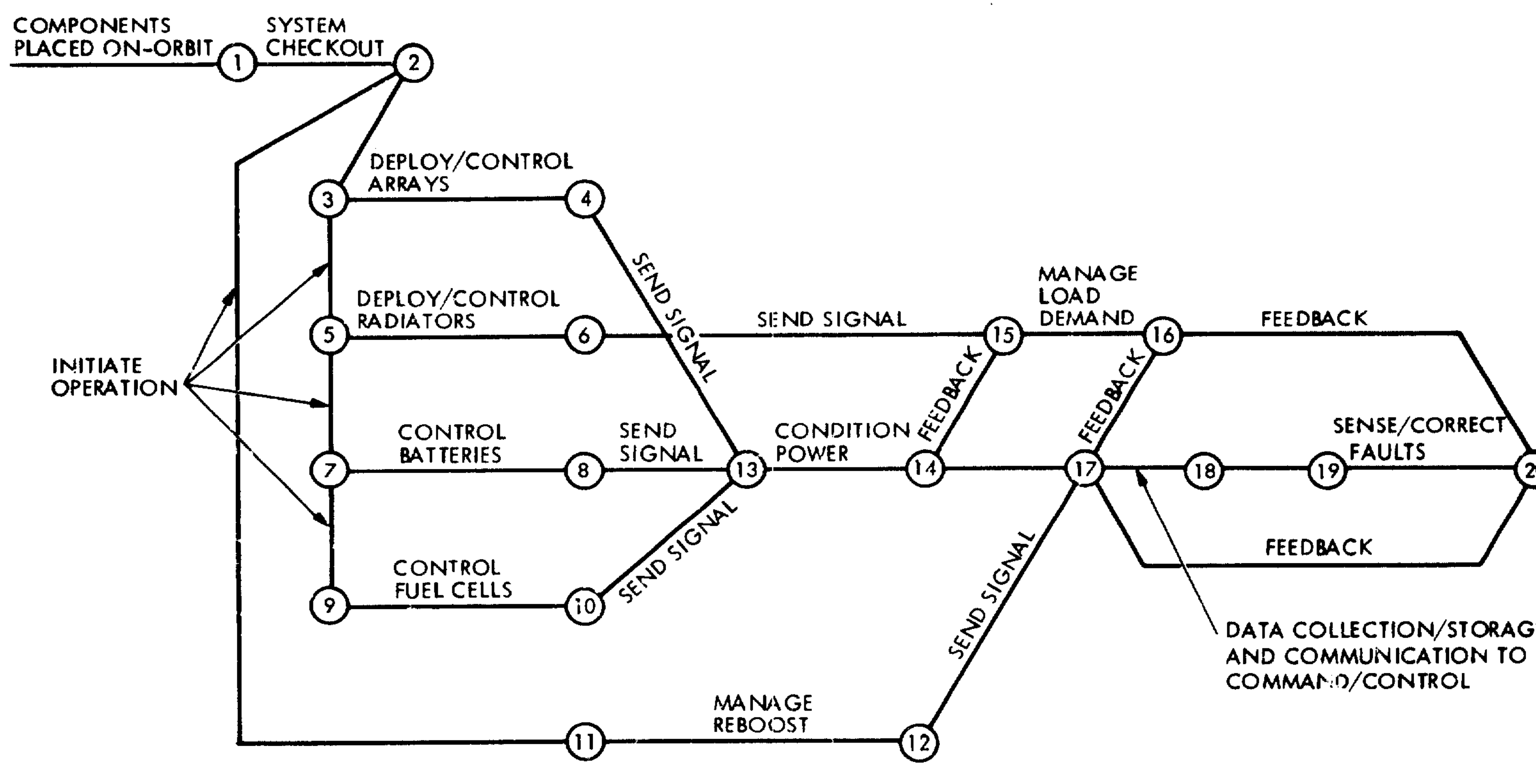


Figure 4-4. High-Level Functional Network for the Power Module

time it takes for the on-orbit or ground crews to send or receive telemetered signals and confirm function completion). The subsystem checkout function (usually a ground-crew task) consumes an average of 1 to 2 h. Fault management has a wide time range and seems to vary from minutes (for simple anomalies such as switches or fuses) to several hours per mission day (as reported for Skylab I and II). The crew involvement in fault management as extrapolated for Space Station would be done from the command/control module with EVA assistance as required (see Reference 4-5).

b. <u>Command/Control Module Network</u>. The command/control and assembly module is more complex in terms of man-machine interface. Figure 4-5 provides the high-level functional network for command/control functions with each node-to-node task labeled. A more detailed network is shown in Appendix B. The first activity, perform-mission scenario, is related to changing the state of the spacecraft as part of a planned mission (e.g., reboost, payload pointing, or satellite retrieval). The initiation of the control process is a pre-planned sequence of switch activation, only requiring a few seconds or minutes (see Reference 2-4). However, the monitoring and verification activities that are associated with command and control tasks consume much more time. Presently, the monitoring function (Nodes 3 and 4) is primarily done via ground control. Loftus, in "An Historical Review of NASA Manned Spacecraft Crew Stations," reports that about 70% of the monitoring points are automatically telemetered to ground control (Reference 4-7). The remaining 30%, or approximately 1000 data elements, are monitored by the crew on-board. Using a standard scan rate of 1 second per data element and a 12-h monitoring cycle (as confirmed by the Shuttle Operations personnel), a total time of 0.6 h per mission day results (see Reference 4-6). If the monitoring function were to be completely autonomous from the ground, existing procedures would require an additional hour per day to complete the monitoring function.

The monitoring function often requires verification of an instrument reading, recalibration of an instrument, or adjustment of a servo position. The verification/calibration function (Nodes 5 through 22) and data storage/communication (Nodes 23 and 24) are more complicated because they typically require more than one instrument reading, a comparison of data from either ground control or other instruments on-board, and, possibly, a spacecraft-control decision (Nodes 25 through 28), followed by a system command and follow-up verification. Both Skylab and Shuttle operational histories suggest that verification/calibration functions require about 0.3 crew hours per function per day. Table 4-2 provides both an extrapolated baseline list and time estimations of Space Station verification/calibration and data-management types of tasks, based on present task experience and as superimposed on the Space Station reference configuration. Again, the parallel nature of the activities shown in Figure 4-5 is a result of subsystem functional interactions.

The one area of special interest in Table 4-2 is the experiment calibration function, item (10). This function was included as a command/control function primarily because both Skylab and Shuttle are designed so that the experiments are calibrated from the command/control center and then actually initiated and performed in the lab module. The amount of time required to verify and calibrate experiments depends upon the

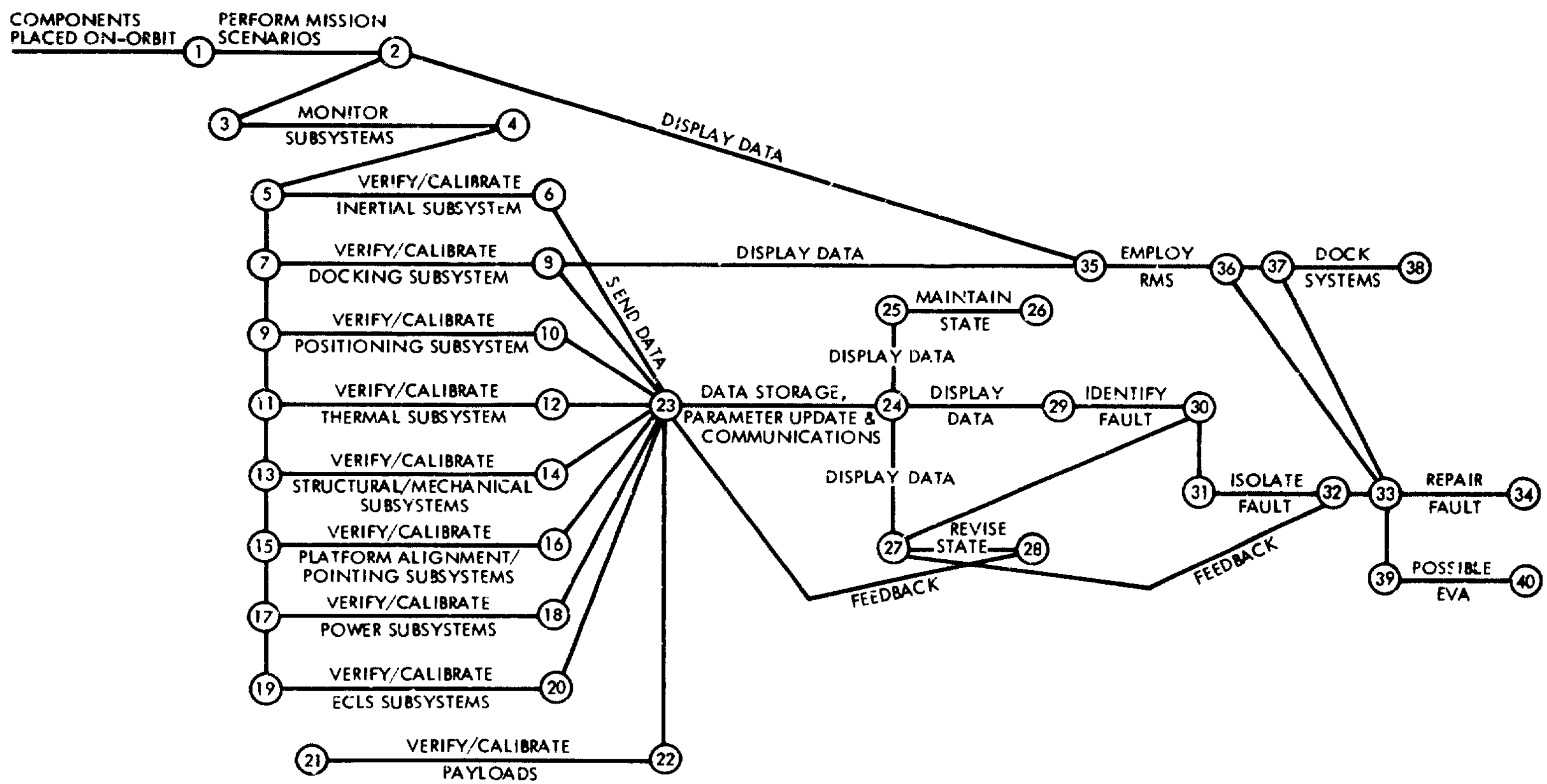


Figure 4-5. High-Level Functional Network for Command/Control Module

Table 4-2. Potential Space Station Verification/Calibration Functions

Functions/Tasks	Descriptions	Approximate Time, Crew h/day
(1) Plan mission	Planning and adjusting mission scenarics	0.5
(2) Verify/calibrate inertial unit	Navigation attitude control (specifically for traffic control)	0.3 (twice/day)
(3) Verify/calibrate docking system	Docking attitude, speed, and alignment (specifically for traffic control)	0.3
(4) Verify/calibrate accelerometers at structural extremities, and GN&C (e.g., global positioning system, GPS)	Confirmation of acceptable impulse vibration levels for structural/experiment loading; guidance navigation and orbital reboost accuracy confirmation	0.3
(5) Verify/calibrate thermal control systems	Confirmation of temperature readings in pressurized areas, as well as at structural extremities where experiments are located; includes adjustment of temperature control systems	0.3
(6) Verify/calibrate structural and mechanical loads	Determination of relative movement of Space Station structural end-points due to thermal and inertial loading (specifically applies to fine adjustments on experiments and includes joint loading, fluid coupling, drive loading, etc.)	0.3
(7) Verify/calibrate station, experiment, and platform pointing or relative alignments	Refers to maintenance of communication links, proper pointing of station/experiment instruments toward targets; also applies to adjustments of experiment or platform geometry to protect experiment from thermal damage and provide for maintenance access	0.3
(8) Verify/calibrate power subsystems	Confirmation of load demands and proper power distribution, fuel-tank crossover management (essentially an instrument scan/comparison accompanied by switching as necessary)	0.1
(9) Verify/calibrate ECLS subsystems	Confirmation of habitat parameters (contamination control and management of loads caused by crew movement/rotation)	0.1
(10) Verify/calibrate experiment instrumentation	Refers to actual instrument adjustment process based on feedback from internal-external station variables which customer has not taken into account when calibrating instrument on ground (total time varies as function of number of experiments)	0.6 (IOC station configuration will have approximately same number of experiments as Skylab)
(11) Verify/calibrate test instrumentation on-board	Refers to maintenance of instrument accuracy for those instruments used for test and verification of other on-board measurement devices	No value (function test could be done on ground with test/change-out of verification instruments at the 90-day Shuttle rendezvous interval)
(12) Parameter updates and data storage in preparation for next verification/calibration exercise	Refers to updating the baselines of various operational parameters for use in next calibration activity (primarily a keying-in/data manipulation activity)	0.1
	TOTAL APPROXIMATE DAILY TIME	3.3 (4)

number of experiments being conducted, the schedule or sequence for conducting them, and the duration of the data-taking envelope. Although the average time required for experiment verification or calibration on Skylab was about 0.6 h per day, the experiment schedule on Space Station may eventually be more intensive than either Skylab or Shuttle. Consequently, the 0.6-h figure shown in Table 4-2 may be conservative. Another area of interest related to the payloads is the pointing and alignment function. Technical data received from the Tracking Design Team during the July 1984 JSC Space Station Requirements effort indicated concern over a demanding requirement to coordinate and simultaneously point five of the planned experiments. Finally, the crew will have to manage carrier frequency, signal fluctuation, and data-error anomalies in the process of maintaining communication links with ground operations.

Verification/calibration types of functions may require that a command and control decision be made, followed by a change in state (Nodes 25 through 28) of a given subsystem or the station as a whole (e.g., change in station attitude to allow for platform accommodation). As stated earlier, the command/control function initiated by the station or ground crew is usually a semi-automated function requiring minimal crew interface (i.e., initiation of control sequences by switch activation). Therefore, it seems that the major tax on the crew lies with (1) planning, monitoring, and verifying functions that provide the inputs used in making command/control decisions and (2) making the proper decisions, followed by the appropriate follow-up control sequence.

Figure 4-5 shows that sometimes a command/control decision may require more than a slight change in state of a subsystem. System anomalies and failures both require troubleshooting and decision making concerning corrective actions (Nodes 29 through 34). Both Skylab and Shuttle operational logs indicate that the resolution interval can vary from 5 minutes to hours, and in some cases days [for example, in the Skylab Control Moment Gyro (CMG) problem]. In some cases a failure is never resolved, thereby potentially having a major impact on mission completion. The erratic behavior of the Skylab CMGs is an excellent example of an unresolved failure that had a major impact on the crew productive time and safety. Table 4-3 displays the major system problems encountered on Skylab, along with relative frequencies. Overall, Skylab experienced a system anomaly or failure on the average of once every two mission days.

The anomalies or failures that fell in the 5- to 10-min repair category were film/camera repairs, unjamming/sealing doors, and tape recorder repairs. The difficult problems, moving the troubleshooting and repair times out to the high end of the time spectrum, were the control moment gyros, coolant-system leaks, and experiment problems. Oddly enough, control-panel light failures could also fall into the high end of the repair-time spectrum because it is often difficult to assess whether or not the actual failure is as simple as a non-functioning light or a more serious downstream problem.

Analysis of all Space Shuttle failures has not been completed to date. Therefore, only summary information is provided in this report. Table 4-4 displays the total number of in-flight anomalies or failures for 13 of the Shuttle missions as a function of a major subsystem.

Table 4-3. Major Skylab System Anomalies/Failures

Anomaly/Failure	Frequency (Failure/ Number of Mission Days)
Film processing/camera failures	1/12
Control moment gyros	1/13
Door failures (jammed, will not seal, etc.)	1/17
Tape recorder/DAC failures	1/22
Leaks in coolant/condensate systems	1/22
Leaks in Apollo telescope coolant loop/power interrupt	1/35
Control panel lights not registering malfunction/ component status	1/35
Experimental equipment failures	1/35

Overall, the more recent missions have experienced a major reduction in failures (i.e., a reduction from an average of six anomalies, or failures per mission day, to four). The Shuttle Quality Assurance Office reported that over 13 flights, literally all avionics and instruments have failed at one time or another; major structural/mechanical failures have impacted thermal protection, brakes, and landing gear; software problems have usually involved initiation format errors caused by not reformating all other linked programs when a reprogramming change was incorporated; electromechnical failures have involved television cameras, recorders, printers, actuators, and door mechanisms; fluid problems have included leaks in coolant system as well as valve, pump, and fuel-cell failures; finally, electrical problems have primarily encompassed heaters, thermostats, wiring, circuit breakers, and switches.

Besides troubleshooting and repair activities associated with the station itself, the on-board and external experiments will also require periodic servicing. As shown in Table 4-3, Skylab experienced a small number of "unscheduled" experiment problems. As a start toward identifying the minimum experiment servicing requirements, Appendix C provides the "planned" maintenance intervals for several of the experiments. The major concern here is the potential frequency at which EVA may have to be used to service the external station experiments and the platforms.

As indicated in the functional analysis of the resource (power) module, the high frequency of anomalies/failures plus the substantial amount of time required to deal with an anomaly suggest that troubleshooting and maintenance

Table 4-4. Major Shuttle Anomalies/Failures

Major Subsystems	Total Number of Failures	Frequency (Failures/ Mission Day)
Instruments	105	2
Avionics	78	1
Fluids	72	1
Structural/mechanical	69	1
Electromechanical	42	1
Electrical	38	0.4
Software	9	0.1

are critical functions. It is for this reason that Figure 4-5 (Nodes 35, 36, and 33) includes the use of a Remote Manipulator System (RMS) to facilitate external repairs as an alternative or assist to EVA.

For purposes of assessing crew productivity impacts due to component failures, the failure history provided in the preceding tables should be divided into two components: (1) detailed component-failure frequencies and (2) time required to resolve each type of failure. The product of these two variables yields "repair hours/mission cycle." In terms of the methodology, it is anticipated that this product can be obtained for various classes or groups of components, (e.g., batteries, fuel cells, solar arrays, etc.) so that, when assessing automated fault management, the crew productivity savings (in hours) can easily be established. This effort is addressed under recommendations in Section VIII.

The last command/control function, docking (Nodes 37 and 38 in Figure 4-5), is delineated in Appendix B. The basic Skylab or Shuttle sequence is shown in Table 4-5.

It should be noted that Skylab docking experience indicated that about twice the amount of time (8 to 10 h) was required for the complete docking process. However, the Shuttle Operations group has suggested using the more up-to-date data shown in Table 4-5 because improvements in technology and crew training (especially through advancements in simulators) has greatly speeded up the docking process. The key aspect of the docking process concerning the productivity envelope is the fact that during docking maneuvers at least two individuals are usually monitoring and performing command/control functions for the full 4 to 7 hours. Although not a productivity problem under present Shuttle operations, the planned biweekly or weekly Shuttle and orbital maneuvering/orbital transport rendezvous and dockings could consume a sizable amount of time using present procedures (Reference 4-8).

Table 4-5. Top-Level Docking Functions

Functions	Approximate Time, h
Rendezvous, maneuvering for course alignment, and visual location	4 to 6
Proximity maneuvering and closing of proximity gap	0.5
Fine alignment and hard docking	0.1
Total Time	4.6 to 6.6

In closing this aspect of the network analysis, three caveats need to be clearly stated. First, the preceding discussion concentrates primarily on orbital operations and activities; however, ground-crew control, monitoring, verification, and fault-management activities are basically duplications of the orbital operations. Obviously, productivity time is not a key factor for similar ground-functional networks because the ground crew is not directly interfacing with the payloads and is not time-limited. More appropriately, the key functional network drivers revolve around efficiency (to minimize on-orbit delays while the ground crew performs a control function), and conservation of ground support such as facilities and manpower. Second, although feasible, it is not the intention of this methodology to address reductions in Space Station crew size at this time. The assumption made in this study is that the crew size will remain constant (between 5 to 7), with increases in productivity adding to on-orbit experiment time.

Finally, there is a granularity problem in the task-time data. For example, Table 4-2 displays a verification or calibration time of 0.3 h for the power module. However, Figure 4-4 shows the power module being composed of several primary subsystems, such as solar arrays, batteries, fuel cells, and power conditioning. Therefore, for this initial study, it is assumed that the verification activity is equally distributed among all subsystems. This is not considered a major problem at this time because the Space Station program is currently at a conceptual design stage. Therefore, small errors in task-time allocation are overshadowed by the fact that present cost estimates for hardware and software are only approximations. This assumption enables the remaining steps in the methodology to be developed. It is anticipated that the networks can eventually be expanded to a more granular level by drawing on detailed Shuttle operational logs and actual astronaut and ground-crew experience.

