THE FACILITIES AUTOMATED CONTROL AND TRACKING SYSTEM (FACTS)

by

Richard I. Mouri

Project Report submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree

Master of Science

in

Systems Engineering

APPROVED:

Konstantinos I. Triantis

K. Triantis, Chairman

P.M. Ghare

P. Ghare

B. Schinbeckler

B. Schinbeckler

April, 1990

Blacksburg, Virginia

THE FACILITIES AUTOMATED CONTROL AND TRACKING SYSTEM (FACTS)

by

Richard I. Mouri

Committee Chairman: K. Triantis

Systems Engineering

(ABSTRACT)

The continual rapid growth of a facility has tremendous impact on the construction program that is responsible for space allocation and renovations to accommodate changing tenant requirements. The manual method of tracking key design, construction, and procurement milestones is no longer adequate. Not only does the current effort expend an exorbitant amount of manpower, but the objective is no longer being accomplished.

The solution to this problem involves the application of the systems engineering process. Through the utilization of management science encompassing operations research techniques, human factors, and multiattribute analysis, an optimal solution is determined for automating the tracking and control of all project milestones.

The result is the employment of a project management software package that is written in dBase. It is customizable through access to its source code and the introduction of additional dBase code. This results in a manpower savings of eighteen man-months per year.

ACKNOWLEDGEMENTS

I would like to acknowledge my wife, Ellen, who took on the additional role of father, and my children Sarah and Cameron who learned to accept a situation that they did not fully understand. I would like to acknowledge my sister-in-law, Sarah Clement, for her insightful proofreading and flair for writing. I wish to thank Dr. Triantis, Dean Blanchard, Dr. Ghare, and Brad Schinbeckler for their counsel in completing this final step. I must acknowledge GE, Al Jose, Len Opheim, and Jim Bahler for providing me with time and resources, without which none of this would have been possible. Finally, a special acknowledgement goes to Jennifer Walz who acted as the project engineer for the FACTS program and did the majority of the coding.

TABLE OF CONTENTS

TABLE OF CONTENTS (cont)

TABLE OF CONTENTS (cont)

LIST OF FIGURES

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Everyone today is confronted by problems of labor, automation, inflation, and rising costs. People in all vocations are realizing that information, instantly available and accurate, holds great importance in meeting these problems head-on. Corporations, organizations, managers, churches, schools, and homeowners are all turning to the personal computer to help them solve their portion of these problems. (1)

This project represents one such application. The continual rapid growth of a facility has tremendous impact on the modification program that is responsible for space allocation and renovations. The manual method of establishing and tracking key milestones is no longer adequate. Not only does the current effort expend an exorbitant amount of manpower, but the objective is no longer being accomplished. The constraints are obvious and the goals are simple. All that remains is the establishment of a systems oriented team to put it together.

A classified facility is involved that is owned and directed by the government (the customer). One of the departments has a need for an automated system that will track construction modification milestones. The users of the system are contractor personnel. This situation can limit the extent of application of other solution methods. The system engineering approach, however, adapts to these circumstances quite well.

The remainder of this report is comprised of background information, a main body, conclusions, and recommendations. The main body of this report consists of the Systems Engineering Process and FACTS. The Systems Engineering Process section describes the extent to which Systems Engineering is applied to this project as well as the more intricate details of the solution techniques used.

1.1 Project Background

A 172,000 square foot facility was constructed in 1975 for conducting classified missions. Those missions have been so successful that the facility has continually grown at an average of 34,570 square feet per year for the past 14 years. The interior has been renovated continuously to meet the demands of increasing responsibilities, changing requirements, and new technology. These demands result from the expansion of tenant programs or the introduction of new ones. At any given time, between ten and twenty percent of the existing facility is undergoing construction modifications.

1.2 The Construction Modification Process

All of these dynamic changes have resulted in an efficient and proactive Facility Services Branch (FSB). FSB consists of the Facility Planning Staff (FPS), Engineering, Operations and Maintenance (O&M), and Design. In the specific area of construction, there are two principal scenarios. The first is the construction of a new block. This occurs when a growing program is too large to fit into the existing facility or, a new program is introduced. The second scenario, which this project is concerned with, is the modification of existing space.

Space is made available for modification when a tenant moves off-site or relocates within the facility. After the space is identified for other use, it must be determined who the new resident(s) will be, what their requirements are, who is the approving authority, when they will be able to occupy the area, and at what costs. This involves many phases of planning, estimating, coordinating, purchasing, scheduling, and decision making.

All modifications must go through an approval cycle, as represented in Figure 1. The customer brings an equipment list, a requirement for space and personnel, and a required occupancy date to FSB. This is in the form of a draft Request for Change (RFC). The FPS quickly assesses the

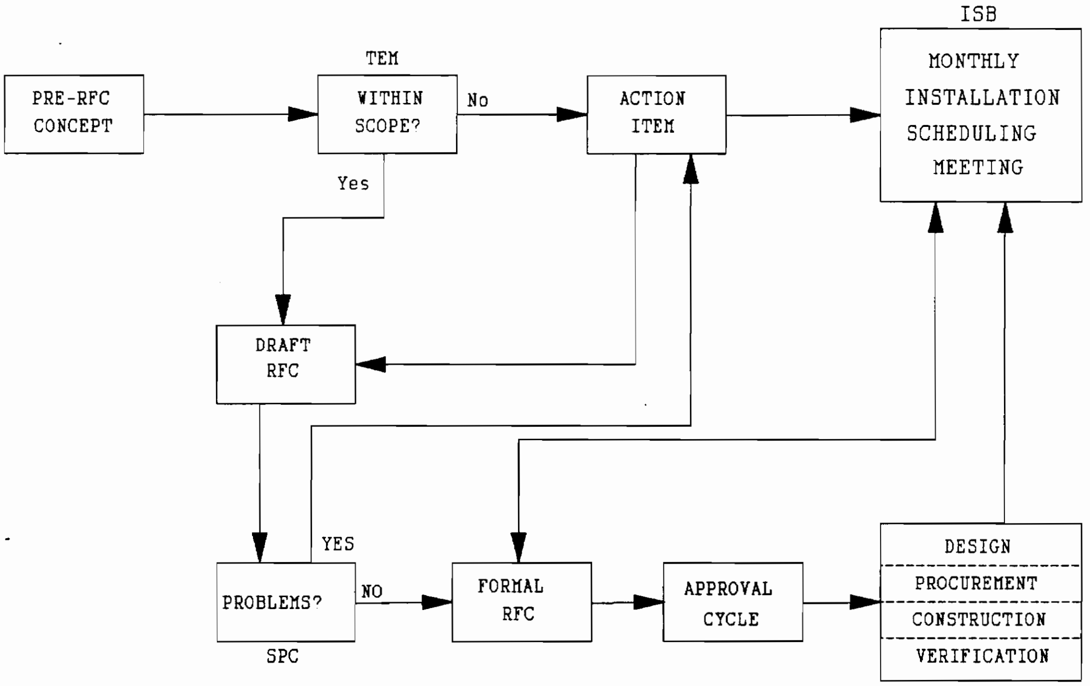


Figure 1 Request for Change cycle

impacts on FSB and schedules the new requirement on the Space Planning Committee (SPC) agenda.

The draft RFC is also sent to all of the facility services support branches for evaluation of issues such as safety, security, logistics, communications, and data links.

The FPS schedules a Technical Exchange Meeting (TEM) where the customer and support branches review the requirements together. This review synergistically finalizes the impacts on the entire Support Division.

Inputs from the TEM are addressed during the SPC meeting. At this time the submitting organization must justify the requirements to the SPC. The equipment must be designed based on performance capability, reliability, maintainability, supportability (including logistics), economic factors, and social acceptability. The space requested cannot exceed the facility's standard allocation, and the occupancy date must fit into the existing Facility Modification Program (FMP) schedule.

After the SPC has made any adjustments to the concept of the RFC, the FPS is tasked to determine where to locate the customer. Options are formulated and presented at the next SPC meeting. The Chairman of the SPC makes the final decision and the customer writes the formal RFC for approval.

Over the next six weeks the RFC is considered by at least two review boards. One higher level of review adds an additional two weeks to the approval cycle. While the RFC is going through the approval cycle, the FPS tentatively schedules the project in the FMP. Depending upon the criticality of each project, this may require some schedules to be delayed. The tentative schedule must be presented to the

Chairman of the Installation Scheduling Board (ISB) for final approval.

The approved RFC authorizes the Design group to layout the spaces and draft the construction drawings, the procurement section to order materials, and O&M to do the construction work once the final construction drawings are approved.

The FPS is responsible for planning, coordinating, and monitoring the execution of all of the above. Because of the success of an earlier project to upgrade the computerized system for preventive maintenance, a tasking was issued to develop a program for the computerization of the FPS planning functions for the modification program.

Under the manual method five users have input to the FMP schedule. They track the milestones associated with all construction modification projects. A sixth person takes their information and produces the graphics for the monthly ISB meeting. These combined efforts consume two man-months of labor every month.

1.3 Project Overview

The automation of the planning functions for the Facilities Modification Program has every indication of being a relatively simple problem for any systems engineer. Although there are a few sophisticated requirements, it appears that the project does not involve much more than the application of database management system (DBMS) software on a personal computer.

Therefore, an underlying goal is to continue educating the customer and management on the value of systems engineering. This is accomplished by emphasizing the difficulties and complexities associated with the requirements of the task and how the application of the systems engineering process brings it all together. It involves the utilization of management science encompassing operations research techniques, human factors, and multiattribute analysis.

1.4 Management Science

A brief discussion about management science is included because it is frequently considered to be an entirely separate solution method. In fact, it can and should be an integral part of the systems engineering process. Management science is concerned with the application of the scientific method to managerial decision problems. In order to make more effective decisions, models are developed that attempt to explain and predict the impact that these decisions have on organizational performance. (2)

However, management science is not just an assorted set of mathematical techniques. It is a systematic approach to organizational problem solving and formulation and has an interdisciplinary focus on organizing data into information for decision making using mathematical, behavioral, and computer skills. (3)

Emphasis is placed on not settling for just a "good enough" approach. Rather, the success of management science models depends upon their contribution toward optimizing the objectives of the organization and the welfare of the people involved.

2 THE SYSTEM ENGINEERING PROCESS

Any system has to deal different external environments. These include social, physical, political, legal, and economic environments, which in turn guide the planning, development, production, and use of the system. The systems approach to problem solving recognizes this and extends the boundaries of the problem to include any resulting effects which are significant to the solution of the problem. (4)

The purpose of this section is twofold. The first point is to indicate how the systems engineering process is affected by this project's environments. The second is to demonstrate how the systems engineering process is actually applied to the solution of this problem.

As mentioned in the Introduction, this project exists within a group of environments that significantly limit the applicability of the system engineering approach. First, customer management does not fully understand what the system engineering process is and just how to apply it. Rather than educate themselves, they tend to avoid it altogether. Second, the customer has no regard for profit or loss. He is only concerned with an allocated "use it or lose it" budget. Therefore, he does not have a strong interest in life-cycle cost, a maintenance concept, or functional analysis.

Third, the rapid growth of the facility has left every department overworked and understaffed. This means that "non-mission" projects, such as this one, do not have a high priority with the Computer Services Branch (CSB). Even high-priority projects confront CSB's two year backlog. Therefore, low priority projects must be contracted out or done in-house.

Finally, many users are computer illiterate and want little or nothing to do with automation. They also feel threatened by the loss of their manual procedures. The problems with this attitude are compounded because the users have difficulty communicating their needs.

These environmental circumstances make it impossible to carry out all of the system life-cycle functions completely. It is far beyond the scope of this project to include everything. Yet, as stated earlier, an underlying goal is to continue educating the customer and management on the value of systems engineering. Therefore, other aspects of the system engineering process are included in this report that are not necessary for resolution of the problem at hand.

2.1 System Life-Cycle

A breakdown of the system life-cycle is presented in Figure 2. The activities evolve from a combination of stated system operational requirements which have a significant impact on follow-on design, production, operation, and support requirements. (5)

A key feature of this system is that it allows for different alternatives to meet the specified needs of the customer and incorporates feedback loops to ensure that progress continues in the right direction and the communicated needs are repeatedly verified. (6)

The specific needs are determined through interviews with the end users and management by the engineering team. A flow diagram of the life-cycle functions with the feedback loops is shown in Figure 3.