D. SELECTION OF AUTOMATION CANDIDATES

The network analysis (Section IV-C) identifies key crew functions and provides approximate task times for those functions. The last step in the network analysis is to identify prime automation candidates. This was done by establishing some subjective selection criteria, based on established human engineering criteria, with guidance from the Shuttle astronauts via the JSC Shuttle Operations Group.

Accepted human engineering standards suggest that the following criteria (equally weighted) be used for determining when to automate functions (References 4-9 and 4-10).

Automate:

(1) To avoid perceptual saturation.

(2) To reduce concurrent tasks.

(3) Tasks on compressed time lines.

(4) To avoid human bandwidth limitations.

(5) Routine tasks.

(6) Memorization tasks.

(7) Sequential and time tasks.

(8) Monitoring tasks.

(9) Time-consuming, boring, or unmotivating tasks.

(10) Emergency-prevention devices.

(11) Complex mathematical or logic tasks.

(12) Complex tasks that must be performed rapidly.

(13) To enhance system reliability.

(14) Safety endangering tasks.

(15) Systems with consideration to crew acceptance.

However, these criteria are only a point of departure. Crew acceptance is extremely important, as will become apparent in the following discussion.

Beginning with the power module, the network analysis indicated subsystem checkout and fault repair as major man-machine interfaces. Consideration is given to the fault-repair function first. Shuttle and Skylab failure histories indicate that power anomalies/failures occur about one every 2 and 17 mission days, respectively. Even though anomalies may not result in actual component failures, they still require frequent monitoring and troubleshooting, which detracts from the valuable 10-h customer productivity envelope. Therefore, maintenance is a critical function. Shuttle and Skylab operation logs report a rather wide variation in the time consumed in correcting anomalies and failures. Repair times vary from 5 minutes to hours.

EVA has been suggested as the alternative for maintenance of power components external to the pressurized modules. Although state-of-the-art, the EVA function is extremely time-consuming (i.e., 3 to 4 hours is usually required for pre-preparation planning activities, donning and checking out the equipment, and de-preparation activities). Additionally, EVA does have several hazards associated with it (e.g., variable pressure environments, potential suit punctures, or uncontrolled decoupling from the spacecraft). Out of the above list of criteria, items (3), (9), (11), and (14) apply directly. Item (3) applies because EVA is a time-limited activity. Item (11) is germane because troubleshooting anomalies or faults can be a complex process of elimination. Item (9) applies because EVA is time-consuming; item (14) applies because of the hazards associated with EVA. The key thrust here is that the EVA function is not eliminated, but reduced in frequency. Therefore, it seems that fault management is a good automation candidate. As a bonus, if fault management were automated, then it seems that the subsystem checkout function might be simplified for either on-orbit or ground crews.

Similarly, the mission monitoring, verification, fault-management, and docking activities controlled from the command/control modules can be evaluated. Table 4-2 suggests that both monitoring and verification/calibration types of functions could consume about 40% to 50% of the 10-h available productive time. Information received from the Shuttle Operations Planning Group suggests that (with the exception of experiments) monitoring, verifying, and calibrating types of functions are considered repetitive and time-consuming by the crew and, therefore, good candidates for automation. Additionally, verification tasks can run in parallel (see Figure 4-5) and so pose a sizable amount of information sorting and assimilation problems. Automation of both monitoring and verification/calibration tasks would be in accord with items (1), (2), (4), (5), (6), (7), (8), (9), and (11) and, in addition, have strong crew support. In the case of experiments, the sheer quantity may make the verification and calibration functions unmanageable without the help of automated monitoring and calibration devices. However, care will have to be taken when assessing automation concepts for this area for the following reasons:

(1) The potentially large number of nonroutine tasks may make the function difficult and costly to automate.

(2) There may be potential interface problems associated with having to monitor, collect, and compare a vast array of different experimental variables and data formats.

(3) There could be a constantly changing variety of experiments.

Automation of the fault-management tasks for the command/control module follows the same logic related to the power module. The mission-planning and rendezvous (or maneuvering) docking tasks had interesting outcomes when measured against the automation criteria. Mission-planning and maneuver-initiation tasks are at opposite ends of the time spectrum. Mission planning requires much more time than activating a switch for a reboost maneuvering command. The planning task requires consideration of many different control variables, trade-offs, and time windows. Items (1), (2), (3), (4), and (11) plus crew support make this task a reasonable candidate for automation.

Similarly, although the time required to initiate a maneuver is small, consideration of numerous control variables and time windows makes planning and maneuvering similar. Nevertheless, the astronauts voiced concern over giving up manual control. Tasks, such as reboost or maneuvering for thermal control, are considered too critical for the crew to relinquish. Clearly, this is an area that requires further definition. Discussions with the Shuttle Operations Group indicate that the final fine alignment and vehicle docking sequence are the two functions the crew specifically wishes to control. The several hours of rendezvous monitoring fit nicely under items (5), (6), (7), (8), and (9) of the automation criteria.

In summary, monitoring, verification/calibration, fault isolation/management, EVA, mission planning, rendezvous, and limited aspects of station-state changes are strong automation candidates. It is recognized that varying degrees of decision making, man-machine interface, and perceptual interpretation are required for the same tasks in different Space Station modules. However, at a subsystem level, there is consistency among tasks because all modules require the same basic subsystems. The network analysis is performed at a sufficient level of detail so that each of the automation candidates can be associated with the various Space Station subsystems identified. As an overview, Table 4-6 relates each selected automation function with its applicable subsystem within the overall system hierarchy, shown in Figure 4-3. This table (Table 4-6) provides a map showing which functions appear reasonable to automate within each subsystem. For example, automation of potential EVA activities (such as module changeout or in-place maintenance) is attached to the power, propulsion, thermal (radiators), structures, and external payloads because these subsystems are largely external to the pressurized areas of the station. Similarly, automation of the mission-planning function is associated primarily with the communication/tracking, data handling, crew systems, and payload (i.e., sequencing and initiating experiments) subsystems.

Table 4-6. Automation Candidates for Major Space Station Subsystems

Space Station Subsystems / Automation Candidates	Monitoring	Verification Calibration	Fault Isolation/ Management	Extra Vehicular Activity	Mission Planning	Rendezvous/ Dock	Subsystem State Change
Power	X	X	X	X			X
Guidance/ Navigation/ Control	X	X	X			X	X
Communication/ Tracking	X	X	X		X	X	X
Data Handling	X	X	X		X	X	X
Propulsion	X	X	X	X		X	X
Environmental Control Life Support	X	X	X				X
Thermal	X	X	X	X			X
Structures/ Mechanisms	X	X	X	X			X
Crew Systems		X	X		X		X
Payloads	X	X	X	X	X	X	X

SECTION V

AUTOMATION CONCEPTUAL DESIGN DEVELOPMENT

A. OVERVIEW

Section IV demonstrates how functions and tasks are assembled into networks that (along with task times, a reference configuration, and sound selection criteria) allow a determination of prime automation candidates. Once the candidate functions have been identified, the next step is to establish conceptual automation designs for each candidate that provide insight into the potential costs of automation. Section V describes the conceptual design approach used, along with the associated costing techniques. Additionally, the array-limiting technique for establishing an efficient set of man-machine alternatives is described. Examples of the design, cost, and efficient set principles are provided where data were available.

B. HIERARCHICAL DESIGN APPROACH

The hierarchical design approach is defined in Section I and graphically depicted in Figure 4-2. This avenue was selected because (1) proper automated system design is hierarchical in nature, providing an understanding of subsystem decoupling and dependencies (see Reference 2-1) and (2) automation candidates and related conceptual designs can be conveniently merged for purposes of modeling the complete system. In developing automation design concepts, it is extremely important first to establish the basic functional architecture. Next, functions are mapped into an implementation architecture. Finally, functions are distributed to resources at different levels. Resources include components, such as processors, actuators, sensors, end-effectors, or thrusters. When identifying and distributing functions, it is extremely important to understand where concurrent processes are taking place. Functional networking early in the design process (as demonstrated in Section IV) coupled with design experience helps to highlight the interdependent, or concurrent, processes. The last element, experience, is where the use of a conceptual design team comes into play. This is a pivotal consideration because of the system-level impacts of interdependent functions (see Reference 2-1). Besides mapping the concurrent processes, it is also important to establish intercommunication links, possible closed-loop processes (e.g., at the dedicated microprocessor level), software requirements (e.g., simple versus complex), and fault management. It should be noted that, for ease of costing and cost-benefit assessment, it is usually more beneficial to establish a conceptual design for maximum automation first. This approach facilitates segregation of the various functions to determine how the design could be simplified if certain functions were allocated to the crew. Experience with the storage battery and rendezvous/docking examples used for this study suggest that the difference between functional allocations to the crew and machines revolves primarily around software complexity (References 5-1 and 5-2). Figure 5-1 shows a sample hierarchical allocation of functions within the power module and demonstrates how functions are associated with their hardware counterparts.

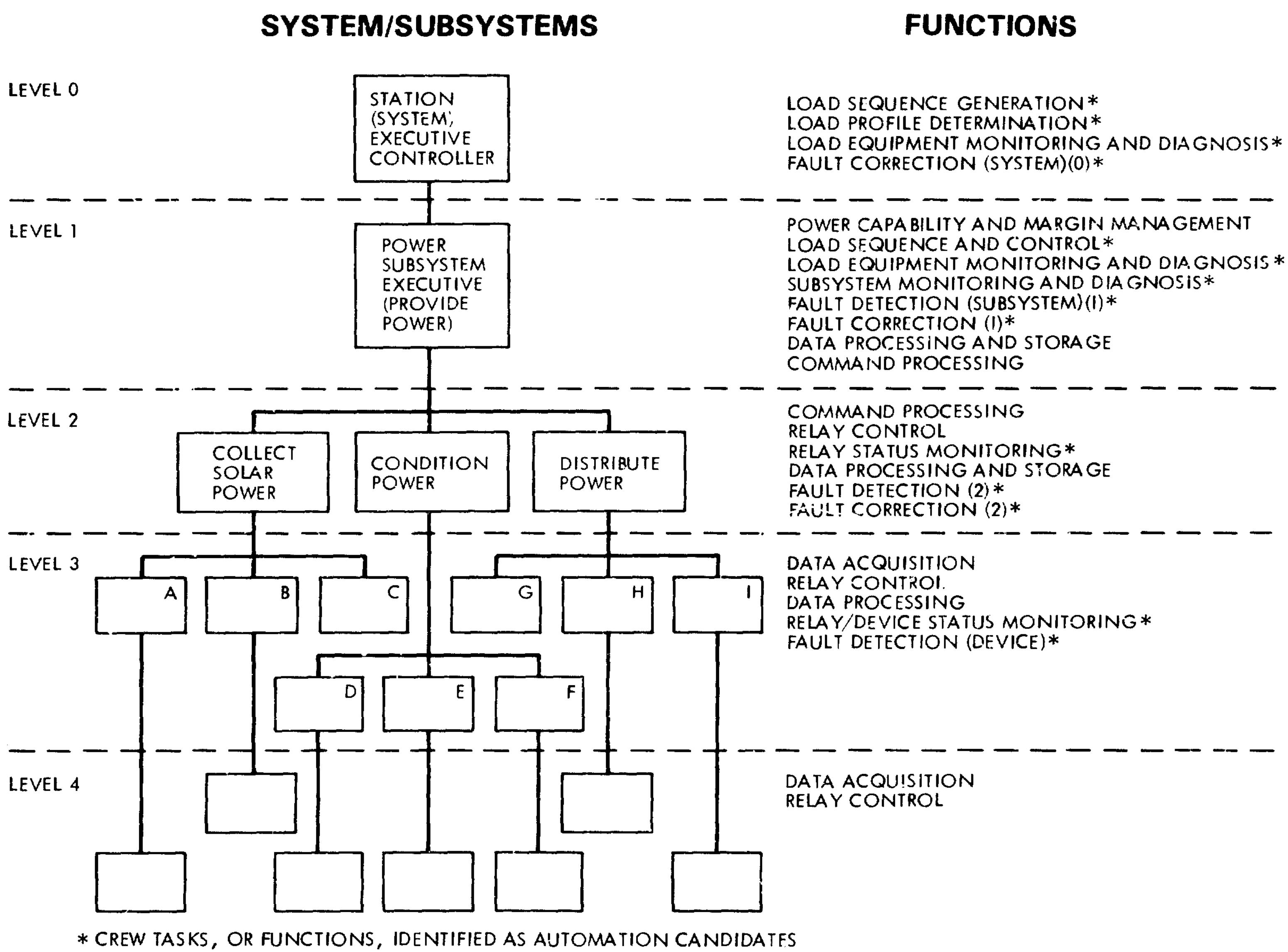


Figure 5-1. Sample Hierarchical Allocation of Power Functions

For modeling Space Station automation impacts, the functions are developed first, followed by the hardware/software concept. It is for this reason that the hierarchical modeling network introduced earlier in Section IV (see Figure 4-2) was designed to be equivalent to the spacecraft automation design framework shown in Figure 5-1. This equivalence allows a rapid transfer of functions to hardware components, followed by translation into costs and trade-offs. Figure 5-2 graphically depicts the similarities between the modeling and design frameworks.

It is important to understand that, although the methodology conceptually attaches man-machine functions to the subsystem level, this does not imply that the subsystem level is the only place where functions such as monitoring, verification, or fault management are performed. Indeed, the same functions can be applied to Levels 2 and above. The methodology was so designed because it is at this level of granularity where (1) actual historical task-time data are available and (2) the various data elements related to tasks, such as monitoring or fault isolation, are collected and displayed to the station or ground crews. Consequently, it is easier to understand the detailed functions and associated blocks of time required to perform various tasks. This understanding clarifies the design complexity needed to automate and prioritize the same tasks (see Table 4-2). For conceptual design purposes, a good idea of the required hardware and software can usually be obtained at Level 3.

In terms of the basic tasks addressed in the preceding paragraph, the complexity and subsequent perceptual overload usually increases as Level 0 is approached. For example, assume that an anomaly or failure has occurred within the solar arrays (the primary power source) and that the backup storage batteries and fuel cells are being depleted. To manage the thermal and power loads until the anomaly can be resolved, the spacecraft may have to draw on its reboost, guidance, navigation, and control subsystems to reorient the spacecraft to a safe configuration to minimize the drain on the backup power sources. This maneuver would be a system-level function (probably exercised from the command/control module) because of the interdependency of the various subsystems. The basic monitoring and verification functions would remain the same, but the fault-management function would then reflect a much greater station or ground-crew involvement (the time required to manage the fault would increase greatly). From a conceptual design and cost viewpoint, the problem would become a matter of deciding where to place (or distribute) the control for the system-level fault management. If the cost (or risk) of automating this specific problem is considered too high, then a hybrid combination of automation and crew involvement might achieve the same end (e.g., the system might continue to do the monitoring, verification, and load management at the power subsystem level, with the crew performing the maneuvering, major fault management, and power shedding at the system level until a safe state is reached). This hybrid combination would represent one man-machine alternative for solving the control problem.

As stated earlier, a Level 3 conceptual design is usually sufficient to establish order-of-magnitude cost for automation hardware and software. As an example, Figure 5-3 shows a conceptual design for automating the monitoring, verification, and fault-management functions associated with the storage battery subsystem on Space Station (see Reference 5-1).

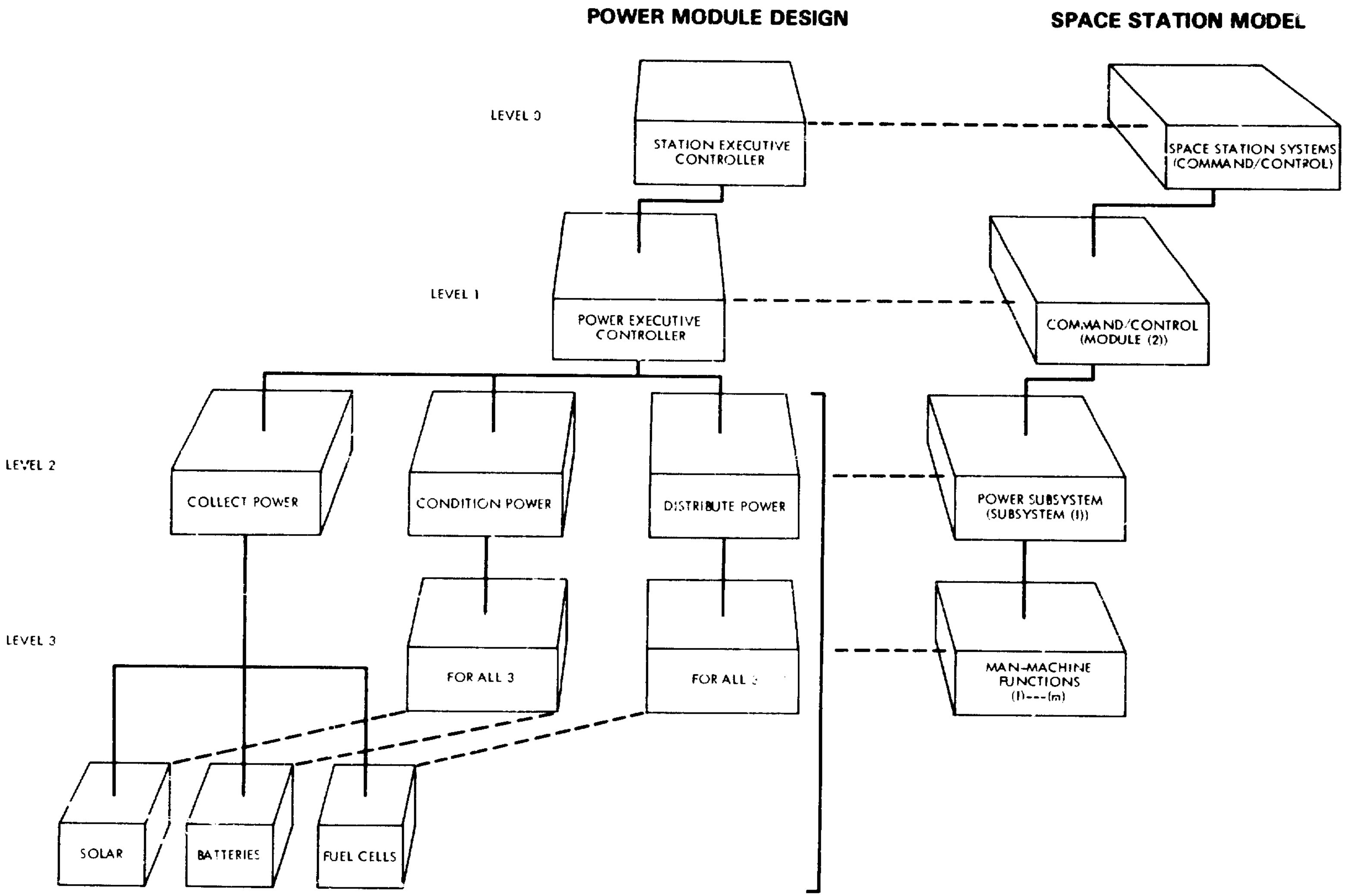
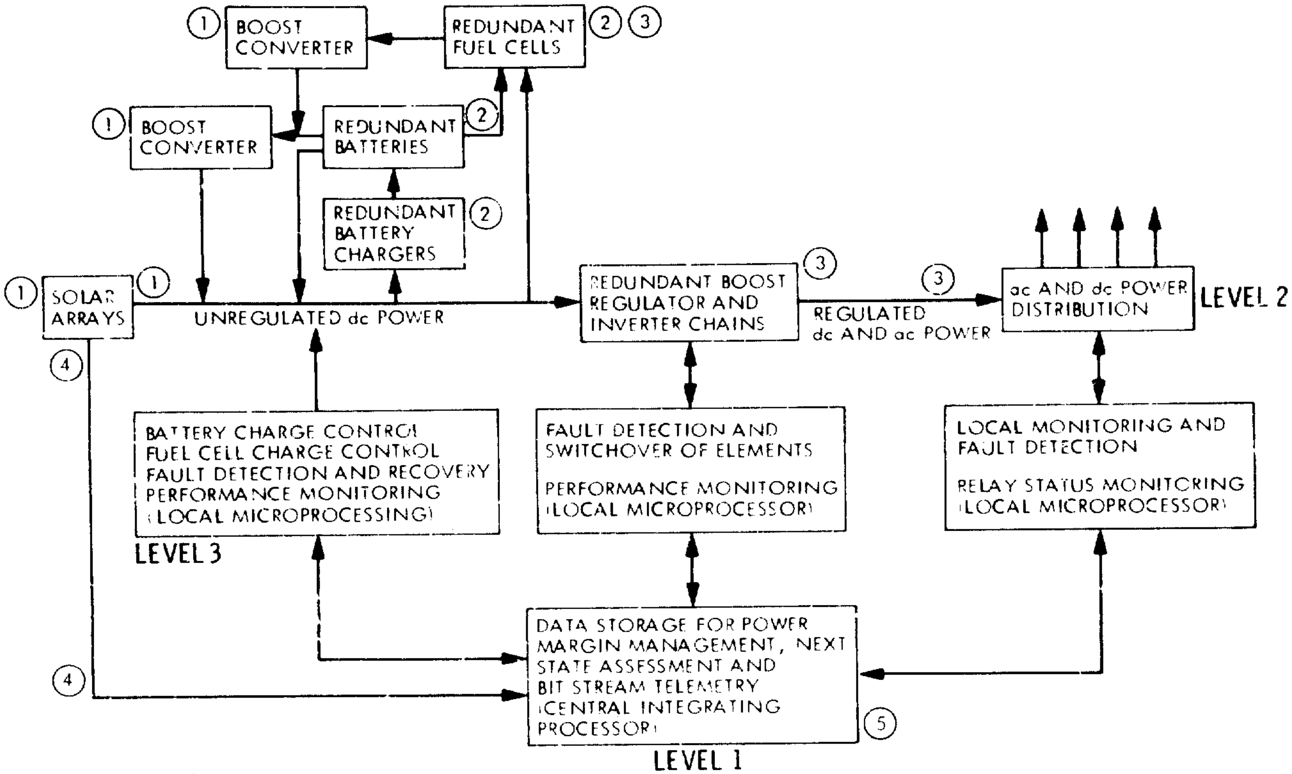


Figure 5-2. Equivalence Between Modeling Network and Design Hierarchy



LEGEND:

(1) POWER LEVEL SENSORS
VOLTAGE CURRENT SENSORS

(2) POWER LEVEL SENSORS
CHARGING RATE SENSORS
TEMPERATURE SENSORS
FLUID LEVEL SENSORS
SWITCHING SENSORS
RECONDITIONING SENSORS

(3) SIGNAL AND SIGNAL SORTING SENSORS
SWITCHING SENSORS
POWER LEVEL SENSORS
RELAY SENSORS

(4) POWER ON-LINE OFF-LINE FOR SOLAR ARRAYS
POWER SWITCHING

(5) DYNAMIC THERMAL LOAD DATA
TIMING CONTROL FOR COLLECTING SAMPLING DATA
DYNAMIC POWER LOAD REQUIREMENTS DATA
POWER ON-LINE OFF-LINE FOR BATTERIES FUEL CELLS
DATA COLLECTION SAMPLING POINTS
DATA COMMUNICATION TO CONTROL CENTERS
FAULT MANAGEMENT DECISION MATRIX

Figure 5-3. Space Station Automated Battery Subsystem from Automated Power System Management (APSM) in Reference 5-1

Figure 5-3 illustrates the distributed microprocessor configuration to implement the battery monitoring, verification, and fault-management functions. Starting on the left of the figure, the first microprocessor monitors and controls the power-source components [solar arrays, batteries, fuel cell, battery chargers (reconditioning) and boost converters]; the middle microprocessor monitors and controls the power conditioning (boost regulators, signal inverters/converters); and the far right microprocessor monitors and controls the power distribution. The central integrating processor manages the power margin, subsystem-level computations/fault-management decisions, and data communication to the command/control centers. The local (or dedicated) microprocessors must have sufficient storage capacity to manage simple anomalies (e.g., switching) and allow the integrating processor to tap their data banks and assess potential problems. Although the integrating processor is shown here with the battery subsystem, it will integrate data for the other power components, and so its cost will be shared among other power subsystems. The total software, because it is shown encompassing other power elements, will probably not exceed the battery management package by much. The use of one integrating processor for all three power subsystems underlines the point made earlier in this report concerning the importance of the conceptual-design step in identifying economies of scale. As shown in Figure 5-3, the solar arrays, batteries, and fuel cells represent the Level 2 functions; the dedicated (or local) microprocessors perform the Level 3 functions; and the central integrating processor supports the Level 1 functions. The basic sensor and control data for each level are also listed.

The automated rendezvous and docking concept, which is the other automation test case referred to in Section IV-C, has just started and is presently in the functional allocation stage. The results of this first research stage are shown in Appendix D (JPL IOM from J. Matijevic, "Automation of the Rendezvous and Docking Functions," August 1984).

In the following paragraphs, the battery example is pursued to demonstrate how such a system is costed at the conceptual-design stage.

C. IDENTIFICATION AND COSTING OF AUTOMATION CONCEPTS

As stated in Section III, the conceptual design effort provides estimates of:

(1) The number of dedicated microprocessors and integrating networks.

(2) Dedicated and integrating communication links.

(3) Required software.

(4) Potential software complexity.

(5) The number and types of additional sensors, backup microprocessors, etc., needed for fault management.

Each of the battery automation components was described in the preceding subsections. As a departure point for the costing discussion, the primary components of the automated battery design are listed in Table 5-1 in terms of the preceding five estimates.

Table 5-1. Battery Automation Components

Component	Number Required
Dedicated microprocessors	3
Integrating processors	1
Dedicated communication links	10
Simple software programs	3
Complex software programs	1
Additional sensors	None

Contemporary dedicated microprocessor technology is capable of handling the power monitoring and switching for a large number of batteries (Reference 5-3). Furthermore, because the concept was breadboarded and tested, the complexity of the software was calibrated. In the case of the dedicated microprocessors, the software was considered standard and, therefore, was not considered a new software requirement (see Reference 5-1). The integrating software was more complicated but was still considered well within the state of the art of on-board computational capability. The dedicated communication links are primarily between the microprocessors and power components and between microprocessors. The power sensor configurations on present spacecraft would suffice for supporting the microprocessor hierarchy; therefore, no additional sensor data are required. One interesting aspect of Table 5-1 is that the additional components required to automate the battery functions conform closely with the observation made by Turner (see Reference 5-2): Given that present spacecraft designs already require the sensor, actuator, and system-level communication framework to be in place for the crew, the basic additional components for automation are processors and software.

Once a reasonable conceptual design is in place, the costing process can commence. The standard approach to life-cycle cost may be used to estimate the present value cost of automation (References 5-4 and 5-5). It should be noted that the following equation represents incremental costs because only select automated crew functions are examined within each subsystem and module.

$$\sum_{i=1}^{n} C_{IC_i} = \sum_{i=1}^{n} C_{I_i} + \sum_{i=1}^{n} C_{OS_i} \qquad (5\text{-}1)$$

where

C_{LC} = incremental life-cycle cost associated with automating subsystem, i, for a given man-machine alternative

C_I = initial incremental cost associated with automating subsystem, i

C_{OS} = incremental operations and support (recurring) costs associated with automating subsystem, i

C_I can further be divided into the following incremental cost components:

$$C_I = C_{RDP} + C_{TR} + C_{MP} + C_{LSTE} + C_S + C_{TD} + C_F \tag{5-2}$$

where, for a given man-machine alternative for subsystem, i,

C_{RDP} = cost of R&D and production; this cost includes the hardware, software, communication, and additional sensor elements

C_{TR} = cost of on-orbit and ground-crew training if subsystem functions not completely automated

C_{MP} = cost of on-orbit and ground manpower; on-orbit workforce costs are reduced by the value of crew hours saved, and ground workforce is composed of system-maintenance/support for test and mission-control personnel

C_{LSTE} = cost of launch support and test equipment (launch support refers to consideration of launch weight constraints, and test equipment refers to special test, verification, calibration or tooling hardware)

C_S = cost of initial and follow-on spares

C_{TD} = cost of supporting technical documentation for training or maintenance

C_F = cost of facilities, such as building space, computers, and ground-crew displays

and

$$C_{OS} = C_{MP} + C_{TR} + C_{STE} + C_S + C_{TD} + C_M \tag{5-3}$$

where, for a given man-machine alternative for subsystem, i,

C_{MP} = cost of on-orbit and ground manpower; on-orbit workforce costs are reduced by the value of crew hours saved, and ground workforce is composed of system-maintenance and mission-control personnel

C_{TR} = cost of on-orbit and ground-crew training if subsystem functions not completely automated

C_{STE} = cost of support and test equipment, exclusive of C_{LSTE}

C_S = cost of initial and follow-on spares

C_{TD} = cost of supporting technical documentation for training or maintenance

C_M = cost of maintenance (primarily the recurring retrofit and ground maintenance costs associated with the repair of failed components and associated software)

At this stage of the research, it sufficed merely to identify the various IOC and operations and support cost elements and mathematically define the incremental nature of each element with respect to the overall structure of the cost-benefit methodology. Specific attention was given to the R&D and production-cost variable because early results from the battery and rendezvous/docking examples suggest software could be a major cost driver. Additionally, there seems to be a wide variation in opinion about how software can be costed. For the baseline conceptual design, the processor hardware costs are rather straightforward, with data obtainable from the computer industry. Volume 3 of ARAMIS will be helpful in identifying and costing automation technology components. Cost-bridging estimates (covering R&D to production) will be obtained from the private-sector data. Estimations of software costs require a sub-model within the life-cycle cost variable, C_{RDP}. A point of departure for developing this sub-model is the embedded COCOMO software model (Reference 5-6). The COCOMO model seems appropriate for this application because it is based on a substantial empirical database and provides development costs and schedules relevant to complex, tightly regulated systems that pose substantial safety hazards (e.g., nuclear reactors). Furthermore, because the overall Space Station program has just been initiated, data rates and quantities can only be described credibly as large or small, simple or complex. The COCOMO structure provides a means of converting subjective software requirements into preliminary cost estimates. For example, in the case of the battery example, the dedicated microprocessors and integrating processor would be respectively rated as small to medium (2-32KDSI) and large to very large (128-500KDSI). The term "KDSI" refers to thousands of lines of Delivered Source Instructions. Using "embedded" equations, Boehm (see Reference 5-6) developed the following estimate of the cost in workmonths, called manmonths (MM) in Boehm's equations, required to write the software:

Dedicated microprocessors (reasonably simple software): $MM = 3.6\ (KDSI)^{1.2}$ (5-4)

Integrating microprocessor (complex software): $MM = 5.4\ (KDSI)^{1.2}$ (5-5)

For the battery example the preceding equations and associated data quantities (32K for the dedicated processors and a mid-point value of 200K for the integrating processors) yield the following results for initial software cost:

$$MM = 3.6\ (32K)^{1.2} = 230.4\ (19\ \text{manyears})$$

$$MM = 5.4\ (200K)^{1.2} = 2160\ (180\ \text{manyears})$$

$$\text{Total manyears} = 3(19) + 180 = 237\ \text{manyears}$$

The cost of the software is easily determined by multiplying programming effort by the cost per workyear (called manyear in Boehm's equations above) for programming. The COCOMO model also provides estimates of the amount of <u>time</u> necessary to develop the software. Additionally, the following equations were developed for the recurring software maintenance cost for a given man-machine option in subsystem, i:

$$EDSI_i = ADSI_i \ \frac{AAF}{100} \tag{5-7}$$

where

EDSI = Expected number of Delivered Source Instructions

ADSI = Adapted number of Delivered Source Instructions (this is the original DSI figure)

AAF = Adaptation Adjustment Factor

in which

$$AAF = 0.4\ DM + 0.3\ CM + 0.3\ IM \tag{5-8}$$

where

DM = % design modified

CM = % code modified

IM = % integration required for modified software

Based on the embedded COCOMO criteria for the DM, CM, and IM variables, which seem applicable to the Space Station environment, the calculated AAF values for any dedicated and integrating microprocessors used in automation concepts would be 21 and 74, respectively. The new EDSI value replaces the KDSI value in Equations (5-4) and (5-5).

Once the primary cost variables have been identified, it is possible to provide a hardware and software cost estimate (C_{RDP}) for the battery example. The hardware estimates in Table 5-2 are based on Electronic Memories and Magnetics (EMM) Corporation and INTEL Corporation figures for space-qualified, central-processing units [Model 80286 (integrating processor) and 8086 (dedicated processor) CPUs] and associated software support (Personal Communications from J. Wilkins, Electronic Memories and Magnetics Corporation, and K. Smith, INTEL Corporation, Hardware Quotes, September 1984; also Reference 5-7). The software estimates assume a conservative programmer salary of $50,000 per workyear (manyear) (see Reference 5-7).

Table 5-2. Battery Example Initial Costs (C_{RDP})

Component	Cost, Assuming New Software Required	Actual Cost, Considering Reductions due to APSM[a] Findings
Three dedicated microprocessors	\$75 to \$120K	Same
One integrating processor	\$30 to \$50K (mean \$40K) (1/3) (\$40K)	Same
Communication links and support hardware (text editor, program debugger, compiler, discs, etc.)	\$30K	Same
Dedicated microprocessor software	\$2.8M	0
Integrating software	(1/3) (\$9M)	\$3M
Total (approximate)	\$6M	\$3M

[a]Automated Power System Management (see Figure 5-3).

Table 5-2 shows a total capital of investment of \$3 to \$6 million, depending on whether the software is already in place. The one-third factor included for the integrating processor and software costs reflects the amortization of cost across the solar arrays and fuel cells. One important observation about Table 5-2 is that the software costs seem to be much greater than the hardware costs. As a point of reference, also note that the projected hardware and software costs are on the order of predictions for next-generation power subsystems arriving in the 1990 time frame (see Reference 5-1). Because of the potential magnitude of the software investment, software costing will continue to be a key research thrust in the next phase.

D. INITIAL LIMITING OF AUTOMATION ALTERNATIVES

The last step in this section describing the methodology is to use the productivity and cost variables to help pare the potential array of man-machine mixes to those that offer the best productivity payoff for a given cost. To accomplish this segregation, a parametric mathematical program was formulated that maximized productivity (crew time saved) subject to a cost constraint. Because cost is varied over its full range for the complete array of man-machine functional alternatives, a set of efficient solutions can be generated.

Notationally, let i (i = 1, ... ,m) be the function index, and x_i be a zero or one decision variable. This implies that there are, at most, m man-machine alternatives for each subsystem. The problem to be solved is:

$$\underset{x}{\text{Max}} \sum_{i=1}^{m} P_i x_i, \text{ subject to} \tag{5-9}$$

$$\sum_{i=1}^{m} C_i\ (x)\ x_i \le C \tag{5-10}$$

where

P = incremental crew hours saved if function i is automated

x = automation decision variable for function i, having a value of 1 if the function is automated and 0 if the function is not

C(x) = net incremental life-cycle cost for automating function i

C = cost of the most expensive man-machine alternative (i.e., that alternative in which all functions are to be automated)

When x_i = 0, the default option with respect to the current baseline results. Constraint (5-10) implies that the net life-cycle cost associated with automating a given subsystem can be no more than C dollars. C will initially be set at the lowest value that would make the most expensive alternative feasible (this would not necessarily be the full automation alternative represented by x_i = 1; i = 1, ... ,m) and then be parametrically reduced until infeasibility is reached. The resulting solutions are then recorded. It should be noted that a systemic contraint exists that may include or exclude certain combinations. For example, if the selection of the second alternative for function 1 can be replaced by a more likely third alternative involving both function 1 and function 2, the second alternative would be dropped from the alternative array. This constraint helps make the selection of the efficient subset even easier to solve if, in fact, certain automated functions are linked. Using this approach, one can concisely develop the full array of possible man-machine alternatives for a given subsystem. The array might appear as shown in Table 5-3, which lists man-machine alternatives for battery monitoring, verifying, and fault-management functions within the command/control module. A man-machine alternative is defined as "that function or set of functions that is to be automated within a subsystem."

A certain number of solutions obtained from Equation (5-9) by parametrically varying the right-hand side of Equation (5-10) will be discarded, leaving an efficient set of alternatives with respect to cost and productivity. The rationale for using Equation (5-9) to filter out the less

Table 5-3. Man-Machine Alternatives for the Battery Example

Man-Machine Alternatives	Functions		
	Monitor	Verify	Fault Manage
1 (Baseline)	0	0	0
2	1[a]	0	0
3	0	1	0
4	0	0	1
5	1	1	C
6	0	1	1
7	1	0	1
8 (Total automation)	1	1	1

[a]Where 0 means no automation, and 1 means the function is automated.

desirable alternatives is based on the fact that the reliability, weight, and power measures have already been incorporated in the cost, productivity, and safety attributes; and that safety is typically affected by automation in a positive sense. Note that it would be inappropriate to constrain weight, power, and cost in this stage of the analysis; such a constraint would ultimately limit the ability to conduct system-level trade-offs.

Should it appear that safety is being sacrificed in favor of cost reduction or higher productivity, Equation (5-9) could be replaced by, or examined in conjunction with, an objective function emphasizing safety. The parametric analysis would then be repeated to obtain a supplementary set of efficient solutions. The safety objective function might be "exposure-time reduction."

To demonstrate the technique more fully, consider the set of example battery values for the previous array of man-machine alternatives in Table 5-4. The productivity impacts assume that each of the monitoring, verification, and fault-management task times are evenly distributed across the four key power subsystems (as stated in Section IV). This results in about 0.01 h/mission day for monitoring, 0.03 h/mission day for verification/calibration, and 0.03 h/mission day for fault management (mainly switching batteries). The cost values approximate relative software differences. Figure 5-4 shows a plot of each alternative's cost and productivity values.

Table 5-4. Sample Cost and Productivity Values for Battery Example

Man-Machine Alternative	Approximate Cost, $ million	Crew-Hour Savings, h/mission day
1	0	0
2	1	0.01
3	1	0.03
4	6	0.03
5	2	0.04
6	6	0.06
7	6	0.04
8	6	0.07

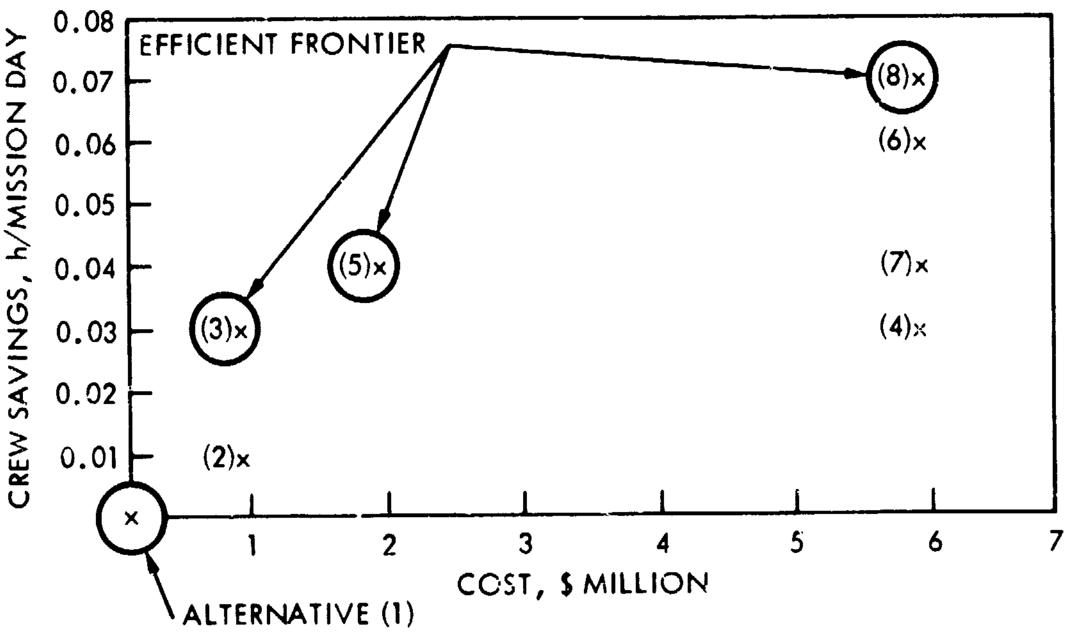


Figure 5-4. Man-Machine Alternative Cost and Productivity Plot (Numbers in Parentheses Correspond to the Automation Alternatives Listed in Table 5-4)

Clearly, Alternatives (4), (6), and (7) are inferior because it is difficult to automate fault isolation without having the software in place to monitor and verify. Alternative (2) is inferior because mere automation of the monitoring function does not enhance crew productivity signficantly. Thus, Alternatives (1), (3), (5), and (8) represent the efficient subset. The efficient subset is probably composed of only three alternatives because Alternative (3) actually fits the previous systemic constraint: one would most likely not automate verification without automating monitoring as well. Although this example is rather simple, it illustrates the principle of the efficient subset. If sufficient task-time data were available, the array of man-machine alternatives could be expanded to consider shades of man-machine involvement in the fault-management task (i.e., segregation of system-level, fault-management functions from subsystem functions). After identification of an efficient subset of man-machine mixes, the final step in the methodology is to consider the complete array of cost, productivity, and safety attributes with the intent of optimizing both the system man-machine mix (as a function of the net automation benefits) and the affiliated technology growth plot. The attribute measures are provided in Section VI, followed by the optimization discussion in Section VII.