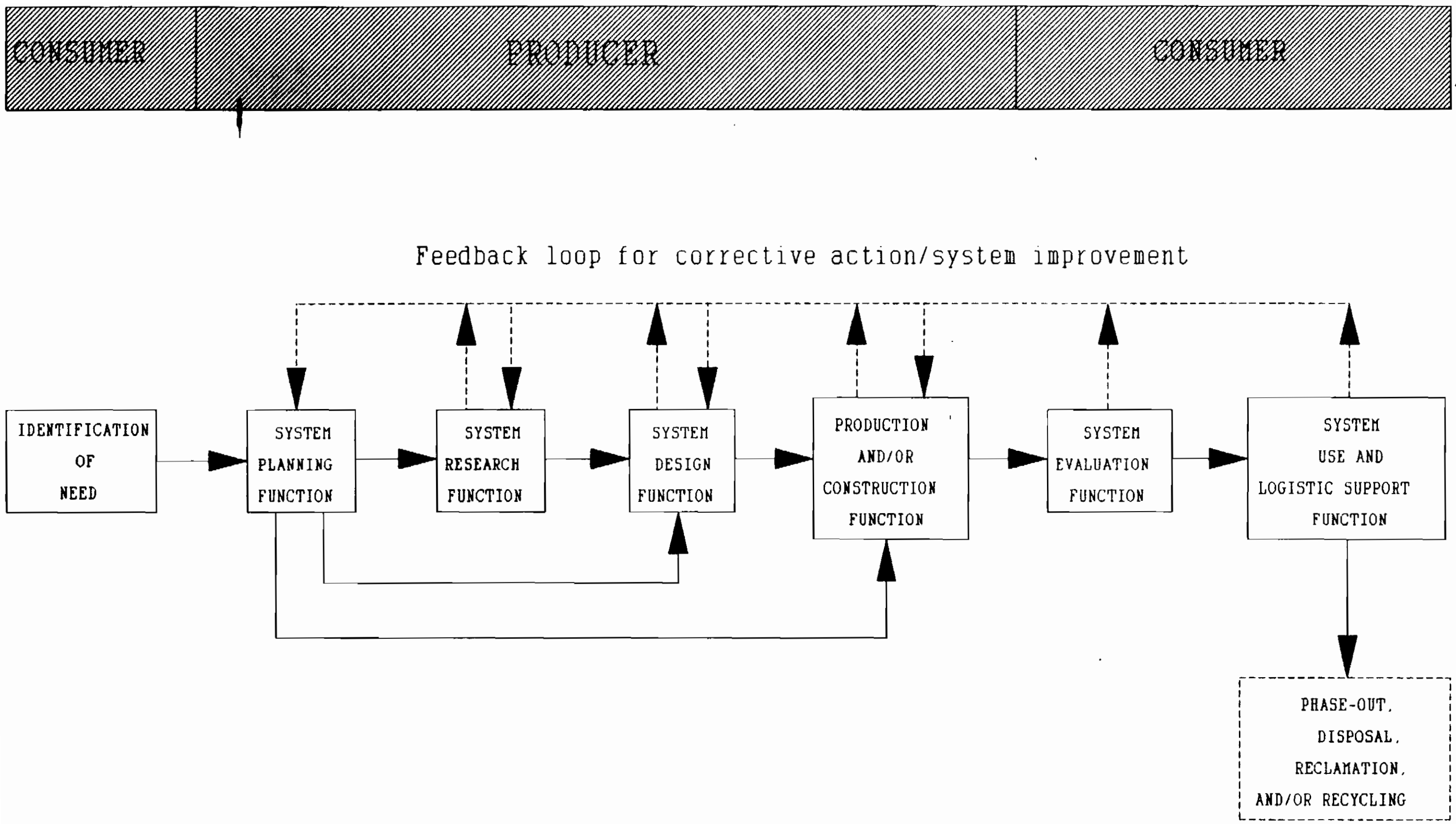
Each major function of the design process ends in a design review. The design review attempts to ensure that the system design is appropriate for the understood need before the design process continues. An inappropriate design may necessitate tracing a feedback loop back to a stage which was correctly satisfied and then starting over from that particular point. An unanticipated change in need may require a return to the System Planning Function. (7)

THE SYSTEM LIFE-CYCLE

CONSUMER	Identifcation of Need	"Wants or desires" for systems (because of obvious deficiencies/problems or made evident through basic research results).
	System Planning Function	Marketing analysis; feasibility study; advanced system planning (system selection, specifications and plans, acquisition plan, research/design/production, evaluation plan, system use and logistic support plan); planning review; proposal.
	System Research Function	Basis research; applied research ("need" oriented); research methods; results of research; evolution from basic research to system design and development.
PRODUCER	System Design Function	Design requirements; conceptual design, preliminary system design, detailed design, design support; engineering model/prototype development; transition from design to production.
	Production and/or Construction Function	Prodution and/or construction requirements; industrial engineering and operations analysis (plan engineering, manufacturing engineering, methods engineering, production control); quality control; production operations.
	System Evaluation Function	Evaluation requirements; categories of test and evaluation; test preparation phase (planning, resource requirements, etc.); formal test and evaluation; data collection, analysis, reporting, and corrective action; retesting.
CONSUMER	System Use and Logistic Support Function	System distribution and operational use; elements of logistics and life cycle maintenance support; system evaluation; modifications; product phase-out; material disposal, reclamation, and/or recycling.

Source: Blanchard, Benjamin S., and Wolter J. Fabrycky. "Systems Engineering and Analysis". Englewood Cliffs, NJ: Prentice-Hall, Inc., 1981.

Figure 2 System life-cycle



Source: Blanchard, Benjamin S., and Wolter J. Fabrycky. "Systems Engineering and Anlysis." Englewood Cliffs, NJ: Prentice-Hall, Inc., 1981.

Figure 3 Life-cycle with feedback loop

2.2 Identification of Need

As mentioned earlier, the engineering team conducts interviews with the users and management to determine and suggest the needs and requirements for the system. There is a requirement to provide for the controlling and tracking of all construction modification project data. The tasks associated with facilities administration that are being performed manually should be automated. The primary function of this automation will be to generate reports and schedules from information in the database files. The focus of the database will be in the Facility Planning Staff area, specifically:

- Tracking of Requests for Change (RFC)
- Tracking of Estimates for RFCs
- Scheduling of Moves and Mods for the monthly Installation Scheduling Meeting
- Scheduling of Technical Exchanges Meetings (TEM)
- Tracking TEM Action Items
- Monitoring of the RFC Approval Cycle
- Controlling the Engineering and Design Schedules
- Tracking of Work Orders Associated with Modifications
- Automating Resource Leveling

2.3 Needs Analysis

There are two major deficiencies with the current manual system. First is the inability to track and manage all of the daily planning tasks that pertain to the Facility Modification Program. Second is the excessive amount of labor that is required in doing the few tasks that are being accomplished. There are no less than three modification projects in progress on any given day. There are an average of 80 modification projects on the schedule at any time. And the backlog of work orders is never less than 100.

There is an initial requirement for one computer work station. Data will be input by each of the contributing individuals or a data entry clerk. If each individual user is to have access to the system, provisions must be made to password protect entry into other specific data files. The work station may be mainframed or it may be a stand-alone system. However, if it is stand-alone, it must be IBM compatible and provisions must be made for future expansion, e.g., local area network (LAN) capabilities.

A mainframed system falls under the service support of the Computer Services Branch with the exception of first echelon maintenance functions. For a stand-alone system, FPS would have the additional responsibility of maintaining all software. The CSB would still maintain all hardware.

Because of the predicted growth of the facility, the customer requests that the system be operational within six months following approval of the project.

2.3.1 Options

Hardware: If the system is attached to the mainframe, the hardware must be compatible and must therefore be the same make. The mainframe linked computer happens to be IBM compatible but that is not a firm requirement. The only requirement for a stand-alone system is that it be IBM compatible and LAN capable in order to match existing inventories.

There is an additional requirement for a laser printer and plotter for producing hardcopies of the reports and graphics. All of the above mentioned hardware exists in the FPS inventory and is available for this project's application. As a result, there is not a pertinent cost issue involved in the evaluation. Since there is no requirement for the system to be attached to the mainframe, either option is acceptable. In addition, the stated resources will be centrally located in a common user computer room.

Software: Regardless of the hardware system, there are three options for software. The first is to use an "off-the-shelf," as is, commercial project management package that best suits the needs of the FPS. The second is to write new code entirely from scratch in order to achieve exactly what is wanted. The final option is to take a commercial package or other existing code and customize it.

2.3.2 General Evaluation

The lead engineer establishes a committee consisting of various levels of expertise and experience from the engineering team, users, technical advisors, and management. This enhances a synergistic approach to the problem by having all interested parties represented. Decision by consensus is also statistically the most efficient and effective way to obtain an optimal solution. More importantly, it opens up the channels of communication across several administrative and political boundaries.

Details of the complete evaluations are presented in the Research Analysis section. The intent of this section is to provide the basis for that analysis.

The government facility utilizes two standard personal computers, the IBM and the ACME[1]. The latest IBM model costs approximately $3000 more than the ACME; the added features, speed, etc. hold no advantage for this application. The ACME

[1]ACME is a fictional name used in lieu of the site sensitive, classified name.

can be linked into the facility's existing mainframe system at a minimal cost; the IBM cannot.

Other personal computer models were surveyed, but a major disadvantage exists that eliminates them from any further serious consideration. Because the facility is classified, all suppliers and service personnel are required to have clearances before obtaining access. The two suppliers for ACME and IBM are fully established and are virtually considered to be sole sources.

There are a vast number of project management software packages commercially available. The ten most common were screened and evaluated for possible acceptance. Three of the ten programs were approved by the evaluating committee for further analysis. They will be identified hereafter as Options One, Two, and Three.

Of the three options, only two are customizable. Option One allows access to the source code which potentially has complete flexibility. Additional code, written in dBase, can also be incorporated. The source code for Option Two allows for built-in customization for report generation and format. However, no changes can be made to the source code and no additional code can be supplemented. Option Three stands alone and cannot be modified in any way.

A fourth option is to write new computer coding from scratch. This will require an estimated 20 man-months of effort. Because much of what must be accomplished already exists in the commercial packages, this option was not given further consideration.

The cost of Option One is $4,200. Option Two has a cost of $3,800. Option Three is only $2,000. The requirement from the customer is to design and program a system that effectively and efficiently solves the given problem in the shortest amount of time. The cost of the base commercial package is irrelevant to the customer but it is an important aspect to the solution method.

2.4 Operational Requirements

This section briefly covers the mission definition, performance and physical parameters, operational life-cycle, utilization requirements, effectiveness factors, and the environment as determined by the evaluation committee.

2.4.1 Mission Definition

2.4.1 The system will provide computer based information control for Facility Modification Program data.

2.4.2 The system will provide summary and detailed reports for design schedules, material acquisition dates, construction schedules, important milestones, construction drawing redlines, and schedules of cost estimates.

2.4.3 The system will have the capability to archive outdated information into a history file.

2.4.4 The system will be user friendly.

2.4.5 The system will have the capability to support multiusers.

2.4.6 The system will provide information protection and security.

2.4.7 The system will reduce administrative time for current and predicted workloads.

2.4.8 The system will provide user training and on-line help.

2.4.2 Performance and Physical Parameters

The customer's hardware specifications are predetermined by the equipment standards of the organization. They will not be redefined in this report. After the specific software package has been determined, the work station is evaluated to ensure that it meets the required specifications. The work station for this project will consist of an IBM Model 80 personal computer with 2MB RAM, VGA monitor, and a twin 20MB removable cartridge disk (RCD) drive. Based on the estimated size of the Facility Modification Program database, memory capacity is not an issue.

2.4.3 Utilization Requirements

The system is required strictly for office use and there is no anticipated field use at this time. The system will be in operation approximately two man-hours per day. Access will be through the program's menu system based on user identification and password.