SECTION VI

ATTRIBUTE UTILITY MEASURES

A. OVERVIEW

Section III defines each of the various design and cost attributes in detail and provides a description of multi-attribute decision analysis. Section V refers to the final optimization step whereby the different attributes are weighed simultaneously so that various subsystem man-machine alternatives, or technology options, can be rank-ordered as a function of their desirability. In the case of man-machine alternatives, the multi-attribute decision technique provides an additional screening mechanism by which to simplify the final system-level optimization process. As applicable to the best technology plot, multi-attribute decision analysis allows consideration of less quantitative factors such as "importance to out-year missions" or "ease of retrofit." Paramount to exercising the multi-attribute decision technique is the development of a decision framework that supports a set objective(s) (i.e., selection of the best man-machine mixes and automation technologies). This decision framework implies that the attributes must be displayed both as a function of cost (where feasible), and relative utility. The concept of "utility" can extend beyond cost to more subjective measures. This section (Section VI) focuses on extending the definition of the set of attributes in terms of their relative utilities. The first part of this section explains the concept of the decision framework and its desirable properties. The second and central part of Section VI describes the development of objectives for Space Station automation assessment, including considerable discussion of the criteria and attribute measures in terms of utility. The final part of this section discusses how these attributes were used in the first application of the automation assessment methodology.

B. ATTRIBUTE DEFINITION

The assessment of automation for Space Station will lead to decisions concerning system and subsystem levels of autonomy. Each automation decision involves consideration of several factors or attributes simultaneously. Such a decision can be difficult to make because not all attributes can be reduced to one common denominator (e.g., costs and cost savings).

To facilitate decisions with several attributes, a useful construct is a progressive structure of objectives, criteria, and attributes. An objective structure provides a means for individuals considered knowledgeable in spacecraft design and automation to express their preferences among different man-machine alternatives or technology options. These responsible individuals are viewed as the decision makers.

Further, the structure enables quantification of the results or outcomes associated with each man-machine or technology option. Quantification draws on well-developed and tested methods of decision analysis (e.g., see References 6-1 and 6-2).

1. Overview of Objectives Structure

The objectives framework expresses the preferences of the decision makers in ever-increasing detail as one proceeds down through the hierarchy from overall objective to a lower-level of subobjectives. Below the subobjectives are "criteria," which must permit a qualifiable measure of the various man-machine alternatives or technology options with respect to subobjectives. Associated with each criterion is an "attribute," the actual measure of the criteria that allows the decision makers to express preferences for its various states. Figure 6-1 shows the objective structure and associated attributes (introduced earlier) for the Space Station problem.

Besides facilitating the cost analysis, the set of attributes jointly satisfies the following established decision elements needed to characterize the preference structure of the decision makers in the utility model (see Reference 6-1):

(1) Completeness: The set of attributes reasonably characterizes most of the factors crucial to the Space Station programmatic decisions.

(2) Comprehensiveness: Each attribute adequately characterizes its associated criterion.

(3) Importance: Each attribute represents a significant criterion in programmatic decision making (at least in the sense that the attribute has the potential for affecting the preference ordering of the alternatives under consideration) and can, therefore, affect the ranking of man-machine alternatives or technology options.

(4) Measurability: Each attribute is capable of being objectively or subjectively measured.

(5) Familiarity: Each attribute is understandable to the decision makers in the sense that they can identify preferences for different states of the attribute.

(6) Nonredundacy: Two attributes do not measure the same criterion, thus resulting in double counting.

(7) Independence: The value model is so structured that changes within certain limits in the state of one attribute do not affect the preference ordering for states of another attribute.

Several pragmatic properties are demonstrated by the objectives structure. Most important, the structure leads to an appropriate ranking of man-machine or technology alternatives that accurately reflects the preferences of the decision maker. Next, the framework is reasonably easy to apply. Ease of application is critical to ranking options within interview time and trip cost limitations. Some aspects of ease of use include:

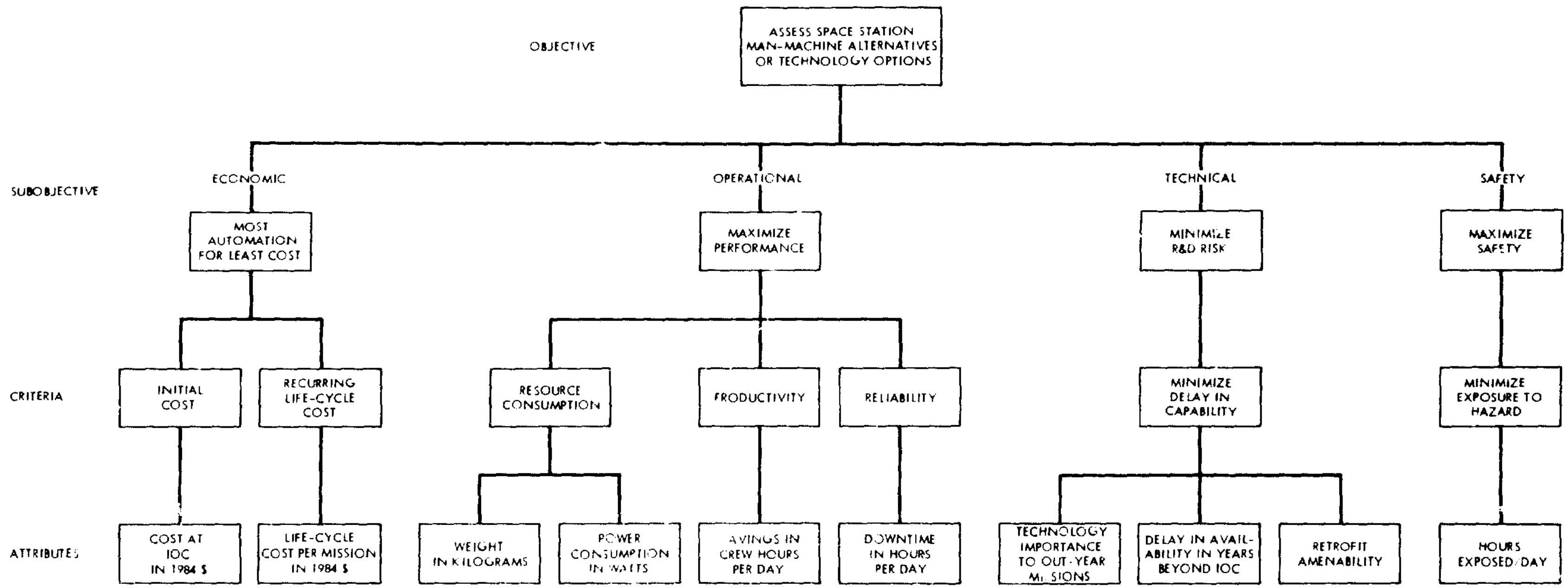


Figure 6-1. Hierarchy of Objectives, Criteria, and Attributes

(1) The ease with which experts (decision makers) can provide preferences for the decision model.

(2) Ease of obtaining performance data for alternatives relevant to the attributes.

(3) Ease of carrying out a sensitivity analysis on the rankings and understanding underlying reasons behind observed shifts in preferences.

2. Discussion of Objectives and Subobjectives

The top level in Figure 6-1 is an overall statement of the objective, namely "assess Space Station, man-machine, or technology options." This objective considers both initial operational capability and future mission needs.

The subobjectives provide distinct categories for the components of the overall objective. These components are chosen to support and facilitate further definition of the objectives. The categories for the subobjectives that apply directly to Space Station include economic, operational, technical objectives, and safety.

3. Subobjective Criteria

The level below subobjectives contains criteria. The criteria selected permit the quantification of performance of the alternatives with respect to the subobjectives. For example, <u>cost</u> is a logical candidate for the criterion related to measuring the <u>economic</u> subobjective.

4. Attributes and Utility Measures

At the lowest level in the hierarchy are the attributes, which provide a measure of each criterion and a means of displaying relative differences between man-machine alternatives or technology options to the decision makers. For example, <u>weight</u> in kilograms may be a performance or utility measure with respect to the <u>resource consumption</u> criterion in Figure 6-1. This display of attributes can aid decision makers to establish preferences for an alternative based on their knowledge of budget limitations or programmatic needs. Although the attributes are discussed in Section III, they are reviewed here from the perspective of utility to the decision maker.

The cost attributes are the first elements shown in Figure 6-1. The division of cost into two attributes is noteworthy. Major technology cost decisions, as demonstrated in Section V, usually take both initial cost and recurring (or operating) cost into account. With Space Station, cost at initial operational capability has been widely discussed as significant because of stringent budget constraints. Also, the continuing cost of operation and new technology, as Space Station missions materialize, is significant for setting the level of automation. Life-cycle cost per mission period is, therefore, a reasonable comprehensive measure of continuing, or operating, cost. As a basis of comparison for each man-machine alternative or technology, present value costs are used.

The attributes of weight in kilograms and power consumption in kilowatts are significant to the choice of automation. This significance is attributed to the weight and power limitations placed on the Space Station with respect to payload weight limitations of the Shuttle (which will ferry Space Station components) and to the general desire to simplify the design by keeping power consumption down. For example, if the experts learn that automation choices are driven largely by software (which has little weight impact), then the weight attribute would not have significant impact on the choices of man-machine alternatives or technology options.

The attribute measure for productivity savings through automation is suggested to be in available crew hours per day. Both ground crew and Space Station crew hours could be included although the primary focus will be on the on-board crew. The utility of additional on-orbit time revolves around the crew being able to tend more payloads. Ground-crew reductions clearly have utility by cutting operating costs.

Automation, with its implications of fault tolerance, self-testing, error correction and system redundancy has an important relationship with system reliability. Several different measures of reliability are (1) mean time between failures, (2) mean time to repair, (3) probability of failure, and (4) expected downtime in hours per day (or per mission cycle). The last of these, expected downtime in hours per day, is suggested as the appropriate utility measure for reliability because it provides a clear understanding of operational impacts, as well as being easily translated into cost.

Technical risk is an important consideration in automation selection. Included in this consideration are technology availability, importance of out-year missions, and amenability to retrofit. Although technical problems can be overcome, given enough time and money, time delay beyond IOC in years has both schedule and cost connotations to the decision maker. Importance of new technology to out-year missions also has schedule and cost overtones to program managers. The ease with which new technology can be incorporated (retrofit amenability) can pose a cost dilemma to program managers and suggests possible limitations in meeting future missions if retrofit requires major system reconfiguration.

Safety, the last attribute in Figure 6-1, is an extremely important consideration in assessing automation and eventual autonomy for the Space Station. In many other technology selection problems, safety is treated by a subjectively scaled attribute (with word description of different safety levels). In the case of Space Station, the utility of safety improvements through automation can be related to the reduction in exposure time of the crew to potentially hazardous situations, such as EVA. Loss of life, or injury, can have cost ramifications in terms of jeopardizing program continuation. However, to the decision maker, the political and social value of crew safety is more visible. Reduction in exposure is, therefore, a more reasonable utility measure of automation.

C. REFINEMENT AND USE OF ATTRIBUTES

The ten attributes presented in Section V were selected to capture the essence of the automation assessment problem. Also, the set of attributes was carefully defined to fit well with the multi-attribute decision analysis described in Section VII. The units of measure were selected to allow careful expression of an individual's preferences, yet not make technical data requirements impractical. The set of ten attributes will be reviewed as technical data are gathered to ensure that the set of attributes is clearly described for the decision makers. The review also provides direction for setting the scale for each attribute. Each attribute scale includes an upper and lower bound on the unit of measure and is wide enough to delineate cost and performance values of the range of man-machine and technology options under consideration.

The first application of multi-attribute decision analysis is for optimization of the man-machine mix at the subsystem level. For this application all attributes, except safety, crew productivity, and the three attributes related to technology risk, are combined into a single, net dollar savings, or cost. The attributes related to risk are reserved for the technology assessment. Therefore, the decision makers are initially asked to weigh only three attributes. In the case of weighing technology options, all ten attributes are used in the assessment. Both processes are described in detail in Section VII.

SECTION VII

COST-BENEFIT STRUCTURE

A. OVERVIEW

Optimization of large-scale systems often relies on hierarchical or decomposition methods to transpose the analytical model into a computationally manageable form. Much of the recent work in this area has focused on applications dealing with production planning and multicommodity distribution (e.g., References 7-1, 7-2, and 7-3). Because most real systems embody several conflicting or different objectives, it has become evident that multiobjective optimization must be part of any successful decomposition scheme (References 7-4, 7-5, and 7-6). In recognition of this fact, a two-stage approach was developed. The first stage, selecting a subset of efficient man-machine alternatives, is discussed in Section V. In Section VII the second stage is developed as a resource allocation problem, which is solved using the empirical (cost) and subjective (safety) data elements of the efficient subset as the decision variables. The objective is to maximize the difference between marginal benefits and costs subject to cost, weight, power, and safety constraints. The modeling and analysis associated with the second stage are presented in this section of the report.

B. DETERMINATION OF NET BENEFITS OF AUTOMATION BY SUBSYSTEM

Section VI discusses the various attributes and utility measures used to assess the net benefits of automation. In this section (Section VII), it is appropriate to relate each attribute to its respective life-cycle cost element. Table 7-1 shows the attribute-cost relationships in terms of the life-cycle cost variables introduced in Section V.

Because the automation cost variable is discussed in detail in Section V, it is not addressed in this section of the report. Similarly, the methodology framework in Section III assigns the crew-safety variable a qualitative value and separates it from the other cost variables.

Table 7-1 shows that the weight and power cost variables are respectively included in the launch support and capital costs. The cost impact of weight reductions or increases are primarily a step function. This means that a rather large launch constraint must be exceeded before a savings or penalty is paid. The savings might result in launching an additional experiment while the penalty might arise in the form of having to use a larger booster rocket for the launch. Similarly, the power cost or savings is expressed by either providing additional solar-array hardware or by using the power savings to operate an additional experiment.

The crew productivity attribute is tied to several cost variables. First, crew-training costs are potentially affected because operator-training requirements typically decrease as more functions are automated. If the same station crew is employed to use the time slack for more experiments, then the training cost may remain unaffected. The workforce (manpower) cost is

Table 7-1. Relationship between Methodology Attributes and Cost Variables

Cost Attributes Directly Related to Man-Machine Optimization Routine and Technology Ranking	Life-Cycle Cost Variables Affected	Definition
Automation life-cycle cost initial (IOC) operating/support	C_{RDP}	Research, development, and production cost
Weight	C_{LSTE}	Launch support and test equipment costs
Power	C_{RDP}	Same as above
Station/ground-crew productivity	C_{TR}, C_{MP}, C_{TD}, C_F	Training, workforce, Technical documentation, and ground-facilities costs
Reliability	C_{MP}, C_{TR}, C_S,C_M, C_{STE}	Manpower, training, spares, maintenance, and support/test equipment costs
Safety	No dollar value assigned	Reduction in hazard-exposure hours
Additional Attributes Related to Technology Ranking	**Life-Cycle Cost Variables Affected**	**Definition**
Technology availability	C_{RDP} (Subjectively considered)	Reduction in hazard-exposure hours
Technology importance	C_{RDP} (Subjectively considered)	Same as above
Retrofit amenability	C_{RDP}, C_S, C_M (Subjectively considered)	Same as above

directly related to productivity. This cost has three components: (1) ground maintenance, (2) ground crew, and (3) station crew. The ground-maintenance component will be required, regardless of the degree of automation. The ground-crew component could be driven downwards because of the possible reduction in ground support. The station-crew cost component will be considered a constant, only reduced by the value of the time savings due to automation (see Section III). The technical documentation cost element is similar to the workforce (manpower) element in that (1) the ground-maintenance component could remain the same or increase and (2) both ground- and station-operational documentation could decrease as more functions are automated. Finally, the ground facility cost variable could also experience a reduction as ground workforce (manpower) is reduced.

Table 7-1 indicates that the reliability attribute is reflected in several cost variables. The ground-workforce cost could be reduced by automation as a result of inherent fault-management capability and, therefore, lower crew involvement in the troubleshooting of anomalies or faults. In the case of the station crew, more payload time becomes available, which could be valued in the same manner as the productivity attribute. Again, operator-training costs could be driven lower because of the reduction of crew involvement in fault management. On the other hand, hardware-maintenance training and costs may increase due to the higher complexity of the equipment and software. The last cost variable, support and test equipment, might experience a reduction because the built-in fault-management aspect of automation could reduce the need for duplicate ground-support equipment.

The last three attributes associated with reducing R&D risk affect three cost variables: research and development costs, on-board spares, and maintenance. The R&D costs could reflect risk if programmatic guidelines require that untested technology be ready by IOC. The net impact could be an extremely high investment in research, testing, and retrofit kit design to shorten the normal development schedule. The spares cost is potentially increased because redundancy may be incorporated on-orbit to offset possible lower reliabilities of newer component technology but maintain the overall system reliability at the desired level. Similarly, the higher number of redundant components should jointly increase the repair rate. As an overview of the preceding discussion, Table 7-2 summarizes the expected effects of automation on each cost variable and attribute.

Table 7-2 is not provided as an automation cost guide, but as a departure point for the next phase of investigation. To demonstrate the intended direction of follow-on research, consider the following set of equations and simple example.

In the standard life-cycle cost equation from Section V:

$$C_{LC_i} = C_{RDP_i} + C_{TR_i} + C_{MP_i} + C_{LST_i} + C_{S_i} + C_{TD_i} + C_{F_i} + C_{OS_i} \qquad (7\text{-}1)$$

Table 7-2. Expected Subsystem Cost Impacts of Total Automation

Attribute	Cost Variable Affected	Expected Cost Impact
Automation cost	C_{RDP}	Increase in research, development, and production costs
Weight	C_{LSTE}	Little or no effect on Shuttle payload capacity and resulting launch costs
Power	C_{RDP}	Little or no effect on additional power hardware requirements
Station/ground-crew productivity and efficiency	C_{TR}	Decrease in ground and station crew operations training; little or no effect on ground-maintenance training
	C_{MP}	Decrease in ground and station crew work-force costs; little or no effect on maintenance workforce costs
	C_{TD}	Decrease in ground and station operations technical documentation; possible increase in maintenance documentation
	C_F	Reduction in ground facilities (computers, building space, etc.) commensurate with reduction in ground workforce
Reliability	C_{TR}	Decrease in ground and station crew fault-management training; increase in ground-maintenance training
	C_{MP}	Decrease in ground and station crew involvement in fault management
	C_S	Decrease in on-board spare components
	C_M	Increase in cost of maintenance due to greater hardware/software complexity
	C_{STE}	Decrease in ground support and test equipment due to in-place fault management
Technology availability/ importance	C_{RDP}	Possible increase in R&D costs to make new technology available on time
	C_S	Possible increase in spares to achieve desired system-level reliability
	C_M	Increase in maintenance costs due to greater number of hardware/software failures
Retrofit amenability	C_{RDP}	Additional retrofit kit design costs to make new technology compatible with system

let the benefit of automation be given by $\pm b$ (a fractional cost-reduction or increase factor), where now C_{LCB} becomes the incremental life-cycle cost benefit for automating subsystem, i; then

$$C_{LCB_i} = \left(b_{RDP}\ C_{RDP}\right)_i + \left(b_{TR}\ C_{TR_i}\right) + \left(b_{MPG}\ C_{MPG} + b_{MPS}\ C_{MPS}\right)_i$$
$$+ \left(b_{LSTE}\ C_{LSTE}\right)_i + \left(b_s\ C_s\right)_i + \left(b_{TD}\ C_{TD}\right)_i + \left(b_F\ C_F\right)_i + \left(b_{OS}\ C_{OS}\right)_i \qquad (7\text{-}2)$$

The difference between Equations (7-1) and (7-2) represents the revised life-cycle cost for subsystem, i, as a result of incorporating automation. This can be written as:

$$C_{LC_i} - C_{LCB_i} = \left(1 - b_{RDP}\right)_i C_{RDP_i} + \left(1 - b_{TR}\right)_i C_{TR_i}$$
$$+ \left(1 - b_{MPG}\right)_i C_{MP_i}(\text{ground}) + \left(1 - b_{MPS}\right)_i C_{MP_i}(\text{station})$$
$$+ \left(1 - b_{LSTE}\right)_i C_{LSTE_i} + \left(1 - b_s\right)_i C_{S_i} + \left(1 - b_{TD}\right)_i C_{TD_i}$$
$$+ \left(1 - b_F\right)_i C_{F_i} + \left(1 - b_{OS}\right)_i C_{OS_i} \qquad (7\text{-}3)$$

The b_{RDP} fraction actually has two components: (1) the capital cost component and (2) the power component (i.e., a decrease in power usage could result in a reduction in power hardware). Similarly, Equation (7-3) shows the workforce (manpower) component divided into ground and station components. As stated in Section V, the storage battery example (APSM) was actually breadboarded and tested. The net results of the APSM initial cost assessment are shown in Table 7-3 in terms of the preceding cost-benefit variables (see Reference 5-1).

Using Equation (7-3) and substituting in the appropriate storage battery benefit values yields:

$$C_{LC} - C_{LCB} = C_{RDP} + 0.5\ C_{MP} + 0.88\ C_{LSTE} + 0.5\ C_F$$

Using Voyager cost experience as an example and substituting in the respective values for the various cost elements results in a revised initial life-cycle cost of \$7.6 million. The actual cost without APSM is calculated to be \$8.1 million. Thus, the net benefit due to automation is estimated to be approximately 6 to 7% (see Reference 5-1). Consequently, by automating the monitoring, verification, and fault-management functions associated with the batteries, a net cost savings is indeed predicted.

Table 7-3. Automated Power System Management (APSM) Battery Cost Benefits

Cost-Benefit Variable	Fractional Benefit[a]
C_{RDP} (Capital-cost component)	0 - No fractional benefit
C_{RDP} (Power component)	0 - No significant savings
C_{TR}	1 - Operator functions are totally automated
C_{MP} (Ground component)	0.5 - Reduced from 4 to 2 persons
C_{MP} (Station component)	1 - Unmanned platform
C_{LSTE} (Weight)	0 - Only a 3-lb reduction in hardwiring
C_{LSTE} (Equipment)	0.12
C_S	0
C_{TD}	Insignificant
C_F	0.5 - In accordance with manpower reduction
C_{OS}	Not calculated for initial costs

[a]See Equation (7-2).

Follow-on research in this area will pursue the development of benefit curves that display the fractional cost benefit for a given cost variable as a function of the increasing degree of automation. It is anticipated that reasonable historical experience will be obtained from Shuttle as well as the aerospace and auto industries.

C. OPTIMIZING THE MAN-MACHINE MIX

Section VI describes how the costs and benefits are calculated for a given automation alternative and subsystem. However, station productivity and crew safety were not included in this net-benefit cost figure. As stated in Section VII-A, a resource-allocation approach was taken to resolve this dilemma of conflicting multi-objectives. The multi-attribute technique, introduced in Section III, along with an elaboration of the attributes and supporting decision structure in Section VI, is discussed in detail in the following paragraphs.

1. Multi-Attribute Utility Theory

Multi-attribute analysis was developed to deal with complicated decision problems for which the outcomes must be evaluated in terms of several objectives (also called goals or criteria). Section V' indicates that objectives and subojectives of decision analysis must be stated in terms of properties, either desirable or undesirable, that determine the decision-maker's preferences for the outcomes. For the assessment of Space Station automation, the four subobjectives stated in Figure 6-1 are: (1) minimize cost, (2) maximize performance, (3) minimize technical risk, and (4) maximize safety. The purpose of the decision analysis is to take the subsystem man-machine alternatives or technology options, determine the degree to which the alternatives or options satisfy each of the subobjectives, and then establish the necessary weights for the subobjectives to arrive at a ranking for the alternatives that accurately expresses the preferences of the decision makers. To establish the weights of the subobjectives, a unit of measurement must be assigned to the lowest members of the objectives framework. Attributes are used to measure subobjectives, and they are scaled conveniently to assess the degree to which associated subobjectives are satisfied. The alternatives of the associated system model are expressed as ten-component vectors, with each component corresponding to an outcome of one of the ten attributes in Figure 6-1 [i.e., $x = (x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8,x_9,x_{10})$ where x_i is the ith attribute of the decision model]. A specific outcome of an attribute is called a state of the attribute. An "attribute state" for the subobjective "maximize safety" might be $x_8 = 0.1$ hours of hazard exposure per day.

a. Aggregating Subobjectives into a Preference Model. Once attributes and states have been assigned to all the subobjectives, it is necessary to aggregate the attribute states into a single unit of measurement that accurately represents the decision maker's preference ordering of the various states.

One common method for aggregating the attribute states is the "willingness to pay" or "pricing out" technique (see Reference 6-1). Usually, one attribute is singled out as the key measurement attribute, preferably an attribute quantified in dollars. Then, one at a time, each of the other attributes are changed to a reference state, with the money state of the measurement attribute adjusted by means of an assessed trade-off or rate of substitution to compensate for the corresponding change in the other attributes. Through this process, all the outcomes are expressed in terms of n attributes, n-1 of which all have been adjusted to the same reference attribute state. The preference ranking of the decision maker is simplified because it is expressed by the state assigned to the measurement attribute. Decision makers are usually interviewed separately to prevent group bias from entering preference selections. Although easy to apply, this method is valid with constant rates of substitution only when two conditions are satisfied:

(1) The set of trade-offs for the measurement attribute and any other attribute are independent of the states of the other n-2 attributes (e.g., the decision maker provides a constant trade-off between initial cost and productivity for all states of safety and

reliability). This condition is not meant to imply that cost is not a function of productivity or reliability. The condition merely addresses the ability of an individual to make pair-wise preferences. Indeed, consumers daily make pair-wise comparisons in the presence of other variables (e.g., making a choice between two brands of canned goods in the presence of other brands).

(2) The trade-offs for the measurement attribute and any other attribute do not depend on the states of either the measurement or other attribute (e.g., the decision maker will maintain a constant trade-off between cost and productivity, regardless of the magnitude of the attribute states).

Both conditions allow the analyst to substitute different trade-offs between the measurement and other attributes (constant rate of substitution) while ensuring validity of the decision maker's responses. In practice, condition (1) is easy to achieve. However, decision makers do not always respond consistently when faced with condition (2). In this case the analyst may apprise the decision maker of the inconsistency and request reconsideration of the response. Another approach is to use a model that minimizes the effects of inconsistent responses. This model is the multiplicative form of the decision analysis.

b. Multiplicative Model. For the formulation described in the following paragraphs the attribute states are quantified on a numerical scale that represents the range of preferences of the decision maker for the various states the attribute can assume. The function that transforms an attribute state, for a given man-machine alternative or technology option, into a numerical representation of attribute preference is called a utility function. The utility of the ith attribute in state x_i is written as $u_i(x_i)$. The proper algebraic expression combining all the attribute utility functions is called an outcome utility function $u(x)$, with $(x_i, \ldots, x_n)$ being the nth-attribute outcome. An outcome utility function is a numerical representation of the decision maker's preferences for the outcomes. It is convenient to measure attribute utility functions on a scale from 0.0 to 1.0, where $u_i = 0.0$ corresponds to the least-preferred ith attribute state that occurs among the outcomes under consideration, and $u_i = 1.0$ corresponds to the most-preferred state. The multiplicative utility equation is shown in the following expression:

$$u(x) = \frac{1}{k} \left\{ \prod_{i=1}^{n} \left[1 + k k_i u_i(x_i) \right] - 1 \right\} \qquad (7\text{-}4)$$

where

n = number of attributes

$\prod$ = symbol for the "product" of n expressions

$u(x)$ = outcome utility function

$u_i(x_i)$ = attribute utility function of the ith attribute

k_i = scaling constant ranging between 0.0 and 1.0 that determines the "weight" or "importance" of the ith attribute

k = master scaling constant that is an algebraic function of the k_i, scaling $u(x)$ from $u = 0.0$ to $u = 1.0$.

The attributes and their measures are defined in Section VI. The utility functions and scaling constants are determined through interviews with the decision makers. A common technique for developing utility functions and scaling constants is the lottery method (References 7-7 and 7-8). The lottery method is initiated by presenting the high- and low-attribute state values to the expert (e.g., the values could represent high- and low-cost figures for a set of man-machine alternatives or technology options). Through a controlled question-and-answer process the expert provides the intermediate data point at which he is indifferent in his preference. This point is equal to a utility of 0.5 and represents the third data point necessary to complete the utility plot. A similar question-and-answer process is used to establish the scaling constant (or weight) for each attribute because the preceding overall utility expression considers that not all attributes are equally important to the expert.

An important consideration is the stability of preferences resulting from multi-attribute decision analysis. First, the multiplicative model tends to mute inconsistencies in an expert's responses. Second, the interviewer may apprise the decision maker of preference inconsistency and request reconsideration of the answer. On a more global level, the interviewer may return after a set period of time and retest the same group of experts to establish preference stability. Preference changes are usually related to alterations in the decision-making environment, and their impacts must be assessed at that time. These impacts would be incorporated in the alternative rankings via sensitivity analysis (e.g., if preferences change due to this event, then the rankings are affected in the following manner).

In the next subsection the battery example is used to demonstrate the multiplicative technique. See Appendix E for a more rigorous discussion of the multi-attribute decision theory.

2. Optimizing the Man-Machine Mix at the Subsystem Level

This subsection elaborates on the decision-analysis technique by providing a practical ranking example involving the battery subsystem referred to throughout this report. The technique used to rank the man-machine alternatives for the battery subsystem is the multiplicative decision model. The same three man-machine alternatives explored earlier in the report are used. These alternatives reflect different degrees of battery function automation. The three alternatives, in order of increasing automation, are:

(1) Automating Verification only (AV).

(2) Automating Monitoring and Verification (AMV).

(3) Automating Fault-management, Monitoring and Verification (AFMV).

As previously indicated for the subsystem optimization of potential man-machine alternatives, only three of the ten attributes given in Section VI are considered: Initial cost savings in millions of dollars, crew hours saved per mission day, and crew hours exposed to hazards per mission day. These three attributes serve as measures for initial cost, productivity, and safety, respectively.

The steps required for ranking the alternatives are as follows:

(1) Specify man-machine alternatives.

(2) Establish the attributes to measure the alternatives.

(3) Obtain the attribute-state data (i.e., cost, productivity, and hazard-exposure data).

(4) Obtain decision-maker preferences.

(5) Rank alternatives.

(6) Analyze individual rankings and elminate the least desirable rankings.

The respective cost, productivity, and safety data for the man-machine alternatives are shown in Table 7-4. The cost and productivity data are taken from Table 5-4. The safety values are assumed merely for example purposes. Note that larger values are preferred to smaller values for both initial-cost savings and crew-hours savings while the reverse preference applies to crew hours exposed to hazards. The ranges listed below the attribute-state data were used to obtain an individual's possible range of preferences with regard to the three attributes.

Three steps are usually taken to obtain an individual's preferences using the multiplicative approach. First, a utility function is obtained for each attribute by posing a single lottery question to the expert to establish the three data points necessary to derive a utility curve. Next, the attribute states are ranked in order of importance to demonstrate the flow from the worst-possible to best-possible state. Last, the attribute scaling constants or weights (k_i) are obtained by posing a different set of lottery questions to the expert to establish the relative importance of each attribute.

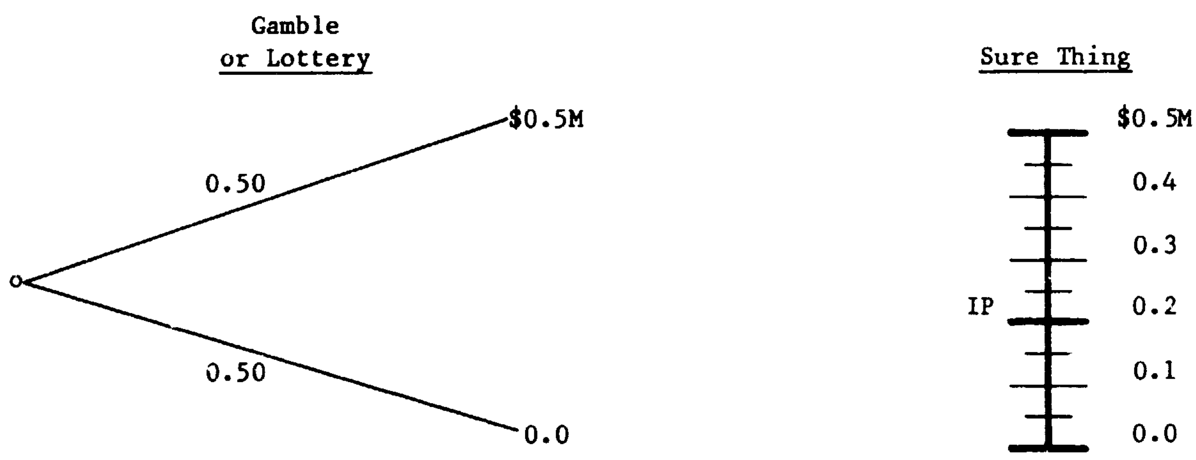
The utility function for initial cost savings was obtained from the answer to the hypothetical lottery question posed in Figure 7-1, which shows

Table 7-4. Attribute-State Data for Battery Example

Man-Machine Alternative \ Attributes	Initial Cost Savings, $M	Productivity in Crew Hours Saved/Mission Day	Safety in Crew Hours Exposed to Hazard Per Mission Day
Automating verification	0.07	0.03	0
Automating monitoring verification	0.14	0.04	0
Automating fault-management, monitoring and verification	0.42	0.07	0.20
Ranges[a]	0 to 0.50	0 to 0.07	0 to 0.20

[a]Usually the ranges for attribute states are indicated by rounded values.

Attribute: Initial Cost Savings



Question: FOR WHICH VALUE OF THE "SURE THING" ARE YOU INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE?"

Response: THE EXPERT MIGHT GIVE AN INDIFFERENCE POINT (IP) OF 0.2.

Figure 7-1. Sample Question for Obtaining a Utility Function that the individual was indifferent between a sure thing of $0.2M in initial cost savings and a 50-50 lottery between initial cost savings of zero or $0.5M. Setting the utility of the most-preferred value ($0.5M) equal to 1.0, and that of the least-preferred value (zero) equal to zero, yields the utility of the value of indifference to the lottery. This $0.2M saved must be equal to the expected utility of the lottery at the point of indifference, or 0.5. The approximate utility function for initial cost savings is shown in Figure 7-2. More information concerning the lottery approach and utility functions is provided in Appendix E.

Applying similar questions like those in Figure 7-1 allow the productivity (in hours saved per mission day) and safety (in crew hours exposed to hazard per mission day) utility functions to be plotted. These are shown in Figures 7-3 and 7-4.

Given the three utility functions shown in Figures 7-2, 7-3, and 7-4, one can obtain specific utilities for attribute-state values from the graphs on the linear segments depicted therein.

The next step in obtaining individual preferences is to find the order of importance of changes from worst to best state for the three attributes. The format used for this lottery question is shown in Table 7-5. For the battery example, the order of importance for the attributes is initial cost savings safety, and productivity.

The order of importance for the attributes was used as a check on the consistency of the scaling constants for the three attributes. As a demonstration, the attribute scaling constants for the multiplicative model were assumed to be 0.6 for initial cost savings, 0.2 for productivity, and 0.4 for safety. Because these do not sum to 1.0, a master scaling constant must

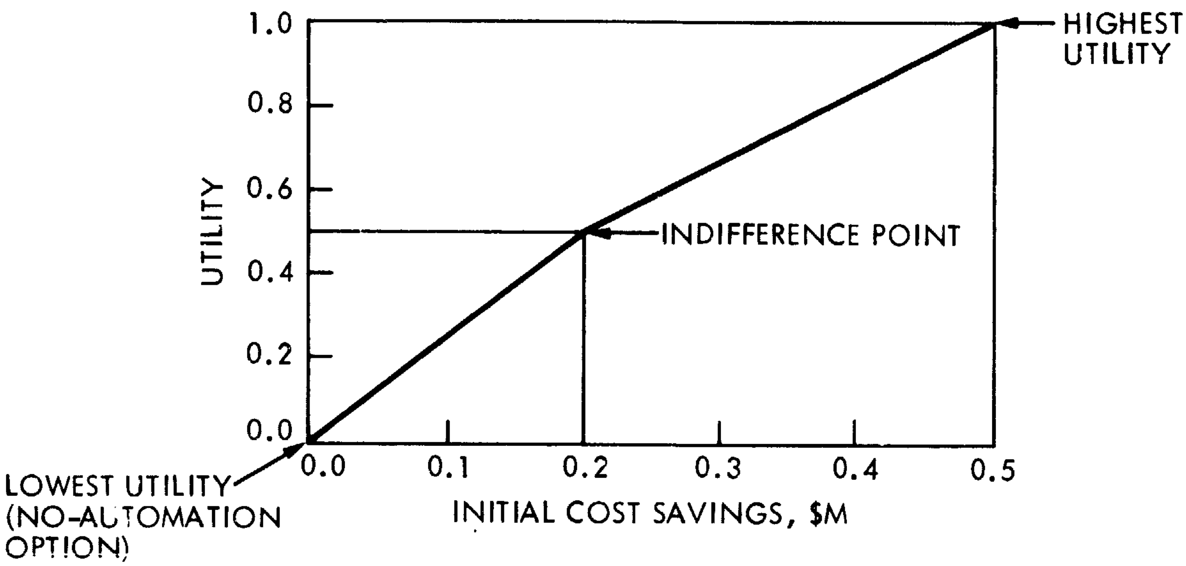


Figure 7-2. Utility Function for Initial Cost Savings

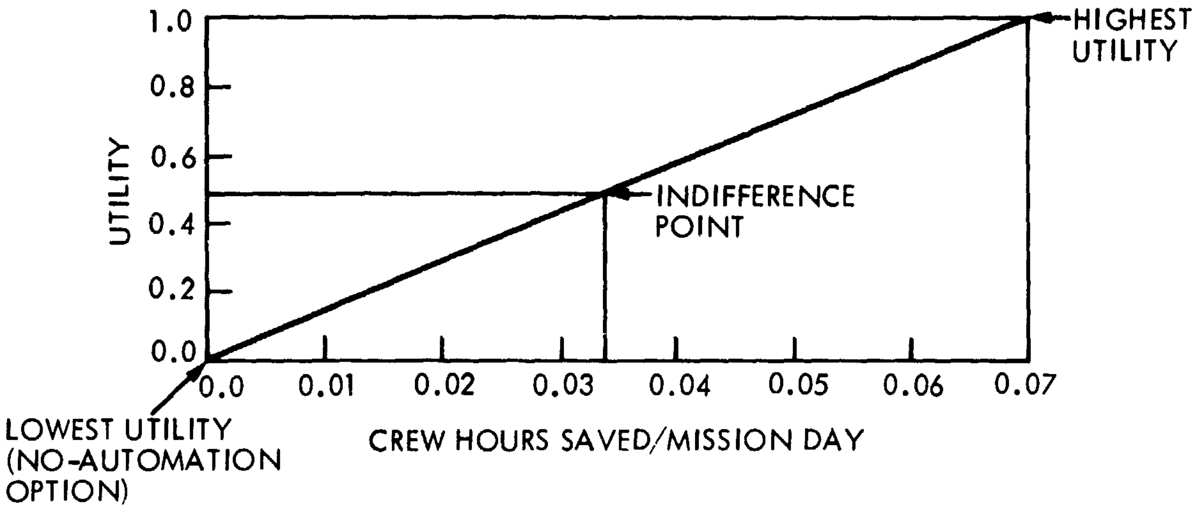


Figure 7-3. Utility Function for Productivity in Crew Hours Saved per Mission Day

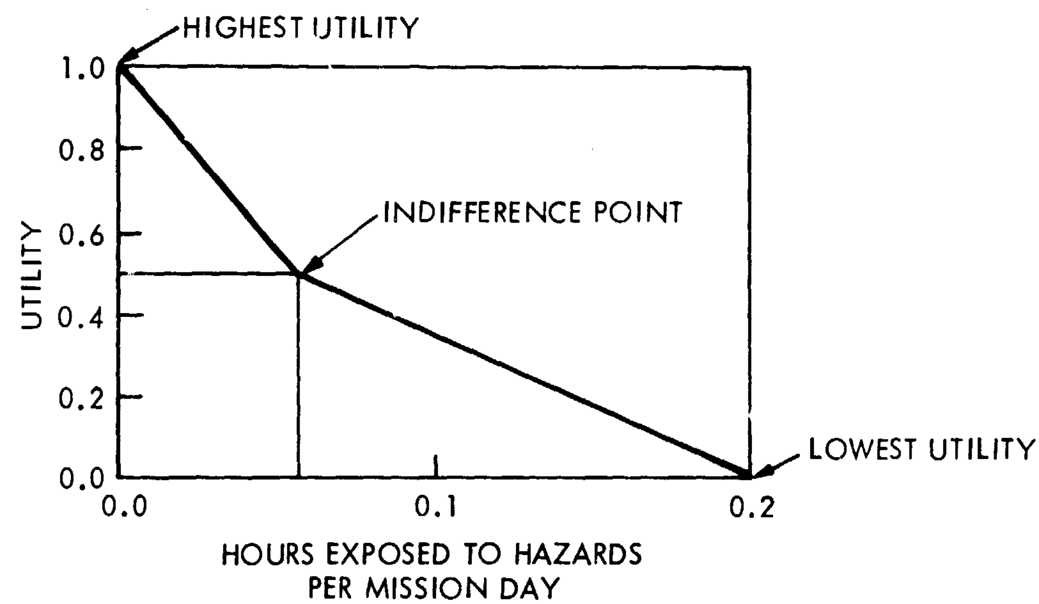


Figure 7-4. Utility Function for Safety in Crew Hours Exposed to Hazards per Mission Day

Table 7-5. Question to Obtain the Order of Importance of Attributes: Which Attribute Would You Change from Its Worst State to Its Best State First? Second?