2.4.4 Effectiveness Factors

Effectiveness factors are based on the latest IBM proposal and are not discussed in this document. Those system requirements were developed for the organization's standard and can be found under Division Policy 7.2 "Standards for Hardware and Software Systems."

2.4.5 Environment

The system is designated for office use under normal operating conditions. The basic environmental specifications are a dry bulb temperature of 72° ± 2° F with relative humidity at 50% ± 5%.

2.5 System Maintenance Concept

This section addresses the different levels of maintenance support. The purpose is to establish a maintenance baseline for the first echelon and identify total logistics support requirements. Because of the fact that all of the hardware is already present, a maintenance concept, in turn, is in place and does not have to be determined.

2.5.1 Maintenance Baseline

Three levels of maintenance exist for the system: Organizational maintenance, intermediate maintenance, and depot maintenance. Organizational maintenance at the user level is the primary concern. Intermediate and depot maintenance are both handled via the Computer Services Branch.

2.5.1.1 Organizational Maintenance

Organizational maintenance will be limited to user preventive maintenance, operational checkout, and minor troubleshooting and servicing. These maintenance tasks are defined further in Section 2.6.2, Maintenance Functions.

2.5.1.2 Intermediate/Depot Maintenance

These levels of maintenance are conducted by the Computer Services Branch. The details of that maintenance are not defined in this report. However, the times for such maintenance are identified in Section 2.6.2.

2.5.2 Logistics Support

Logistics support requirements are handled by the CSB. All new installations are considered for the stocking of repair parts, associated supplies, support personnel, etc. The Logistics Branch is flagged to be made aware of the potential increase in stock and product demands.

2.6 Functional Analysis

This section presents operational and maintenance functions in the form of flow diagrams. They have been formulated to define all of the elements of the system. The first three levels of the operational functions and the first two levels of the maintenance functions are depicted.

2.6.1 Operational Functions

Figures 4 through 13 illustrate the operational functions through the first three levels.

2.6.2 Maintenance Functions

Figures 14 through 21 illustrate the maintenance functions through the first two levels.