	Attributes and States		
	Cost	Productivity	Safety
State Limits	Initial Cost Savings, $M	Crew Hours Saved per Mission Day	Crew Hours Exposed per Mission Day
Best State	0.5	0.07	0.0
Worst State	0.0	0.4	0.2
Order of Importance	1.0	3.0	2.0

also be determined. First, the attribute scaling constants, $k_1 = 0.6$, $k_2 = 0.2$, $k_3 = 0.4$, are substituted into the multiplicative expression with the condition that all attributes be at their preferred utility values (1), then the overall utility u(x) is 1.0, and the multiplicative equation becomes:

$$u(x) = 1.0 = \frac{1}{k}\left\{\prod_{i=1}^{n}\left[1 + kk_i\right] - 1\right\}$$

or

$$1 + k = \prod_{i=1}^{n}\left[1 + kk_i\right]$$

The above equation is solved numerically for k = -0.47964264 (see Reference 6-2, Vol. II, pp. B-15 to B-17 for the specific subroutine).

With the attribute and master scaling constants at hand, the next step is to apply the attribute utility functions to the attribute state data to obtain utilities. Using the attribute utility functions illustrated in Figures 7-2, 7-3, and 7-4, the resulting attribute utilities are summarized in Table 7-6. The no-automation option is the trivial case and is not included in the table.

Table 7-6. Battery Example Attribute Utilities[a]

	Attributes and Utility Data					
Alternatives	Initial Cost Savings, \$M	Utility $u_1(x_1)$	Productivity in Crew Hours Saved/Mission Day	Utility $u_2(x_2)$	Safety in Crew Hours Exposed/ Mission Day	Utility $u_3(x_3)$
Automating verification	0.07	0.1750	0.03	0.4286	0	1.0
Automating monitoring verification	0.14	0.3500	0.04	0.5714	0	1.0
Automating fault-management, monitoring and verification	0.42	0.8667	0.07	1.000	0.2	0

[a]Scaling Constant k_i 0.6 0.2 0.4

Master Scaling Constant k = -0.49764264.

The utilities, attribute-scaling constants, and master-scaling constant are substituted in the multiplicative equation with the following results:

(1) For alternative AV the overall utility, considering all attributes, is 0.5506.

(2) For alternative AMV the overall utility is 0.6528.

(3) For alternative AFMV the overall utility is 0.6701.

Thus, the ranking for the multiplicative model, with highest utility ranked first, is:

Man-Machine Alternative	Utility	Rank
AFMV	0.6701	1
AMV	0.6528	2
AV	0.5506	3

Examination of the attribute data for the example in Table 7-6 gives some insights into the ranking. The AMV alternative had better initial cost savings and better crew productivity than did the AV alternative; however, AMV and AV equal safety. Thus, the AMV must rank better than the AV system, regardless of the model used. In decision-theory terms, the AMV alternative dominates the AV alternative.

Comparison of the AMV attribute data with the AFMV data in Table 7-6, shows that the AFMV alternative has better cost and crew productivity savings, but a greater exposure to hazards. This exposure makes the AFMV's safety attribute less preferable. With the multiplicative model and the scaling constants of 0.6 for initial cost, 0.2 for productivity, and 0.4 for safety, the AFMV alternative's utility of 0.6701 is slightly higher than that of the AMV alternative. One could infer that the combined improvement in cost savings and productivity slightly outweighed the loss in safety. Although the battery example is trivial, it clearly demonstrates the subsystem alternative-ranking exercise. At the completion of the subsystem-level analysis the best alternatives are identified and the system-level, man-machine optimization problem is simplified considerably.

3. Optimizing the Man-Machine Mix for the Total System

Once the subsystem man-machine optimization is completed, the higher-level problem of selecting one alternative from each of the remaining man-machine sets to maximize net present-value benefits needs to be solved. Accordingly, let n be the total number of subsystems and let $A_k = a_{k1}, \ldots, a_{kt}$ be the reduced set of man-machine alternatives correspondingly derived. The overall problem has two solutions, depending on whether productivity has a dollar value:

First, if productivity does not have a dollar value assigned, then the equation takes the following form:

$$\max_{A,a} \sum_{k=1}^{n} \sum_{t=1}^{m} M_{kt}(a_{kt}) \tag{7-5}$$

subject to

$$\sum_{k=1}^{n} \sum_{t=1}^{m} C_{kt}(a_{kt}) \le C_T \tag{7-6}$$

where

a_{kt} = identified man-machine alternative, t, for a given subsystem, k

M_{kt} = crew manhour (workhour) savings associated with a given man-machine alternative, t, for a given subsystem, k

C_{kt} = net subsystem, k, cost considering the benefit of automating alternative, t

C_T = cost target for the total system

In formulating this problem, it is assumed that the objective and constraint functions are linear. This assumption is not absolutely necessary, but it simplifies the problem. It is also assumed that there are no interrelationships between the possible alternatives. Finally, it is assumed that the decision variables (a) have discrete values and that the parameters of the model are known with reasonable certainty. The last "parameter" assumption is not unreasonable in light of the supporting data and analysis provided throughout the methodology.

A slightly different formulation is obtained when a dollar value is assigned for productivity as shown in the following equations and ensuing discussion:

$$\max_{A,a} \sum_{k=1}^{n} \sum_{t=1}^{m} B_{kt} \, (a_{kt}) \tag{7-7}$$

subject to

$$\sum_{k=1}^{n} \sum_{t=1}^{m} \left(C_{kt} - B_{kt}\right) (a_{kt}) \leq C_T \tag{7-8}$$

$$\sum_{k=1}^{n} \sum_{t=1}^{m} W_{kt} \, (a_{kt}) \leq W_T \tag{7-9}$$

$$\sum_{k=1}^{n} \sum_{t=1}^{m} P_{kt} \, (a_{kt}) \leq P_T \tag{7-10}$$

$$\sum_{k=1}^{n} \sum_{t=1}^{m} H_{kt} \, (a_{kt}) = 0 \tag{7-11}$$

$$\sum_{t=1}^{m} a_{kt} = 1, \; k = 1, \; t = 1, \; \ldots \; ,m \tag{7-12}$$

in which

$$a_{kt} \geq 0 \qquad \text{all } k, \text{ all } n$$

where

B_{kt} = net benefit from automating subsystem, k, with alternative, t. This net benefit is made up of the benefit from manhours saved, M_{kt}, and other incremental net dollar benefits, c_{kt}, [i.e., B_{kt} is $(M_{kt} + c_{kt})$]

C_{kt} = net subsystem, k, cost not considering the benefit of automating alternative, t

C_T = cost target for the total system

W_{kt} = incremental weight impact of automating subsystem, k, with alternative, t

P_{kt} = incremental power impact of automating subsystem, k, with alternative, t

W_T = system-level weight constraint

P_T = system-level power constraint

H_{kt} = incremental hazard exposure time reduction due to automating subsystem, k, with alternative, t

a_{kt} = identified man-machine alternative, t, for a given subsystem, k

Equations (7-5) and (7-6) basically stipulate that crew workhours (manhours) saved be maximized subject to the constraint that the cost of a given subsystem (less the net cost-benefits) not exceed a set cost target. In the case where a monetary value for productivity exists, the major constraint Equation (7-8) states that the total monetary outlay for Space Station design, development, test, and evaluation, minus the estimated value of the time saved (both on-orbit and on the ground) and net benefits, cannot exceed the amount of money (C_T) allocated as the cost target for the launch date. Constraints (7-9) and (7-10), respectively, limit the weight and power of the full configuration with automation incorporated. Each of the coefficients on the left-hand side is written as a function of all the decision variables. Constraint (7-11) references the baseline design and stipulates that the total exposure time in hazardous environments must not increase, while Equation (7-12) requires that only one alternative be chosen for each subsystem.

In sum, the objective of Equation (7-7) is to maximize the benefits of automation to the Space Station over the lifetime of the vehicle. It is understood that it could take a number of years before the program begins to pay for itself. Therefore, to view this situation from the proper perspective, one approach is to convert the measure "time saved through automation" to an equivalent dollar value by parametric solution. Similarly, because it is unlikely that the required cost target will be known with certainty, the corresponding term, C_T, can also be treated parametrically and the problem solved for a range of values. At a minimum, this analysis will provide an imputed dollar figure for C_T or M; that is, it will establish what a viable cost target, or unit of time in space, should be worth, based on projected costs and savings. Of course, this approach is only temporary until an actual cost target and productivity value are established.

Because the man-machine alternatives have been pared down by the "efficient subset" and subsystem "decision analysis" routines, the maximization problem is translatable into a fairly small linear program that is solvable with either the branch and bound technique or the simplex method algorithm (Reference 7-11). The branch and bound technique begins by obtaining a bound on the objective function by suppressing the dependencies at the system level, i. e., by fixing the values in Equations (7-7) through (7-10) at their upper values and solving the resultant integer linear program. Next, the branch and bound technique requires that the set of all feasible solutions (i.e., in this case, man-machine alternatives) first be partitioned into several subsets. Because the objective in the previous cost and productivity equation is to maximize workhours (manhours) saved and net benefits without exceeding a cost ceiling, any subset of alternatives that surpasses the cost ceiling is excluded. The remaining subsets are then partitioned further and examined in the same fashion. This process is repeated until a feasible solution is found so that the upper bound of the last subset satisfies the objective function. Such a feasible solution must be optimal because none of the subsets can provide a better solution. This approach facilitates programming of the model. It is possible that no subset meets the objective function. In this event, the next step is merely to select the subsets that minimize the difference between the cost target and upper bound on each subset of man-machine alternatives.

The second solution technique, the simplex method, uses an efficient algorithm for solving linear programming problems. In this method the constraint inequalities are first converted to equalities by introducing slack variables. The resultant system of simultaneous equations is solved repeatedly for sets of basic feasible solutions with each one better than the previous one. The process goes on until an optimal solution is reached. An optimal solution is a feasible solution that has the most favorable value for Equation (7-7). In this application the optimal solution would be the system-wide, man-machine alternative subset that exhibits the maximum benefit in workhours (manhours) saved and cost savings, while satisfying the system-level constraints.

D. DETERMINATION OF BEST TECHNOLOGY GROWTH PATH

The previous subsections demonstrate the use of multi-attribute decision analysis to further trim the subsets of man-machine alternatives associated with each subsystem, followed by an overall system-level optimization. The intent of exercising the decision analysis for the subsystem optimization scheme is to make the final system-level solution as efficient and simple as possible (i.e., to reduce the number of equations and variables to a level manageable by a small, desk-top computer). Once the optimal man-machine alternatives have been selected for the complete system, the final step in the methodology is to plot the best technology incorporation plan for out-year station growth. This plan might require new technology to further automate crew functions as a move towards greater station autonomy, or to meet distinct mission demands.

The earlier application of multi-attribute decision analysis concentrated on only three attributes: (1) net initial cost savings, (2) crew productivity (in workhour savings), and (3) safety (in net reduction to hazards). In ordering the various technologies, the complete range of ten attributes must be considered. Figure 6-1 graphically depicts the total range of attributes required to solve the multi-attribute decision problem associated with technology rankings. The complete list of attributes is as follows:

(1) IOC cost (1984$).

(2) Life-cycle cost (1984$).

(3) Weight (kilograms).

(4) Power consumption (kilowatts).

(5) Station/ground-crew productivity (manhour savings).

(6) Reliability (hours per day).

(7) Technology importance to out-year missions (subjective value).

(8) Technology availability (years beyond IOC).

(9) Retrofit amenability (subjective value).

(10) Safety (hours exposed to hazards per day).

As with the man-machine alternatives problem, the technology alternatives are (1) first specified by subsystem, (2) the attributes are established and defined in terms of their respective states, followed by (3) a determination of individual preferences for certain technologies that ultimately leads to the technology ranking. Although a thorough assessment of technology options will be the subject of subsequent research, this analysis will undoubtedly begin with the likely Space Station technologies identified by the Space Station Advanced Technology Advisory Commission (ATAC) (Reference 7-12). Table 7-7 lists the primary technologies that will be studied during the next research phase. Attribute states will need to be developed for each set of technologies associated with various station subsystems (e.g., projected costs, additional workhour savings, and projected availability times). Although the decision analysis is complicated by the larger array of attributes, the technology ranking problem is somewhat simplified because many technologies apply to several different subsystems.

Several significant results have surfaced in closing this first phase of the man-machine trade-off analysis effort. First, and most important, the overall objective of developing a methodology to assess man-machine automation trade-offs and technology options for spacecraft (and specifically Space Station) was achieved. This result carries considerable weight because the early literature search revealed (1) no apparent system-level method for assessing benefits and penalties of spacecraft automation and (2) no well-defined technique for prioritizing, and planning incorporation of,

Table 7-7. List of Potential Space Station Technologies

Generic Function	Applicable Technology	Application	Area of Application
Sensing	Sensors Vision Tactile Proximity Force/torque Position/velocity	Inspection Cleaning Reconfiguration Manipulation for task execution	Maintenance/repair Station Payloads Construction/assembly
	Smart sensors		
	Sensor fusion	Orientation for task execution	
	3-D vision		
Input/Output	Character recognition	Operator/station communication	Ground orbit: all activities requiring operator/machine-control interface
	Voice recognition		
	Voice synthesis		
	Speech understanding		
	Language representation		
	Natural language		
	Touch input devices		
	Color graphics	Scene analysis	
	Heads-up displays	Dynamic scene simulation	
	Holographic displays		
Data Storage	Optical data storage devices	Short-term archiving Procedures references	
	Magnetic bubble storage	Activities/events logs	

Table 7-7. (Cont'd)

Genric Function	Applicable Technology	Application	Area of Application
Artificial Intelligence	Expert systems	Planning Path/trajectory	Operations
	Advisory knowledge base systems	Tracking/control Traffic ILS	Planning/scheduling: Gnd-based
	Analogical reasoning	Resource utilization Service tasks	On-orbit Housekeeping
	Monotonic reasoning	Maintenance management	
	Nonmonotonic reasoning	Subsystem management	
	Heuristic search	Mission profile optimization	
	Knowledge representation		
		System/subsystem test	System verification acceptance
	Automatic learning	Constraint monitoring	
	Adaptive database management	Fault detection	Fault management
	Self-adaptive control	Anomaly analysis	
		Fault correction	
		Maintenance planning/modification	
		Productivity/scheduling impact assessment	
		Station and free flier information control	Stationkeeping
		Free flier approach control	
		Proximity operations	
		Momentum management	
		Orbit maintenance	

C-2

Table 7-7. (Cont'd)

Genric Function	Applicable Technology	Application	Area of Application
Artificial Intelligence	Supervisory control Expert process controllers Expert maintenance controllers	Process control	Payloads
Remote Operation	Teleoperation/telepresence Dexterous arm Dual arm coordinator Multi-system coordinator Gross manipulator	Equipment handling Berthing, securing Unit changeout Visual inspection Propellant/fluid transfer Handling Small loads Small clearance Tool manipulation Stowage	Station Assembly/construction Service/repair Payload/free flier Installation Operation Reconfiguration
Fault Tolerance	Fault-tolerant Architecture Data transfer Storage Processors Software	All data handling and processing	
Software Control	Operating system Procedure-oriented languages	Application software Control algorithms	Operations control Ground Orbit Station Payloads Free fliers Platforms

advanced automation technologies. In terms of developing tools to aid the design and planning of spacecraft systems to be flexible for future growth and built within budget constraints, this methodology clearly represents a keystone in that development process.

The next major result was that a large amount of knowledge was obtained in the process of building the methodology. For example, the problem of deciding what to automate and what not to automate is a complex combination of crew task, design, and cost variables interlaced with consideration of several competing program objectives (e.g., budget, safety, and schedule constraints). Indeed, the approach presented in this report respects the complexity of the problem by incorporating four distinct, but integrated, modeling techniques in the solution framework (i.e., functional networking, conceptual-design and cost-benefit assessment, multi-attribute decision analysis, and system optimization).

The third significant result was the definition of major spacecraft design drivers. Although spacecraft experts have been aware of the design drivers for some time, the importance of this result revolves around the development of a decision framework that integrates both quantitative and qualitative measures of the drivers. A strong decision-making foundation was provided through multi-attribute utility theory. This technique will prove to be a valuable tool for solving the technology-ranking problem in ensuing study phases.

The last major result was that the practicality of the methodology was able to be demonstrated on a simple example. This demonstration was accomplished with the storage-battery subsystem. Other results of this research phase are elaborated on in Section VIII.

SECTION VIII

RESULTS AND RECOMMENDATIONS

A. OVERVIEW

This study establishes an analytical framework for assessing both man-machine mix trade-offs and advanced automation technology options, as related to Space Station. This initial feasibility and methodology design investigation provides an understanding of strengths and weaknesses within the framework and supporting database. Some of the problem areas are discussed separately as each aspect of the methodology is developed. In closing, the following paragraphs summarize the results of the study and problem areas encountered from this initial study phase. Additionally, recommendations are provided for follow-on research.

B. SUMMARY OF RESULTS

Table 8-1 summarizes the results of the Phase I automation trade-off assessment. The methodology was judged "good" in the areas of functional task networks and database support. This assessment was based on the clear existence of manned-spacecraft operational logs, actual astronaut experience, and reasonable availability of cost and logistical support experience. One follow-on goal for these areas is to investigate whether greater granularity can be achieved in the task and reliability data.

From an input data standpoint, it seems that the productivity and design assessment, as well as supporting cost inputs, are fairly in-line with the estimates resulting from models such as PRC.

The conceptual design examples provided in this report strongly indicate that it is feasible to develop conceptual designs and costs for automation. However, while the supporting cost and productivity attributes can be clearly defined, most of the remaining attributes cannot yet be concisely quantified. Similarly, without a value for crew productivity time, the man-machine and technology optimization (or prioritization) techniques, although reasonable, are still incomplete.

One strength that the technique demonstrates is the ability to draw on, or incorporate, several different automation and costing studies under one trade-off framework. This aspect of the methodology is strongly addressed in Section II.

Finally, in the last category (actually applying the technique), it is unclear at this stage of research whether or not the technique will be able to be exercised on subsystems other than the battery example. This uncertainty primarily revolves around the attribute quantification problem addressed above.