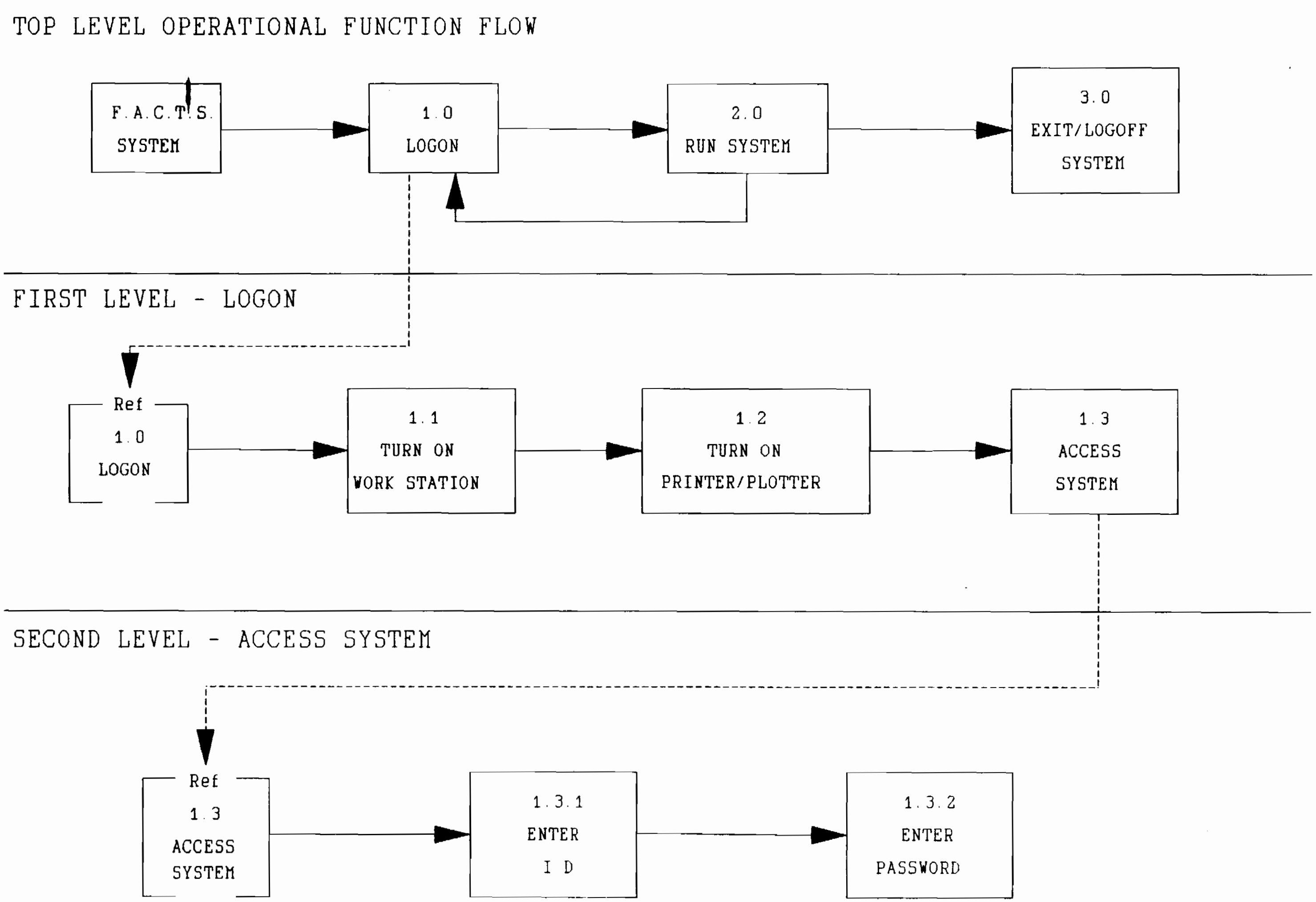


Figure 4 Operational function flow

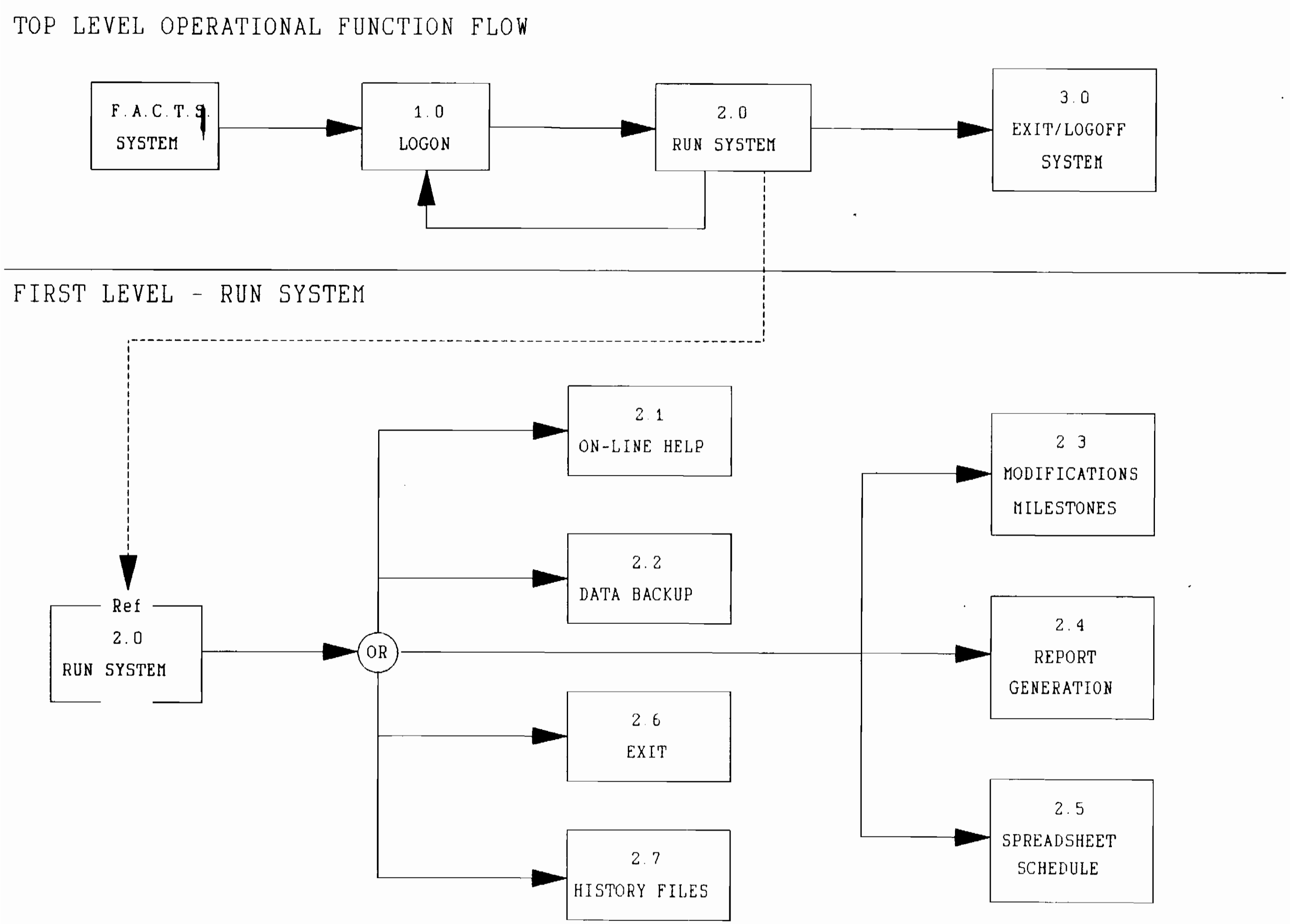


Figure 5 Run system function flow

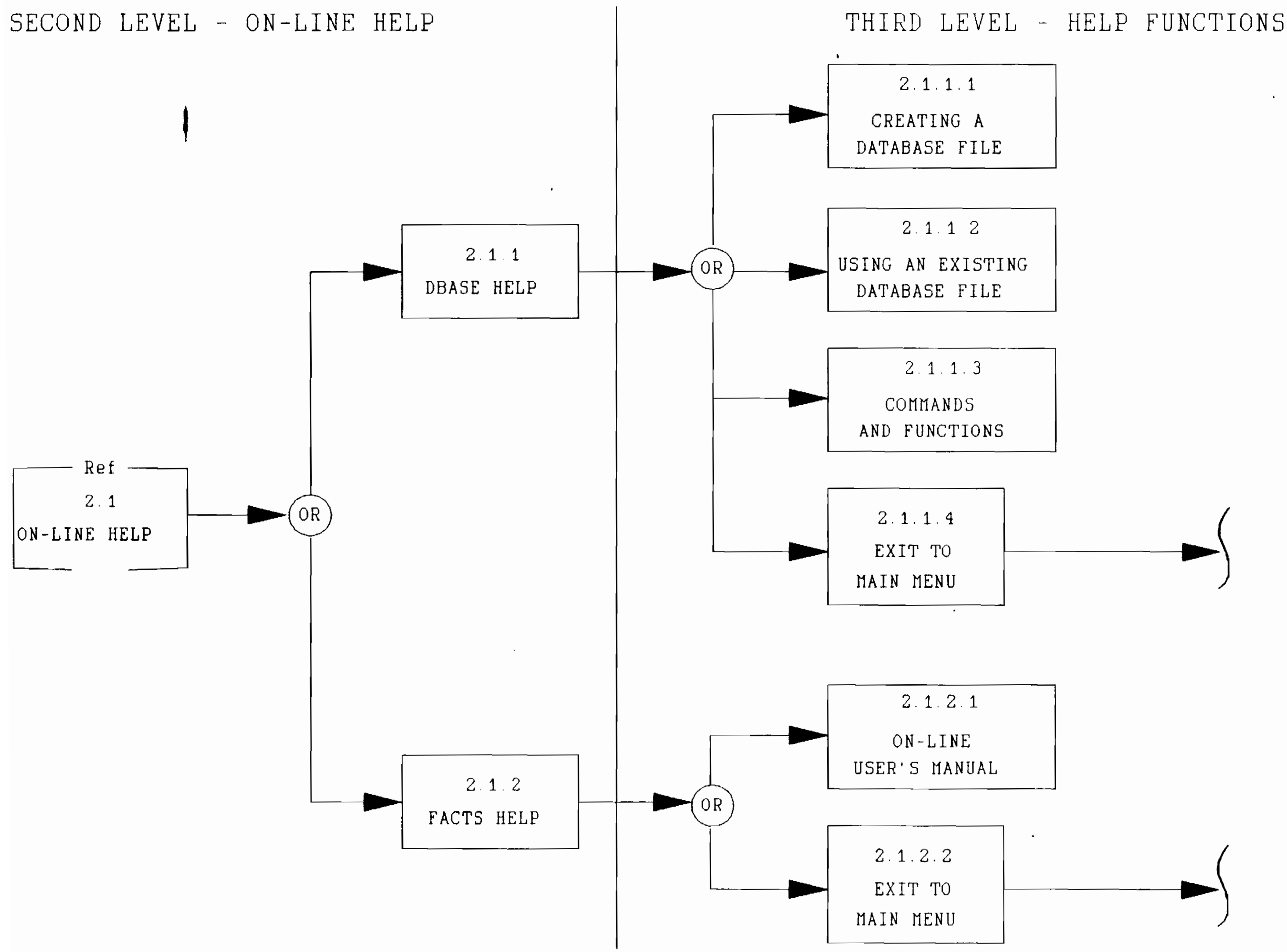


Figure 6 Help functions

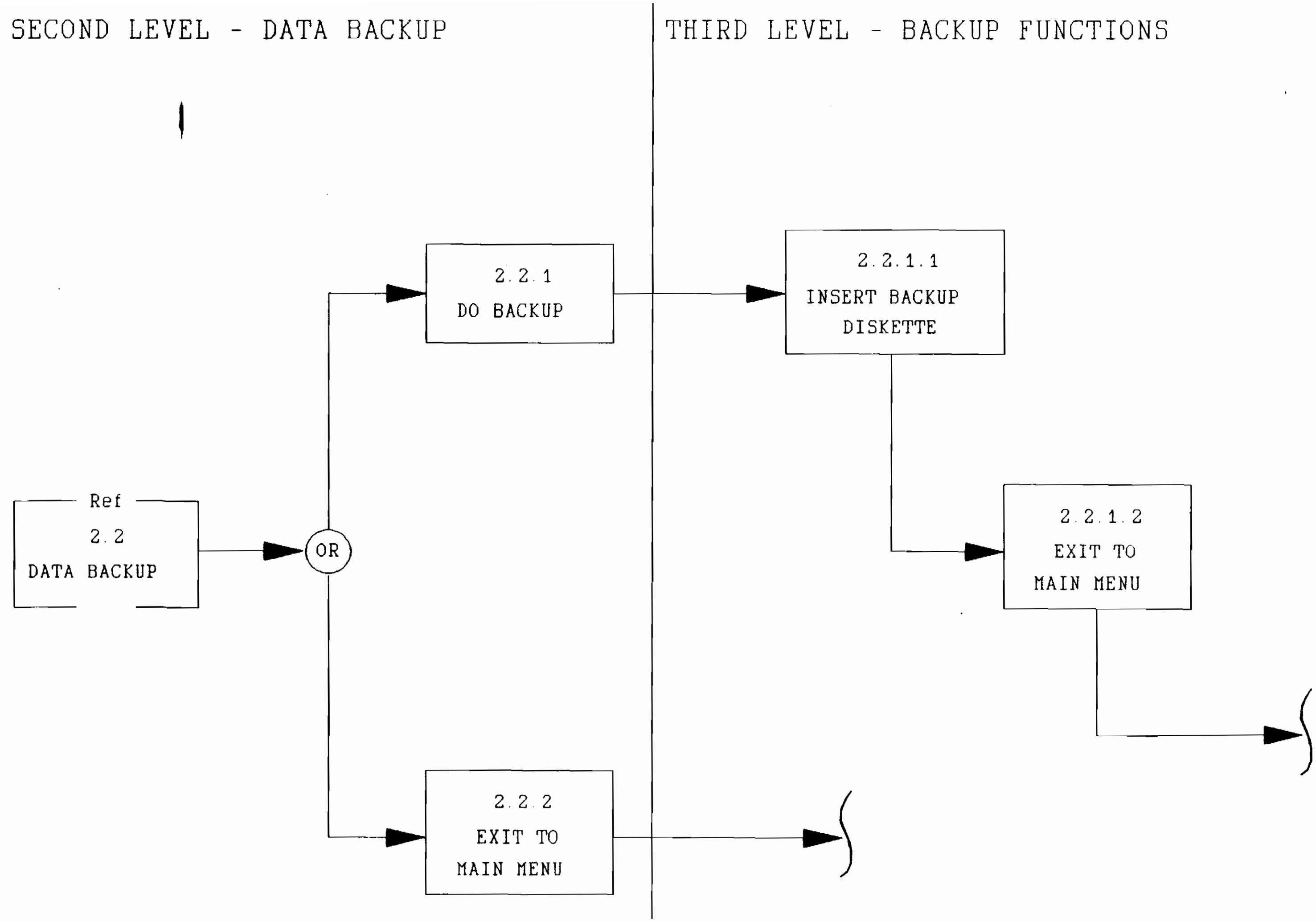


Figure 7 Data backup functions

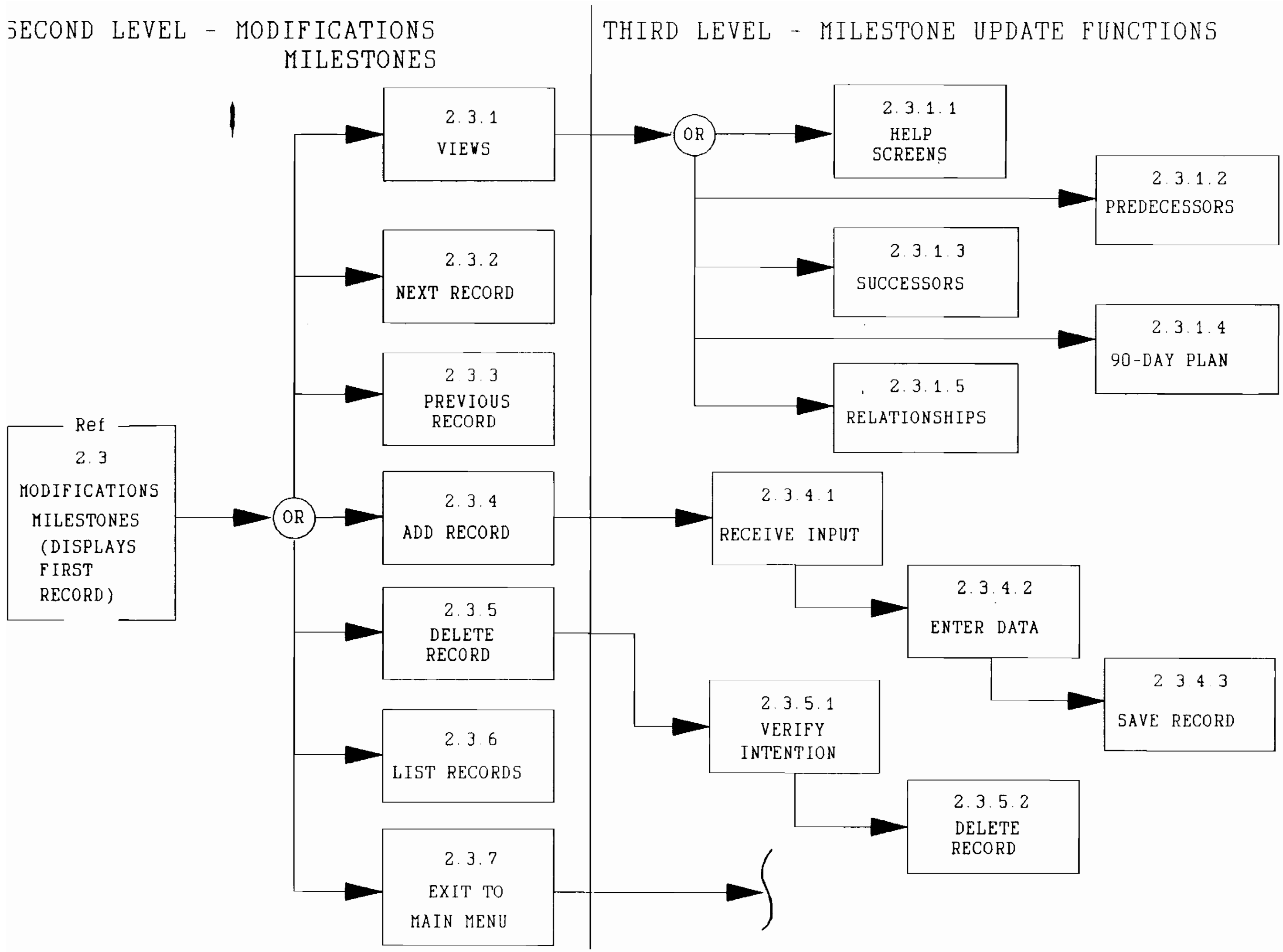


Figure 8 Milestone update functions

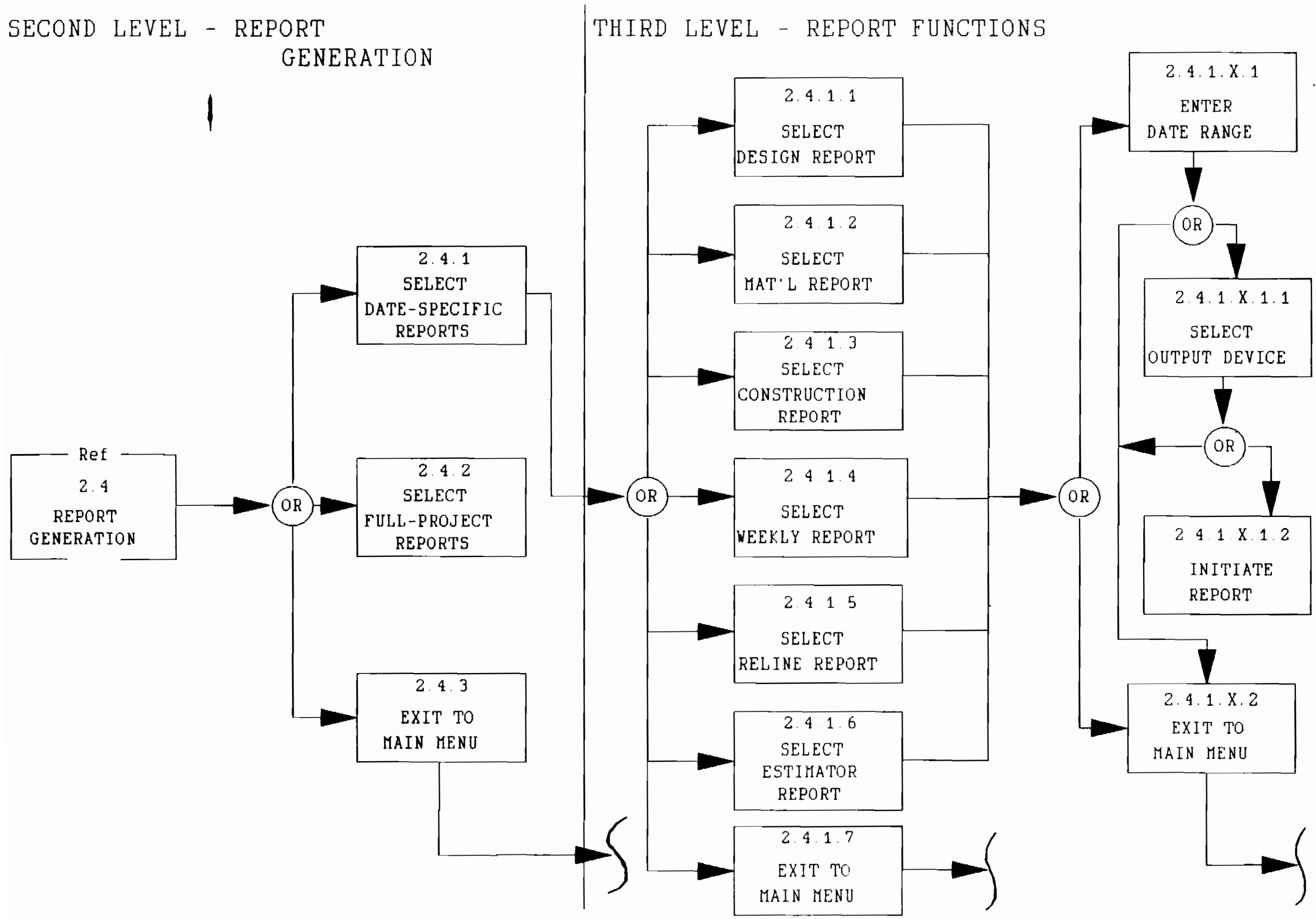


Figure 9 Report functions

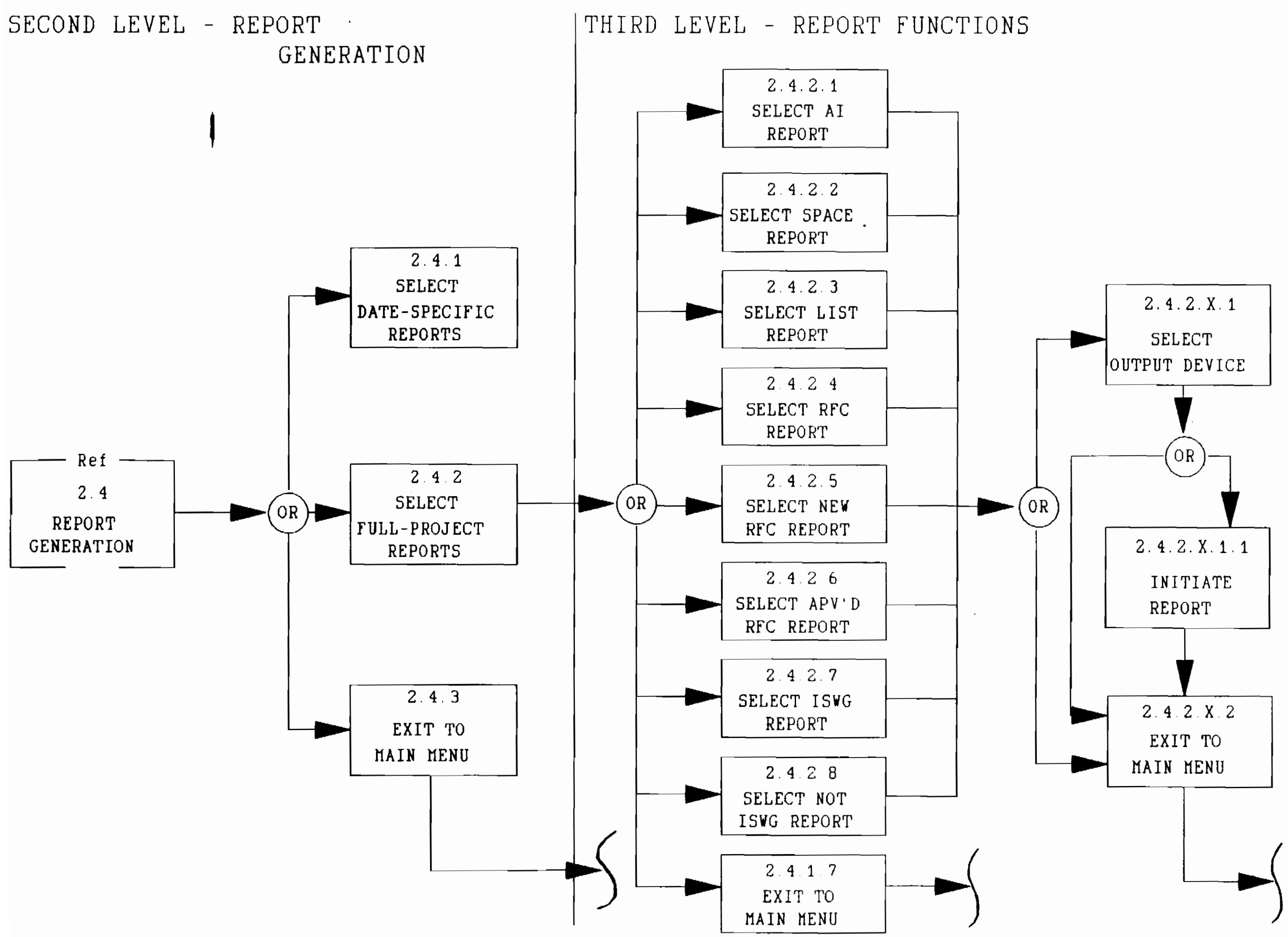


Figure 10 Report functions

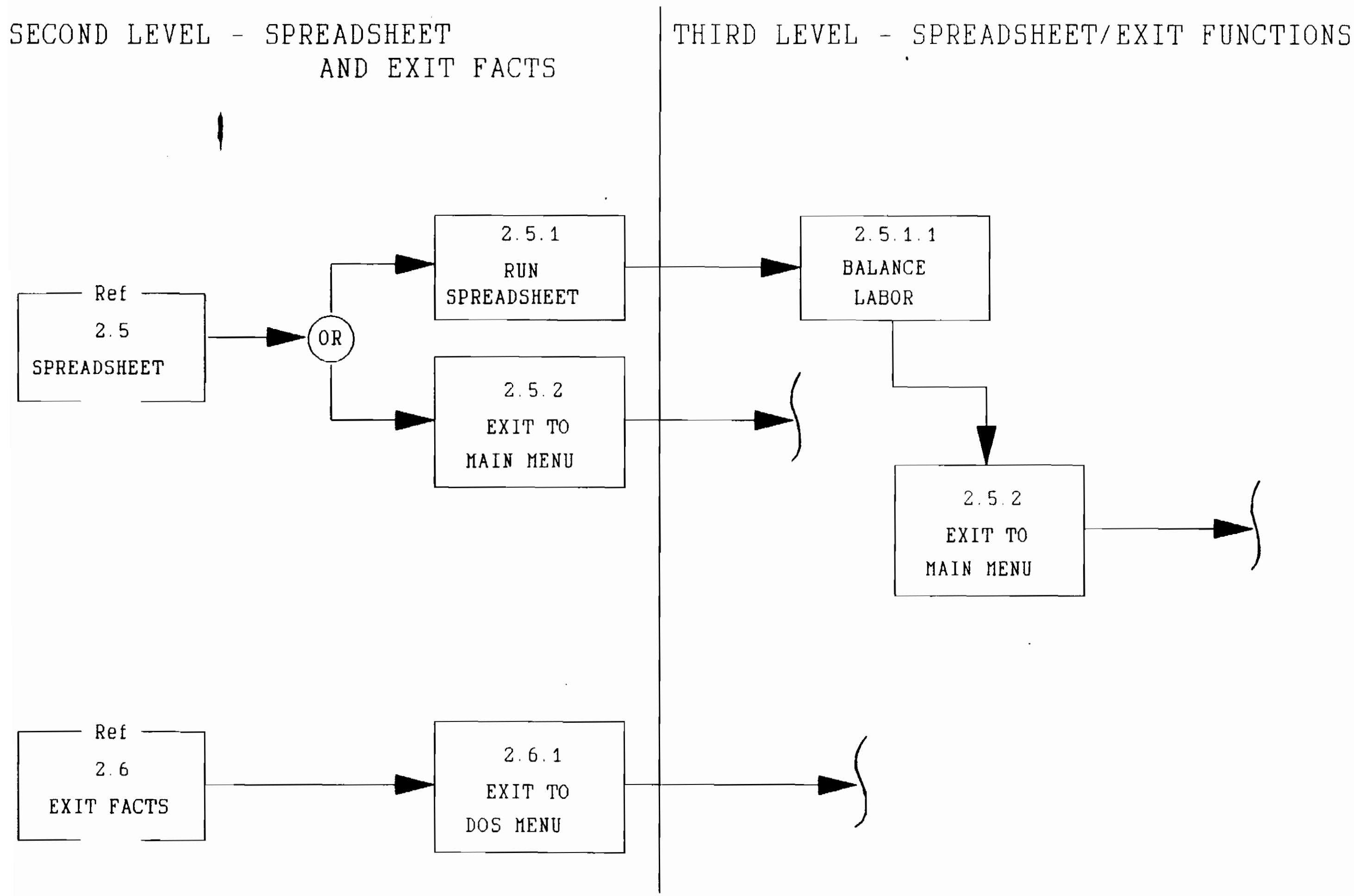


Figure 11 Spreadsheet/exit functions

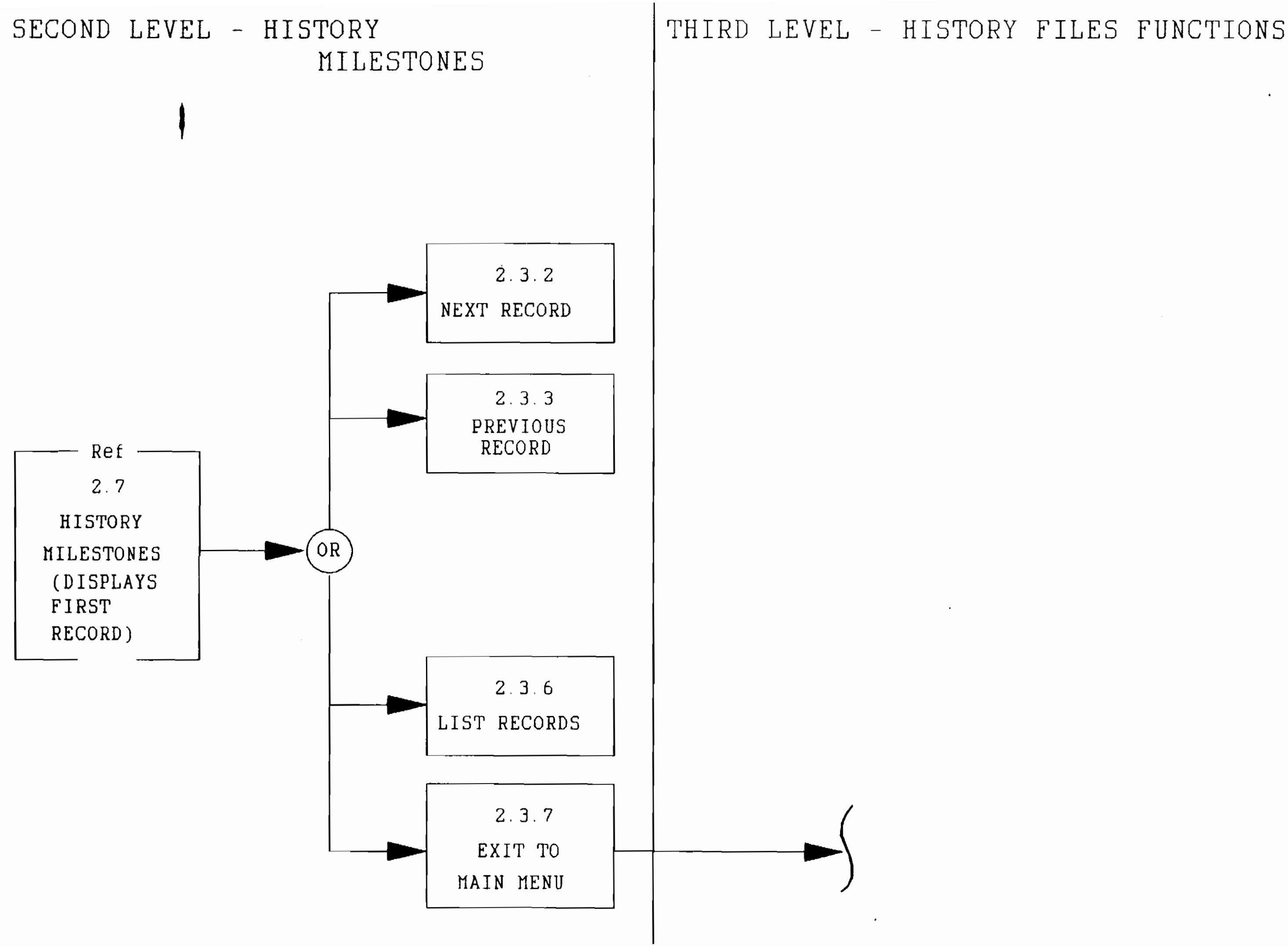


Figure 12 History functions

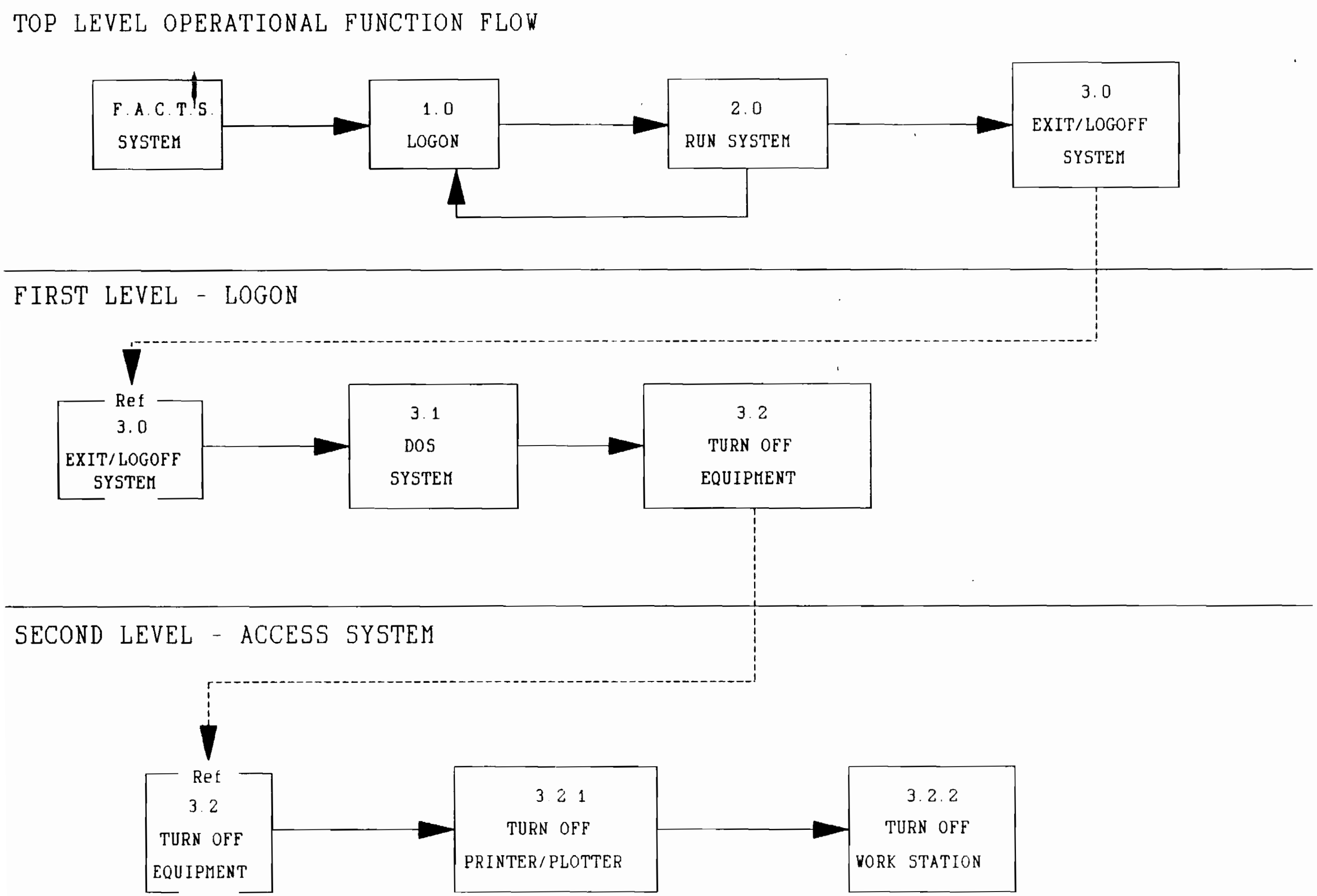


Figure 13 Exit/logoff function flow

TOP LEVEL MAINTENANCE FUNCTION FLOW

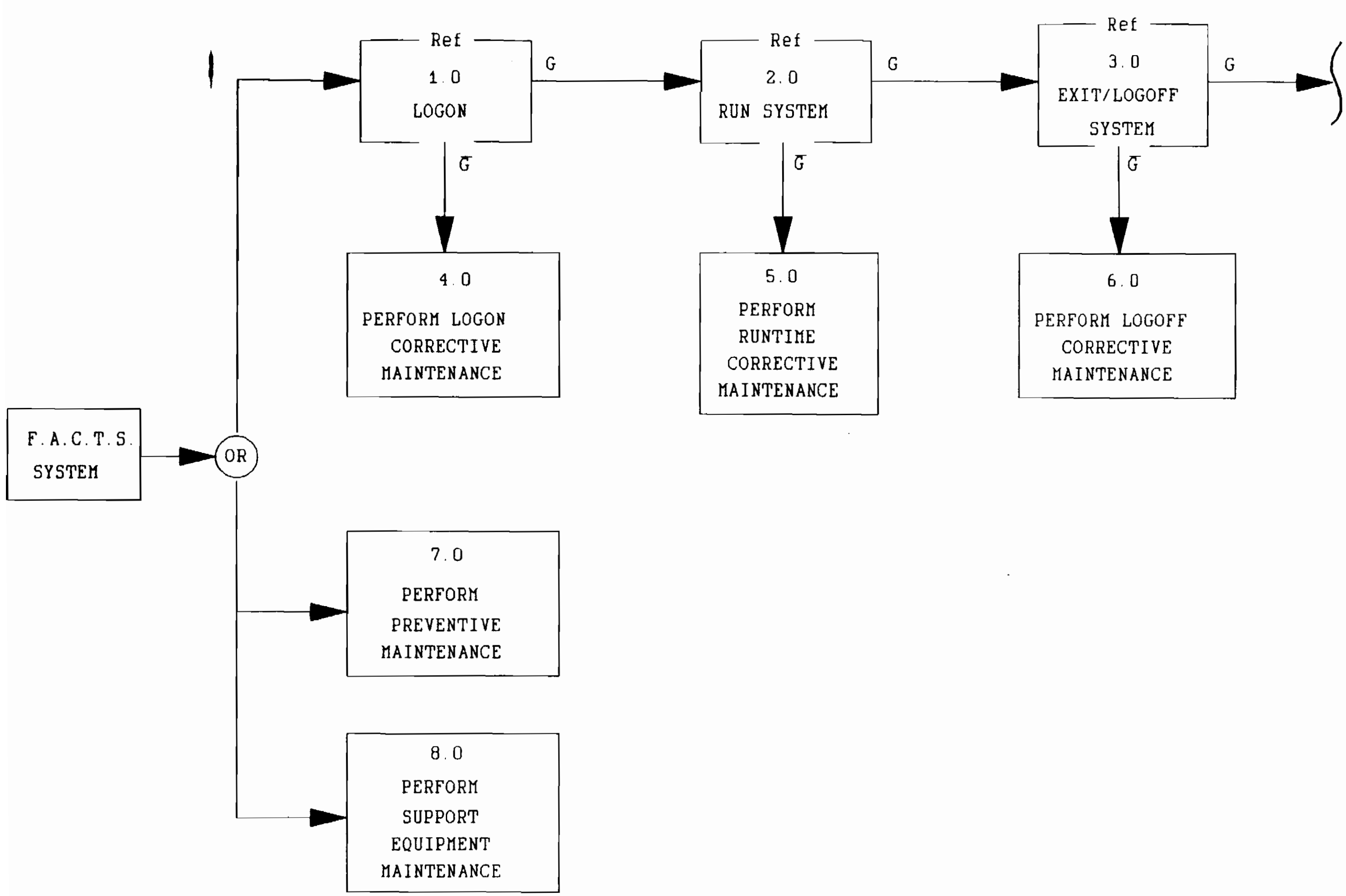


Figure 14 Maintenance function flow

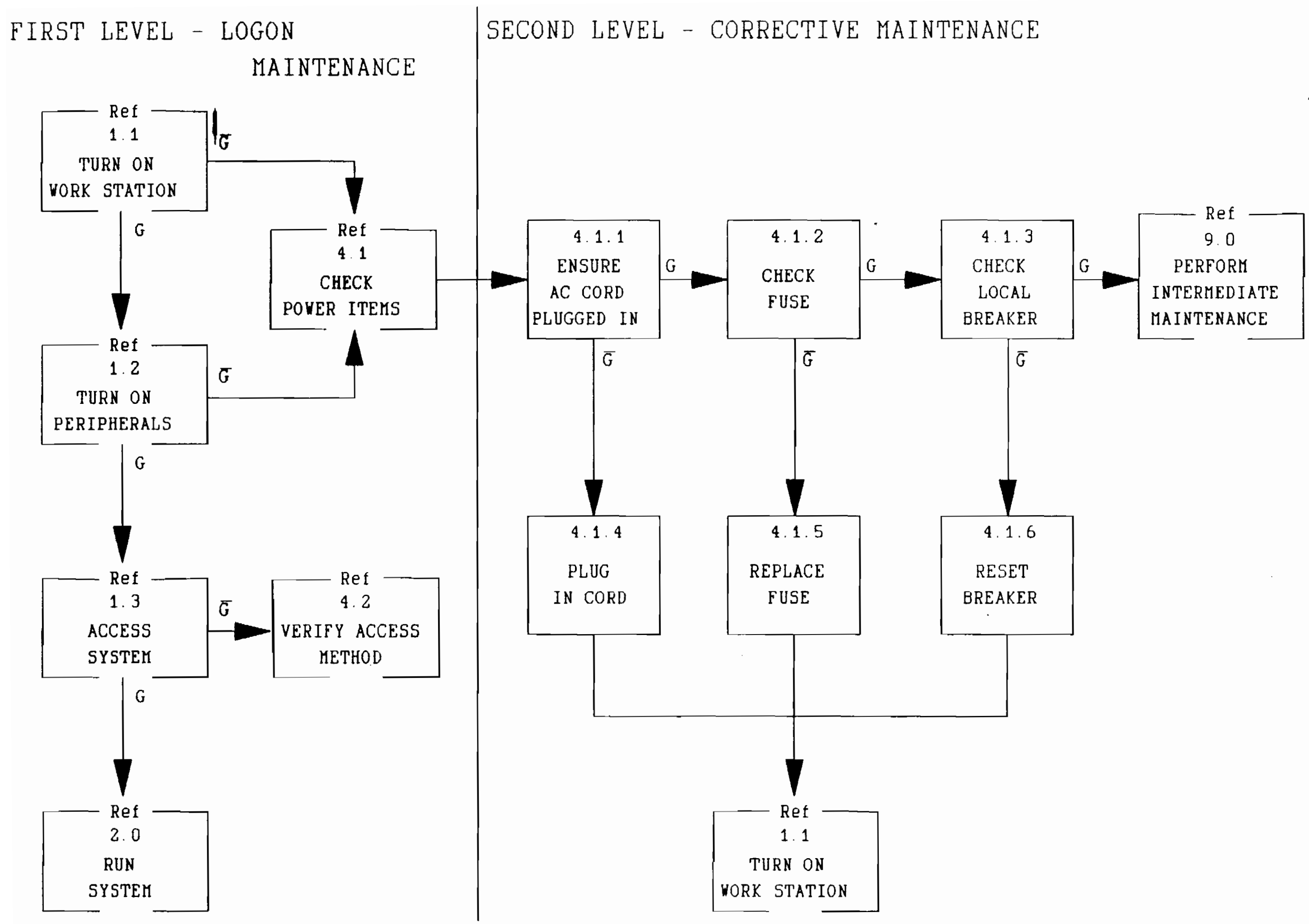


Figure 15 Logon maintenance

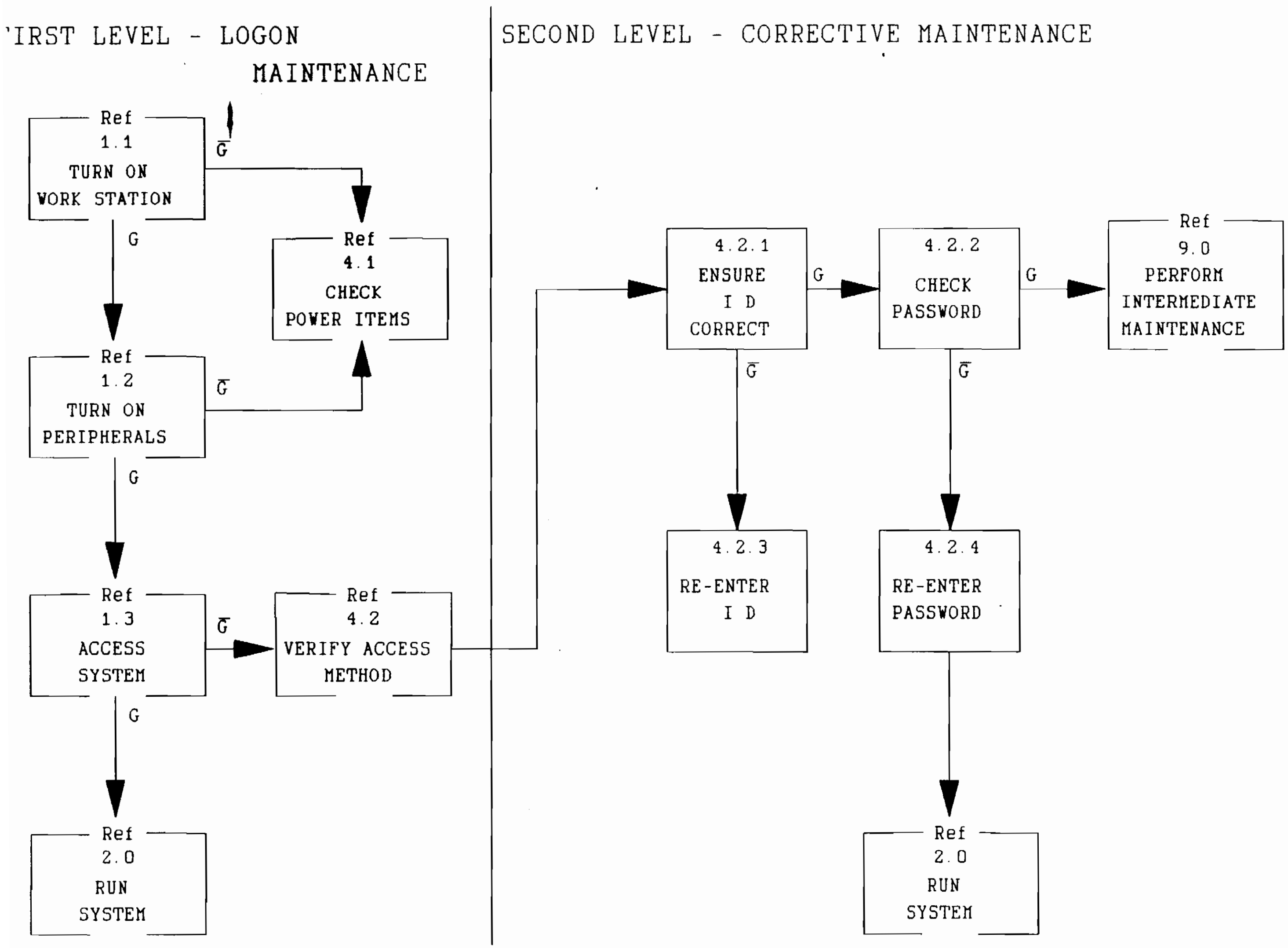


Figure 16 Logon maintenance

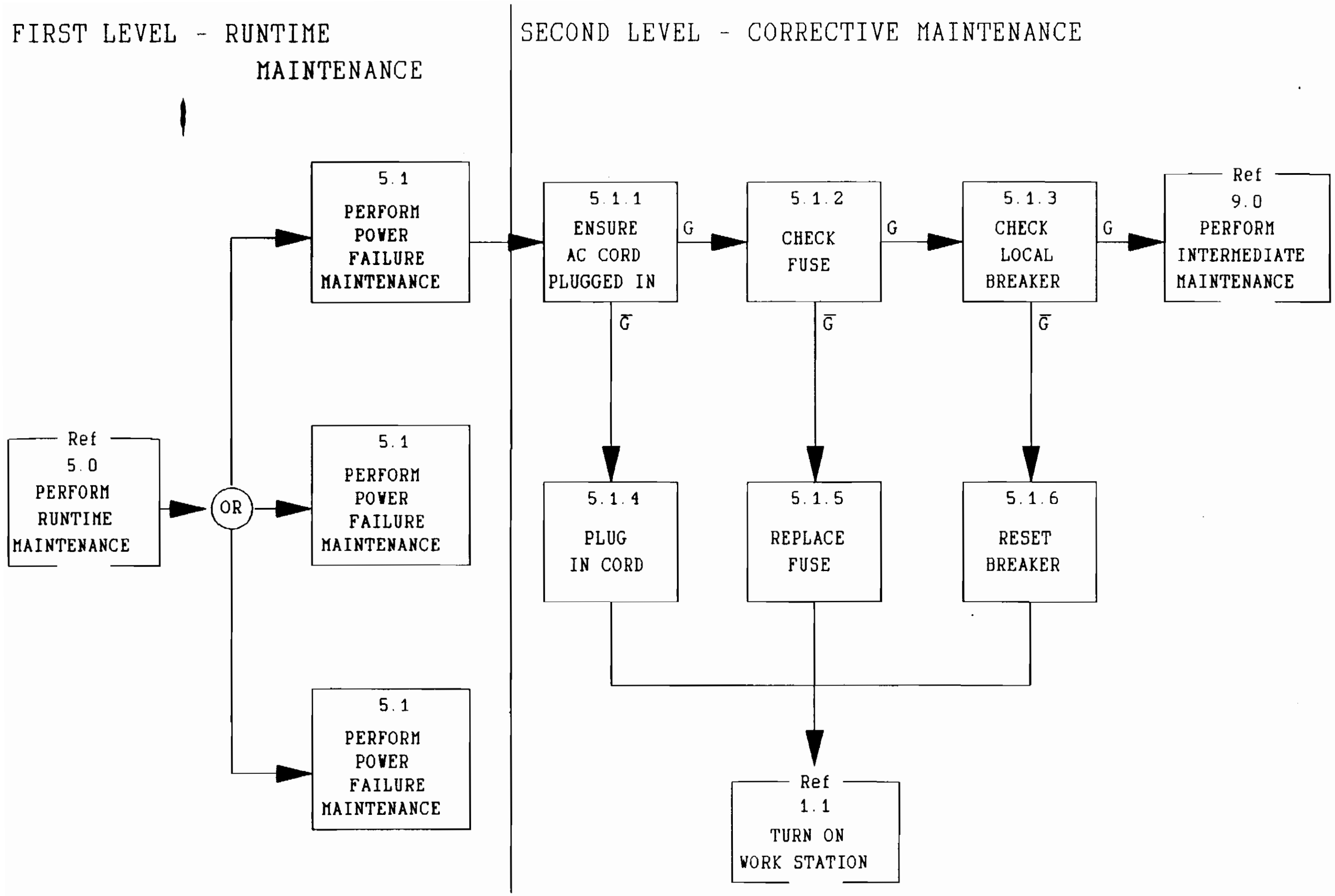


Figure 17 Runtime maintenance

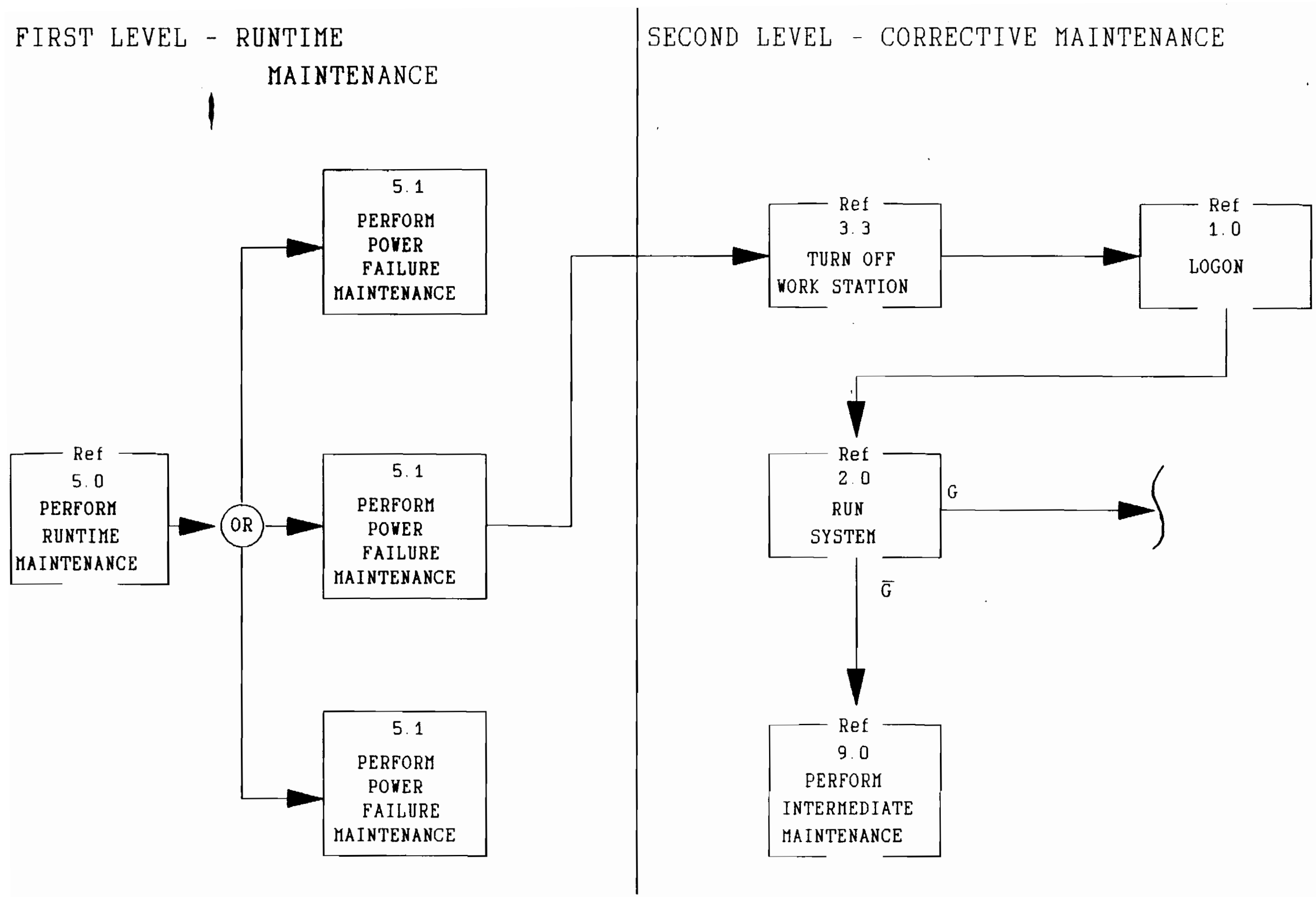


Figure 18 Runtime maintenance

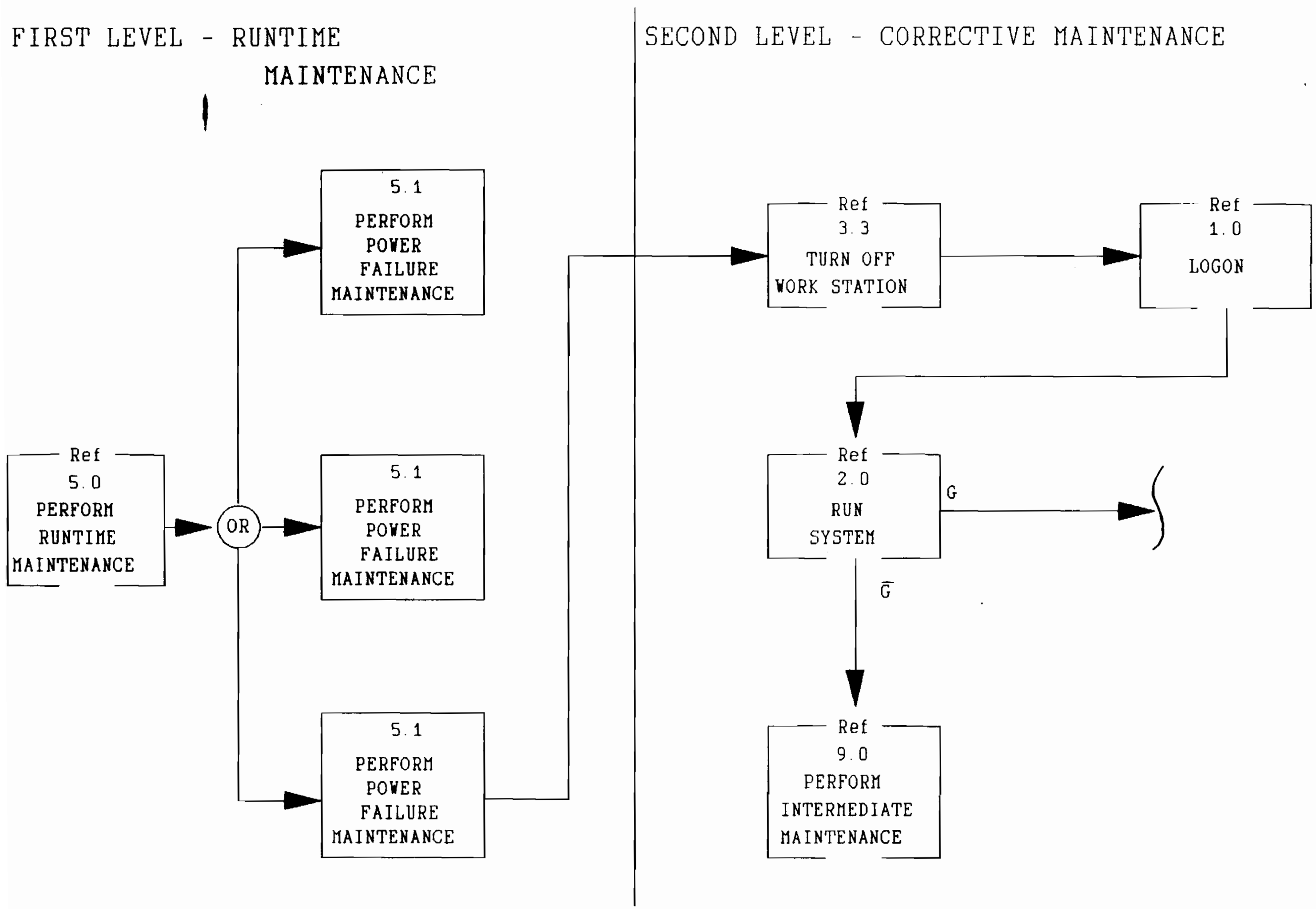