Table 8-1. Space Station Man-Machine Trade-off Findings

Methodology Area	Results in Terms of Data Availability/Quality: Good	Reasonable	Unknown at this Stage
Technique demonstrates capability to develop representative crew functional task networks	X		
Data-base development to support technique seems feasible	X		
Methodology data input/output accuracy appears to be at equivalent to present conceptual design costing bases	X Input		X Output
Technique demonstrates capability to provide reasonable automation conceptual design configuration/cost estimates	X		
Technique demonstrates ability to identify and characterize key design attributes	X		
Technique demonstrates ability to quantify discretely all design attributes		X Cost, Productivity	X Remaining attributes
Technique exhibits a strong approach for prioritizing man-machine and technology options		X	
Technique exhibits strong synergism with other related automation and costing studies such as ARAMIS, THURIS, and the PRC cost model	X		
Technique fully demonstrated on actual subsystem		X Battery example	X Actual Space Station subsystems

C. RECOMMENDATIONS

In summarizing this first stage of the man-machine automation trade-off research, the following prioritized list of follow-on study areas is provided to assist in establishing a plan for the next stage of methodology development.

(1) Database Development.

(a) Explore and define more thoroughly life-cycle cost variables and their relationships to varying degrees of automation.

(b) Continue to tap other associated databases for supporting input data (e.g., THURIS, PRC, Langley database).

(c) Examine task time-line databases to expand ground and station functional networks (for other functions and modules).

(d) Pursue a value of crew time saved.

(e) Initiate the methodology software design/development.

(2) Applications.

(a) Continue developing automation examples and supporting conceptual designs.

(b) Demonstrate the complete technique on more subsystems.

(3) Methodology Design.

(a) Solidify the multi-attribute decision and weighting criteria.

(b) Further quantify attributes and develop the supporting database.

(4) Human-Machine Functional Allocation.

(a) Explore all human-factor aspects of functional allocation problem (e.g., motivational, psychological, etc.).

(b) Revise functional allocation criteria to incorporate complete scope of human-factor variables.

(c) Develop weighting criteria for functional allocation criteria.

SECTION IX

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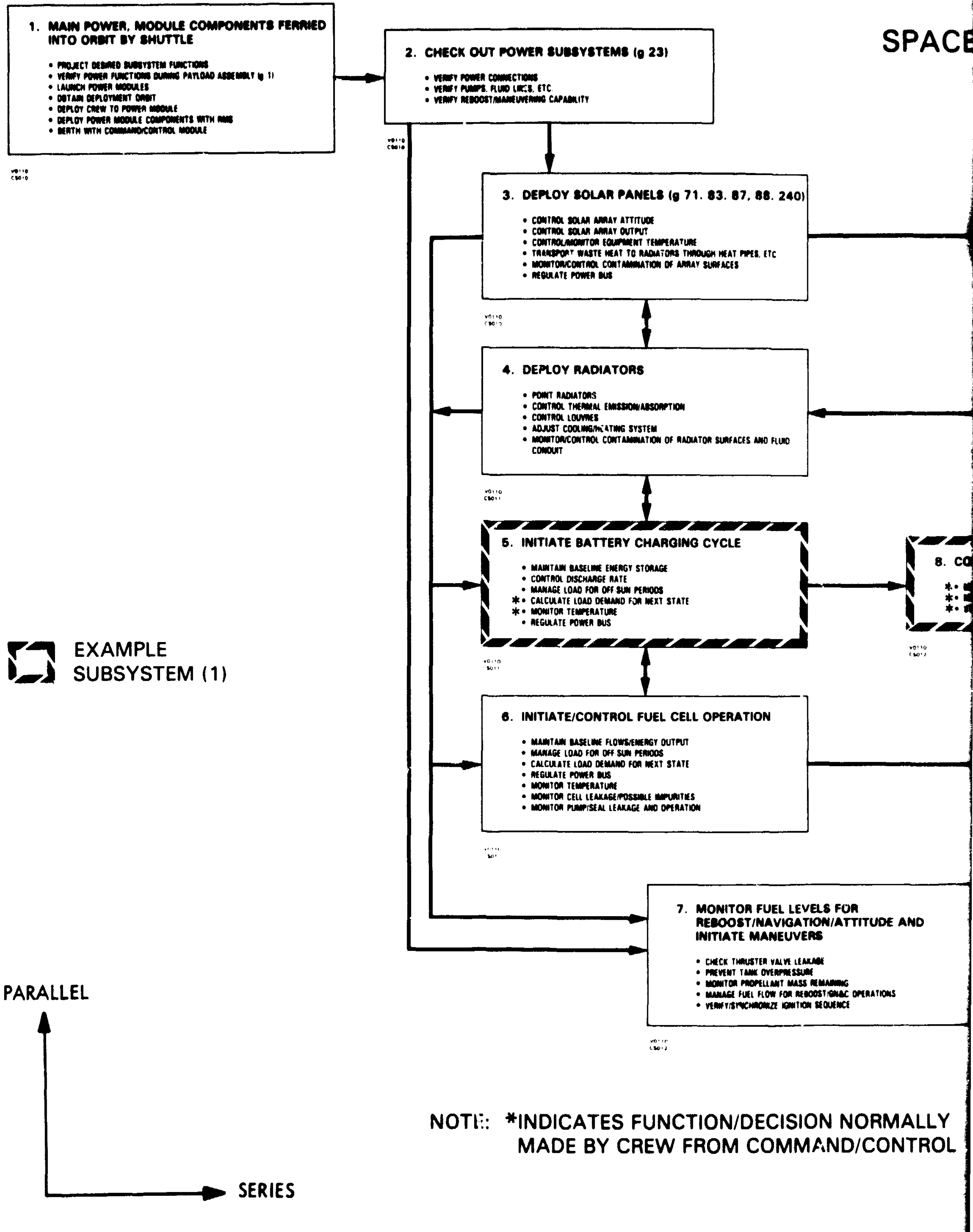
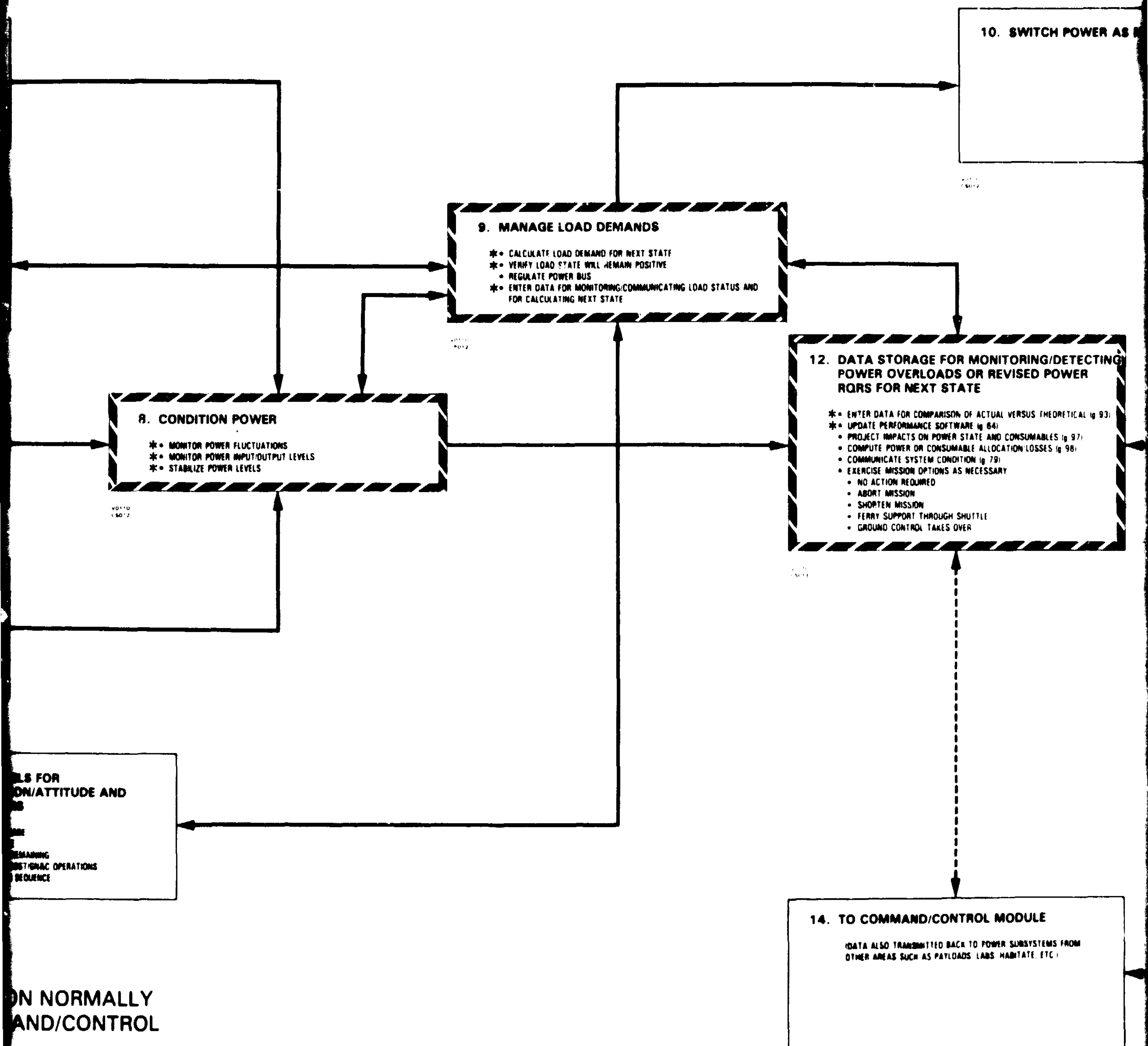
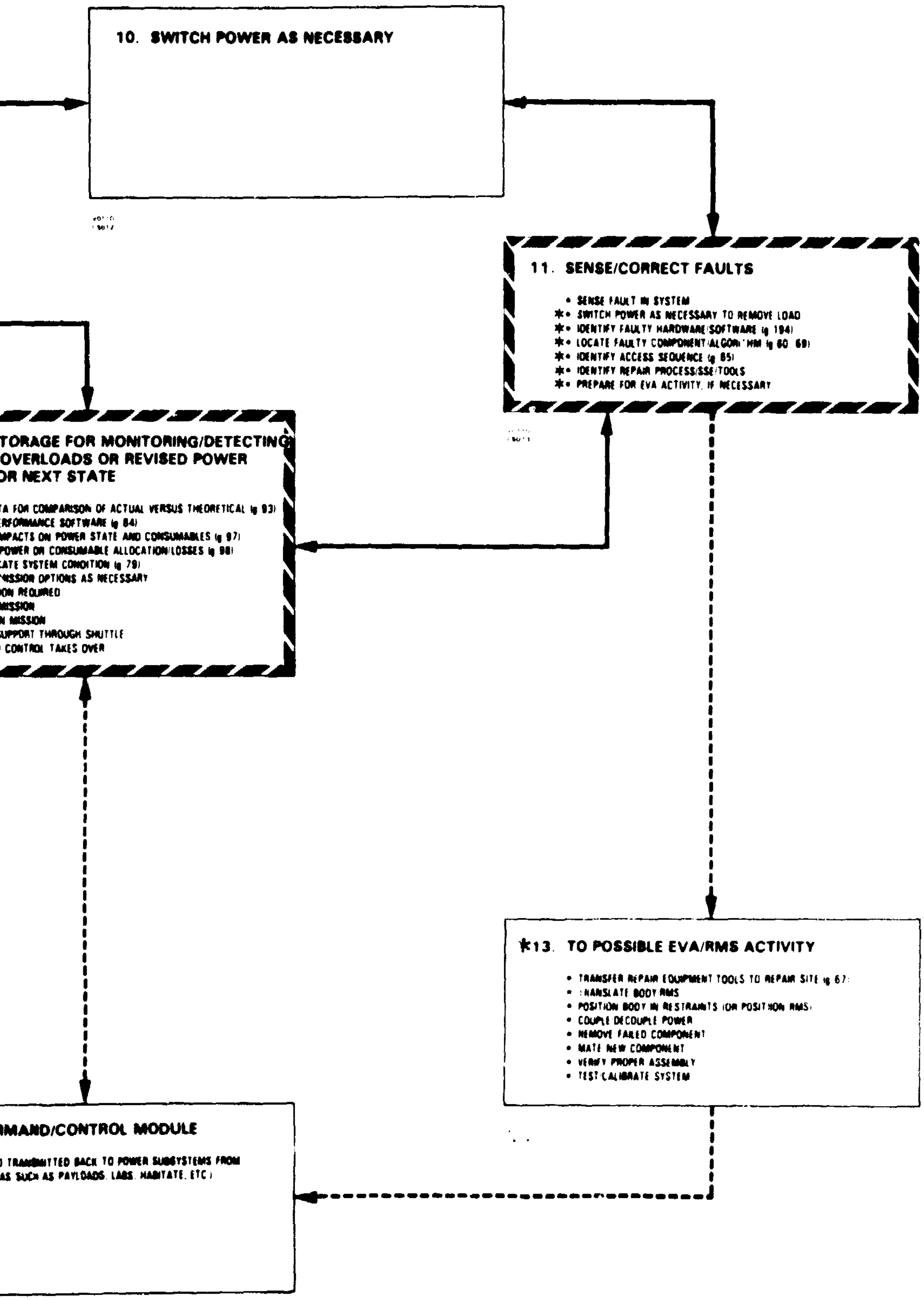


FOLDOUT FRAME

APPENDIX A
SPACE STATION POWER MODULE NETWORK



2 FOLDOUT FRAME


10. SWITCH POWER AS NECESSARY
11. SENSE/CORRECT FAULTS
• SENSE FAULT IN SYSTEM
*• SWITCH POWER AS NECESSARY TO REMOVE LOAD
*• IDENTIFY FAULTY HARDWARE/SOFTWARE (g 194)
*• LOCATE FAULTY COMPONENT/ALGORITHM (g 80, 69)
*• IDENTIFY ACCESS SEQUENCE (g 85)
*• IDENTIFY REPAIR PROCESS/SSE/TOOLS
*• PREPARE FOR EVA ACTIVITY, IF NECESSARY
TORAGE FOR MONITORING/DETECTING
OVERLOADS OR REVISED POWER
OR NEXT STATE
TA FOR COMPARISON OF ACTUAL VERSUS THEORETICAL (g 93)
ERFORMANCE SOFTWARE (g 84)
MPACTS ON POWER STATE AND CONSUMABLES (g 97)
POWER OR CONSUMABLE ALLOCATION/LOSSES (g 98)
CATE SYSTEM CONDITION (g 79)
MISSION OPTIONS AS NECESSARY
ON REQUIRED
MISSION
N MISSION
SUPPORT THROUGH SHUTTLE
CONTROL TAKES OVER
*13. TO POSSIBLE EVA/RMS ACTIVITY
• TRANSFER REPAIR EQUIPMENT TOOLS TO REPAIR SITE (g 67)
• TRANSLATE BODY RMS
• POSITION BODY IN RESTRAINTS (OR POSITION RMS)
• COUPLE DECOUPLE POWER
• REMOVE FAILED COMPONENT
• MATE NEW COMPONENT
• VERIFY PROPER ASSEMBLY
• TEST CALIBRATE SYSTEM
MMAND/CONTROL MODULE
TRANSMITTED BACK TO POWER SUBSYSTEMS FROM
AS SUCH AS PAYLOADS, LABS, HABITATE, ETC.)

APPENDIX B

SPACE STATION COMMAND/CONTROL MODULE

(See pocket on inside back cover.)

APPENDIX C

PAYLOADS ON IOC CO-ORBITER AND POLAR PLATFORMS

Table C-1 describes payloads on-board the Co-Orbiter Platform during the years 1991 to 1993. The service-interval data are extracted from the Mission Requirements Working Group (MRWG), Langley Database, March 30, 1984 version.

Table C-2 describes payloads on-board the Polar Platform during the years 1991 and 1993. The service-interval data are extracted from the MRWG, Langley Database, March 30, 1984 version.

Table C-1. Co-Orbiter Payload Servicing Data[a]

Experiment and Description									Servicing Data	
					Mass		Temperature, °C			
Code	Description	Average Power, kW	Peak Power, kW	Dimensions, (a)	kg	lb	Min	Max	Servicing Consumables	Service Interval, days
SAA0004	Shuttle Infrared Telescope Facility (SIRTF)	0.7	2.0	8.5x4.0x4.0	4,000	8,820	0	40	Superfluid Helium	730
									Configuration Change	1,825
SAA0006	STARLAB	2.2	3.9	7.0x2.0x2.0	3,200	7,055	0	40	Configuration Change	1,095
SAA0007	High Throughput Facility	2.0	3.0	2.0x2.0x2.0	10,000	22,000	0	40	Configuration Change	1,095
SAA0009	Pinhole Occulter Facility	0.57	2.0	50.0x3.3x3.3	3,600	7,940	0	40	None	

[a]Payload is on a 50-m boom.

Table C-2. Polar Payload Servicing Data

Experiment and Description									Servicing Data	
					Mass		Temperature, °C			
Code	Description	Average Power, kW	Peak Power, kW	Dimensions, (a)	kg	lb	Min	Max	Servicing Consumables	Service Interval, days
SAA0208	Moderate Resolution Imaging Spectrometer	0.7		2.0x1.5x0.85	360	795	10	30	None	365
SAA0209	High Resolution Imaging Spectrometer (HIRIS)	1.4		2.9x2.3x2.3	2,100	4,630	10	30	None	365
SAA0210	High Resolution Multi-frequency Microwave Radiometer	1.35		6.5x4.0x1.5	320	705	10	30	None	365
SAA0211	Laser Atmospheric Sounder (LASA)	2.0	4.0	3.6x2.3x2.3	1,300	2,870	10	30	None	365
SAA0212	Synthetic Aperture Radar (SAR)	6.0	8.0	12.0x12.0x1.7	1,000	2,205	10	30	None	365
SAA0213	Radar Altimeter (ALT)	0.24		1.0x0.4x0.4	150	330	10	30	None	1,100
SAA0214	Scatterometer (SCATT)	0.2		1.0x0.4x0.35	150	330	10	30	None	365
SAA0219	Environmental Monitor	0.3		0.8x0.6x0.6	300	660	10	30	None	365
SAA0220	Automated Data Collection and Location System	0.2		1.0x10.0x10.0	300	660	10	30	None	1,100
COM1019	Multi Linear Array Stereo	1.4		1.0x1.0x1.0	92	205	-------- None Specified --------			

[a]Dimensions for SAA0220 include crossed 10-m antennas.

APPENDIX D

AUTOMATION OF RENDEZVOUS AND DOCKING FUNCTIONS

There are several possible rendezvous and docking (henceforth denoted by the acronym REND) scenarios in unmanned platform operations to consider as a model for functional breakout. These scenarios are:

(1) STS RENDs with the platform (both polar and co-orbiting).

(2) Co-orbiting platform RENDs with the Space Station.

(3) OMV RENDs with the platform (both polar and co-orbiting).

For the purposes of the discussion that follows, Scenario (3) is chosen (primarily to support the generation of inputs to a ground-crew operation versus on-board operations trade).

A REND can be divided into three basic phases of operation:

(1) Rendezvous. Operations from the OMV parking orbit or OMV station (at the Space Station or STS) to within a 1-km "box," representing the vicinity of the target vehicle (i.e., an unmanned platform).

(2) Terminal Rendezvous. Operations of the OMV and target vehicle within the 1-km "box" until the OMV makes physical contact with the target vehicle (including any contact with an appendage, such as a berthing mechanism)

(3) Docking/Berthing. Operations of the OMV and target vehicle from the moment of physical contact until the two can be considered a new configuration of the target vehicle.

The following functional breakout is performed for each of these three phases of the REND operation. The focus is primarily the unmanned platform functions in each phase except for rendezvous. Assumptions on the REND operation are:

(1) OMV performs rendezvous, using the target vehicle position telemetered from the ground station. The OMV performs on-board trajectory and navigation updates to a planned rendezvous sequence.

(2) Upon completion of a successful rendezvous, the OMV will be commanded (by ground station or target vehicle) to maintain a station within the rendezvous "box." The OMV remains on station until terminal rendezvous commences.

(3) The target vehicle will be "passive" during the terminal rendezvous with the OMV. However, the target vehicle will perform traffic control, guiding the OMV to the docking port or berthing apparatus.

(4) The OMV receives commands and transmits telemetry directly to the target vehicle during the terminal rendezvous operation.

I. RENDEZVOUS FUNCTIONS

A. Planning: Initial Trajectory Computation

1. Rendezvous timing parameters

2. Target vehicle orbit and OMV orbit input parameters

B. Orbit Transfer: Execution

1. Control

a. Thrust vector alignment

b. Attitude control

2. Guidance

a. Update/optimization of trajectory computation

b. Update propellant usage profile

3. Navigation

a. Compute update to OMV orbit

b. Target orbit achievement assessment

4. Communication (through TDRSS) and Tracking (through GPS)

a. Telemetry and audit trail transmission to ground

b. Command receipt from ground updating target vehicle position

c. Receipt of signals from GPS

5. Propulsion

a. Propellant remaining

b. Center of mass drift

C. Orbit Trim: Stationkeeping

1. Control

a. Orbit correction

b. Translational control

c. Attitude control

2. Navigation

a. Orbit parameter computation

b. Relative position to target vehicle determination

c. Stationkeeping translational command generation

3. Communication and Tracking

a. Telemetry and audit trail transmission to the ground

b. Receipt of stationkeeping commands from target vehicle

c. Command receipt from the ground

d. Signal receipt from GPS

II. TERMINAL RENDEZVOUS FUNCTIONS

A. Planning

1. Communication and Tracking

a. OMV acquisition

b. Ranging by target vehicle of OMV

c. Signal receipt from GPS

d. Command/data receipt from ground stations

2. Navigation: Orbit parameter computation

3. Traffic Control

a. Generation of approach corridor for OMV: Command sequence

b. Generation of collision avoidance command sequence

4. Payload Control

a. Cage or shuttering of instruments

b. Control gain reset for docking/berthing disturbances

5. Attitude Control

a. Control law selection for docking/berthing disturbances (e.g., use of manipulators)

b. Sensor complement readiness (e.g., gyros, accelerometer turned on/readied)

c. Update of fault protection

d. Caging/damping selection for arrays, antennas

e. Thruster selection

6. Manipulators

a. Uncaged and commanded to berthing position

b. OMV model selection for acquisition

7. Propulsion: Thruster and tank-usage selection

B. Commanded Translation of OMV

1. Communication and Tracking

a. Transmission to OMV of:

(1) Collision avoidance commands

(2) Translational/attitude commands

b. Receipt of OMV telemetry: attitude and axial rates, status

c. Ranging for OMV translational position, rate

d. Telemetry and audit trail transmissions to ground station

2. Traffic Control

a. Update to approach trajectory: command generation of translation, approach rates and OMV attitude, attitude rates

b. Update to collision avoidance: command generation

3. Manipulators

a. OMV acquisition

b. Synchronization of manipulator motion with OMV attitude and rates

III. BERTHING FUNCTIONS

A. Initiation

1. Traffic Control

a. Determines OMV within berthing cone

b. Generates command for OMV to station keep within the berthing cone

2. Manipulators

a. Receive command (from on-board executive) to berth the OMV

b. Positions end effector for attachment to OMV

B. Attachment

1. Communication and Tracking

a. Transmits command to OMV to suppress attitude control

b. Receives OMV telemetry

c. Transmits telemetry to ground station

2. Manipulators

a. Attaches manipulator to OMV

b. Performs residual rate control and disturbance suppression of berthed manipulator/OMV configuration

3. Attitude Control

a. Control OMV and manipulator induced rates and disturbances with combined use of thrusters and MEDs

b. Senses disturbances using gyros and accelerometers

IV. DOCKING FUNCTIONS

A. Initiation

1. Traffic Control

a. Determines that OMV (or attached OMV/manipulator) is within cone of docking port

b. Generates commands for OMV to perform translation to docking port at a given rate of approach, to achieve a given attitude, to reduce attitude rates

2. Manipulators: In case of OMV/manipulator berthed configuration

a. Generates approach sequence to position OMV at the docking port

b. Selects/updates control law for manipulator/OMV configuration

B. Attachment

1. Traffic Control: Commands OMV contact with the docking port

2. Communication and Tracking

   a. Transmits command to OMV to perform contact and suppress attitude control

   b. Receives OMV telemetry

   c. Transmits telemetry to ground station

3. Manipulators: Performs attachment of OMV to the docking port

4. Attitude Control

   a. Controls OMV and manipulator induced rates and disturbances with combined use of thrusters and MEDs

   b. Senses disturbances using gyros and accelerometers

   c. Attenuates the docking disturbances

   d. Determines new mass/inertia of combined systems and updates control laws

5. Power and Thermal Control

   a. Provides power and accepts the thermal load of the docked OMV

   b. Perform grounding and static discharge of the docked OMV

6. Data: Provide direct communication link with the docked OMV

APPENDIX E

DETAILED DISCUSSION OF MULTI-ATTRIBUTE DECISION THEORY

This Appendix expands the multi-attribute decision theory discussed in Section VII, which summarized the multiplicative utility model and included a supporting example to demonstrate how alternatives are ranked, based on decision makers' preferences. The following paragraphs provide a more detailed theoretical foundation for the multiplicative model and a means of verifying results.

The formulation described in the following paragraphs quantifies attribute states on a numerical scale that represents the preferences of the decision maker for the various states that the attribute can assume. The function that transforms an attribute state into a numerical representation of attribute preference is called an attribute utility function. It is represented by the expression $u_i(x_i)$, the attribute utility function value for the ith attribute in the attribute state x_i. The proven algebraic expression combining the attribute utility functions is called an outcome utility function u(x), with $(x_1, \ldots, x_n)$ being the n-attribute outcome. An outcome utility function is a numerical representation of the decision maker's preferences for the outcomes. The use of the word "utility" to represent preference or value has a rich and venerable history in economics. It is convenient to measure attribute utility functions on a scale from 0.0 to 1.0, where $u_i = 0.0$ corresponds to the least-preferred ith attribute state that occurs among the outcomes under consideration, and $u_i = 1.0$ corresponds to the most-preferred state. A hypothetical utility function for station power (attribute x_4 of Figure 6-1) might be as shown in Figure E-1. Note that, because $u_4(x_4) = 40 = 0.5$ in Figure E-1, one could interpret this as meaning that the decision maker has the same preference in decreasing power consumption from 50 to 40 kW as decreasing power consumption from 40 to 10 kW.

If all the other attributes of an outcome are held at constant states, it is theoretically possible to construct an attribute utility function as shown in Figure E-1. There are several techniques for determining the form of the attribute utility function. These include direct-magnitude estimation, preference-difference assessments (either rank ordering of preference differences or equal preference-interval scaling), ratio scaling, and the lottery method (References 7-7 and 7-8). The lottery method is recommended because of its simplicity, theoretical consistency, its widespread discussion in the literature, and the fact that it provides a straightforward way of handling uncertainty. Figure E-2 illustrates a question that might be asked to obtain utility function values using a lottery or gamble technique.

If the other attributes are not held at constant states then the concept of an attribute utility function has no theoretical or practical validity unless certain independence conditions are satisfied. The most obvious independence condition is that the form of the attribute utility function should not change if the other attributes are held at constant, but different, attribute states. This independence condition allows the concept of an attribute utility function to be meaningful. The name given to this type of

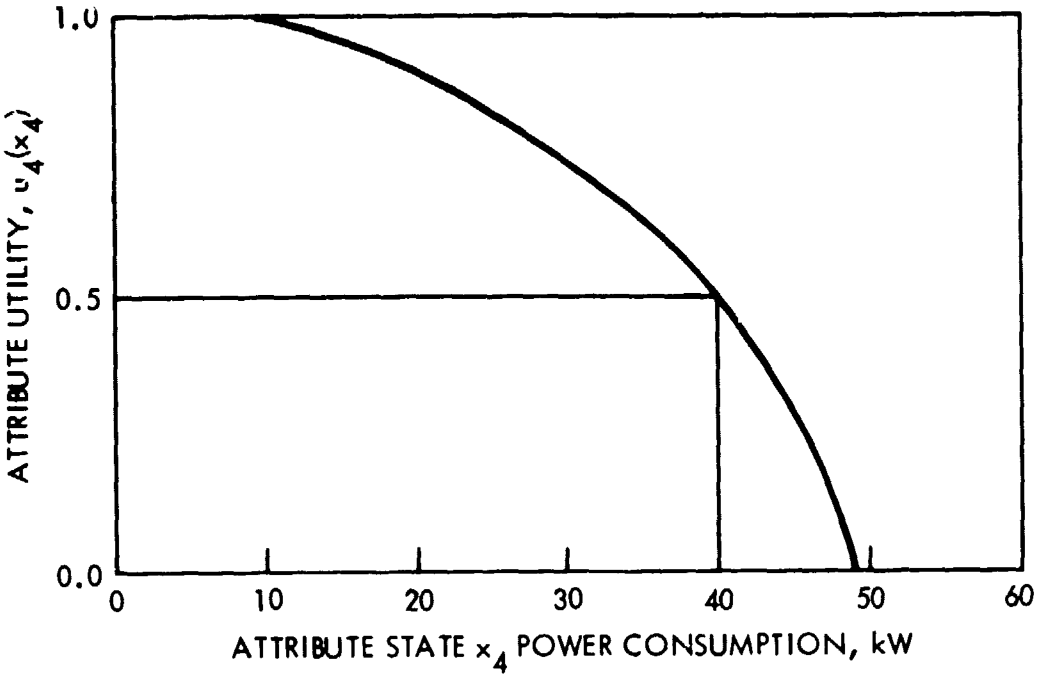


Figure E-1. Typical Attribute Utility Function

attribute independence is utility independence. In other words, the responses to questions posed to obtain a utility function for power consumption should not change if the levels of the other attributes such as weight or initial cost change.

If the attributes satisfy utility independence, then the utility of the outcomes can be computed as a weighted sum of the attribute utilities, e.g., where $x = (x_1,x_2)$,

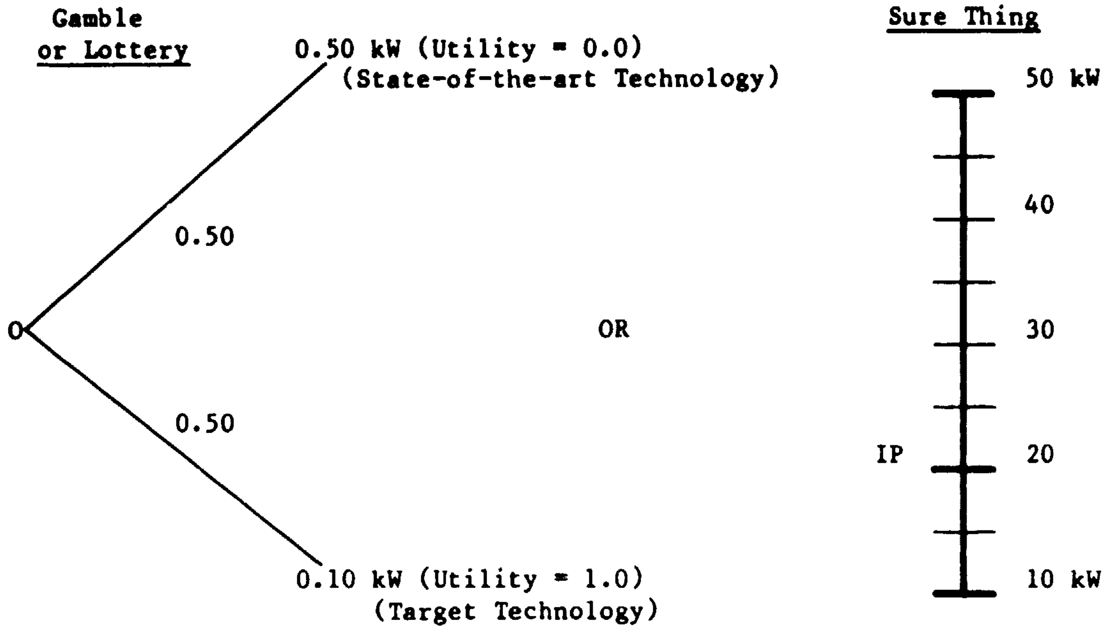
$$u(x) = k_1u_1(x_1) + k_2u_2(x_2)$$

Unfortunately, utility independence of the attributes alone does not suffice mathematically to ensure that the outcome utilities can be correctly computed as the weighted sum of the attribute utilities. Keeney and Raiffa (see Reference 6-1) show that for the two-attribute case, $x = (x_1,x_2)$, the correct formula, assuming utility independence, is actually:

$$u(x) = k_1u_1(x_1) + k_2u_2(x_2) + (1 - k_1 - k_2)\, u_1(x_1)\, u_2(x_2)$$

The established mathematical derivation shows the presence of a multiplicative term $u_1(x_1)\, u_2(x_2)$ with a weighting factor of $(1 - k_1 - k_2)$.

Attribute: Power Consumption



Question: CHOOSE A VALUE OF THE "SURE THING" FOR WHICH YOU ARE INDIFFERENT BETWEEN THE "SURE THING" AND THE "GAMBLE."

Response: EXAMPLE INDIFFERENCE POINT 20 kW.

(THE RESPONSE TO THIS QUESTION YIELDS THE "SURE THING" VALUE FOR POWER CONSUMPTION THAT HAS A UTILITY OF 0.5.)

Figure E-2. Illustration of a Lottery to Obtain Utility Function Values

A simple example can illustrate why the weighted sum can yield incorrect orderings of outcome preference. Consider the selection of an aircraft with the two attributes of concern being x_1 = payload weight and x_2 = aircraft range. A weighted sum could incorrectly give preferential ranking to an aircraft with a very large payload weight [where $k_1 = 1$ and $u_1(x_1) = 0.8$], but whose range was less than the majority of the routes being considered [where $k_2 = 1$ and $u_2(x_2) = 0.2$]. In this case, $u(x) = 0.84$ and would, therefore, rate this aircraft alternative rather high as a preference even though the utility of "short" range (0.2) is low.

To prevent inaccurate results such as the above example, Keeney (see Reference 6-1) has developed a practical algebraic expression for combining the attribute utility functions to obtain an outcome utility function. Rather than testing each attribute for utility independence, Keeney has shown that it is only necessary to test one attribute for utility independence (call it the reference attribute) and then to verify that the pair-wise trade-offs of the reference attribute versus each of the other n-1 attributes are independent of the states of the remaining n-2 attributes. This pair-wise trade-off independence is called preferential independence and is not difficult to verify in practice. To illustrate this concept, consider the trade-off between initial cost and power consumption. For preferential independence to hold, this trade-off would have to be independent of the states of the six other attributes shown in Figure 6-1 of the report. These n independence conditions (one utility independence and n-1 preferential independence) then lead to an algebraic expression for the outcome utility function of the form:

$$u(x) = \frac{1}{k}\left\{\prod_{i=1}^{n}\left[1 + kk_i u_i(x_i)\right] - 1\right\}$$

where:

- n = number of attributes
- $u(x)$ = outcome utility function
- $u_i(x_i)$ = attribute utility function of the i<u>th</u> attribute
- k_i = scaling constant ranging between 0.0 and 1.0 that determines the "weight" or "importance" of the i<u>th</u> attribute
- k = master scaling constant that is an algebraic function of the k_i, scaling $u(x)$ from $u = 0.0$ to $u = 1.0$

For the details of the proof, see Reference 6-1. This utility function will henceforth be called the multiplicative function or multiplicative model.

The n scaling constants, k_i, determine the relative importance of the associated attributes. The range for k values is from 0.0 to 1.0, with the larger values associated with the more important attributes. If the n k_i's sum to 1.0, then the multiplicative model simplifies to the additive model.

When the necessary independence conditions are violated, it is possible to divide the attribute-state ranges into intervals over which the independence conditions are approximately valid, or the set of attributes can be redefined so the independence conditions are valid. It is important to distinguish these independence conditions from the "technical dependence" of variables that define the system model. This latter type of dependence arises naturally in engineering systems and only restricts the set of feasible states of the system model. In the aircraft example cited earlier, the engineering constraints on the design of the aircraft result in a technical dependence (or functional relationship) between aircraft range and payload weight. It must be stressed that this "technical dependence" has no effect on the value model. Preferential independence conditions required of the multiplicative formulation address the ability of a decision maker to make a pair-wise trade-off between two attributes in the presence of other attribute states. As shown in Section VII-B-1a, consumers practice pair-wise trade-offs in the presence of other attributes on a daily basis.

Use of the multiplicative model has on occasion raised the issue that the model is difficult to understand and that it is opaque. The term opaque here indicates that it is cumbersome to follow the calculations and to see how much impact a change in an attribute state value, or scaling constant, has on the overall utility of an alternative. One might also note that this opacity concomitantly carries a benefit of reducing the impacts of an individual who is hiding true preferences to influence the ranking results or who is not totally consistent in forming preferences.

The difficulty of the calculations required by the multiplicative model raises doubts in an audience seeing a ranking based on this model. If one alternative is ranked higher than another, a normal set of audience questions includes "Why?" and "How much higher?"

A utility function that features transparency and yields audience understanding of its resultant ranking is the additive function mentioned earlier:

$$u(x) = \sum_{i=1}^{n} k_i u_i(x_i)$$

where

$u(x)$ = outcome utility function

$u_i(x_i)$ = attribute utility function of the ith attribute

k_i = scaling constant ranging between 0.0 and 1.0 that determines the "weight" or "importance" of the ith attribute

n = number of attributes

The additive model does, however, require a more restrictive independence condition than the multiplicative form. This condition is additive independence. Additive independence for attributes $x_1, x_2, \ldots, x_n$, applies "if the preference order for lotteries does not depend on the joint probability distribution of these lotteries, but rather depends only on their marginal probability distributions."

To illustrate additive independence, consider lotteries L_1 and L_2 as shown in Figure E-3. Lottery L_1 yields equal (0.5) chance at the consequences (x^o,y') and (x',y^o). Note that both lotteries have an equal (0.5) chance at either x^o or x', and also that both have an equal (0.5) chance at y^o and y'. By definition, then, the marginal probability distributions on both the attributes X and Y are the same. If X and Y are additively independent, one must be indifferent between lotteries L_1 and L_2. This same indifference condition must hold if either or both x' and y' are changed in Figure E-3 because L_1 and L_2 would still have the same marginal probability distributions on the two attributes (see Reference 7-10).

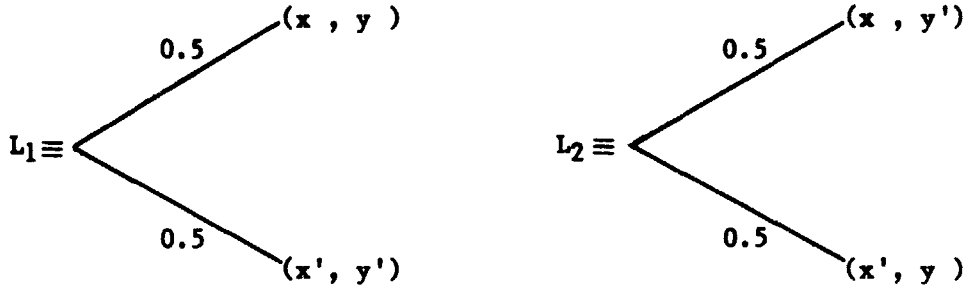


Figure E-3. Lotteries to Illustrate Additive Independence

For n attributes, the additive utility function exists if and only if all attribute pairs are additively independent. Often, additive independence of <u>all</u> pairs of attributes does not hold in practice.

At this point, one is faced with a dilemma: One could use the additive model, which is easier to understand but which is less rigorous because the required additive independence conditions are less likely to hold. Alternatively, one could use the multiplicative model, which is more rigorous because the required utility and preferential independence conditions are more likely to be verifiable but which is more difficult to understand.

One solution to this dilemma is to use both the multiplicative and additive models to prepare sets of rankings. If one gathers the utility functions and scaling constants for the multiplicative model, the scaling constants can be normalized to sum to 1.0 and used in the additive model. Microcomputer programs to accomplish this are already available. For example, see Appendix B in Volume II of Reference 6-2. Thus, the additional effort to determine rankings using both the additive and multiplicative models is quite small.

A legitimate concern regarding the use of both utility models is that the resulting rankings may differ significantly. If this is a concern, then the analyst should use the multiplicative form because of its rigor. In practice, however, differences between rankings from multiplicative and additive models do not seem to be statistically significant. For example, Feinberg, et al. found few differences between rankings produced by the two models for 39 individuals for 10 alternative advanced-vehicle technologies. The resolution of when to choose one form of utility model over the other, or whether a choice is necessary, will continue to be explored as more decision applications are completed.