Figure 19 Runtime maintenance

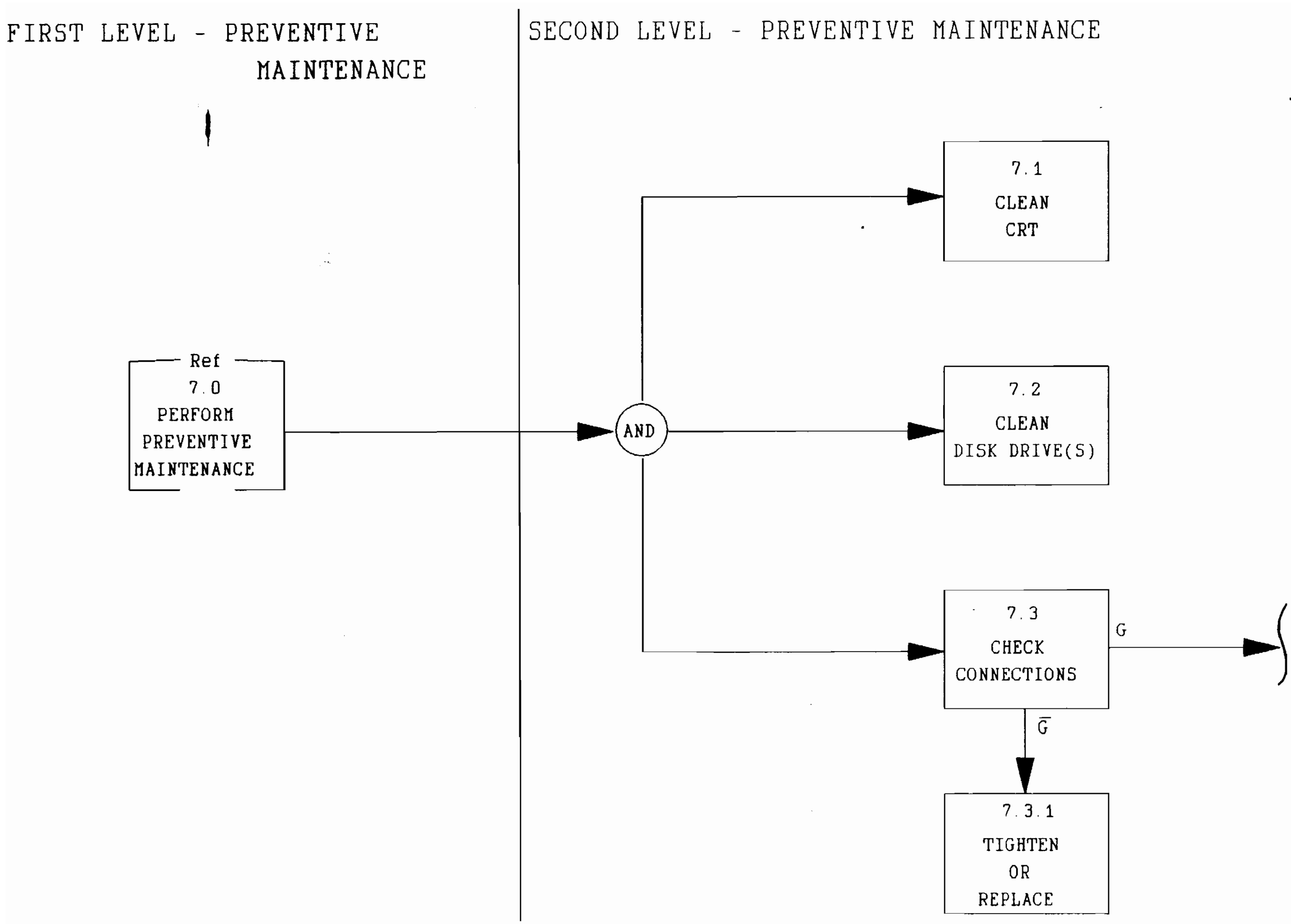


Figure 20 Preventive maintenance

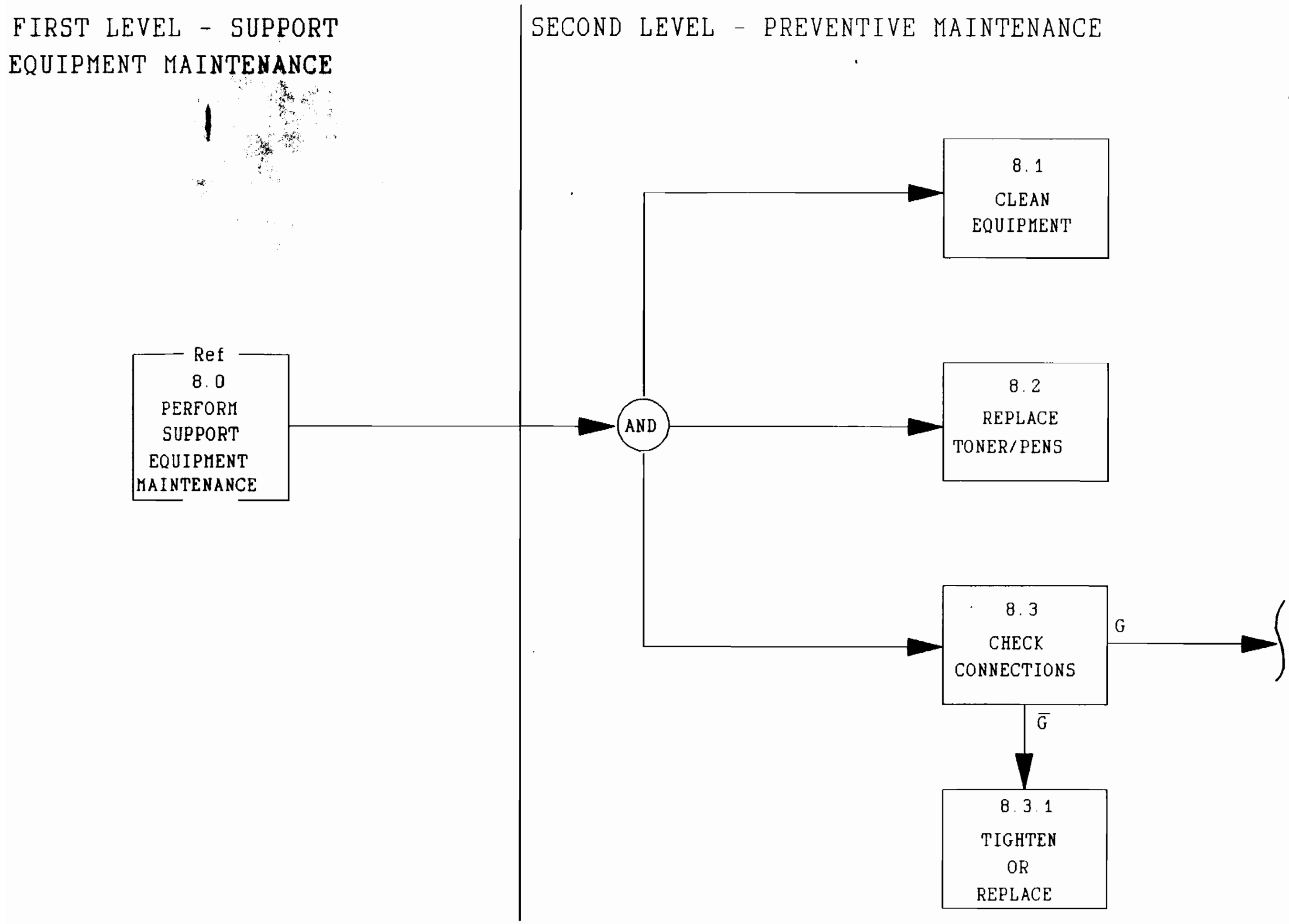


Figure 21 Support equipment maintenance

2.7 Requirements Allocation

This section involves the allocation of top-level system factors to various sublevels in order to provide the design team of each element with solid guidelines. It covers the requirements for reliability, maintainability, manability, and logistic support.

2.7.1 Reliability and Maintainability

All of the hardware for this project are existing station standards and are not a part of the overall design. However, records do indicate that the reliability of a work station must be 0.95 with a mean time between failure (MTBF) of 1500 hours, and the availability must be 0.9980. There is no data available, nor is there a requirement, for reliability or maintainability requirements on peripherals.

2.7.2 Manability Allocation

This section covers the allocation of human factors as they pertain to operations and maintenance. These allocations apply primarily to the system level. Sublevel allocations are included as prescribed by task requirements.

2.7.2.1 Operation

2.7.2.1.1 Anthropometric Factors: work station operations can be performed by persons ranging anywhere between the 5th to 95th percentile of anthropometric data. The requirements for this system are based on MIL-STD-14772B, Military Standard, "Human Engineering Design Criteria for Military Systems, Equipment, and Facilities."

2.7.2.1.2 Human Sensory Factors: work station operations require operator vision correctable to 20-20 or better. The noise range of the work station is not to exceed 50db. The illumination requirements for the work area is between 50 to 70 foot-candles. Egg crate diffusers will be used to reduce monitor glare from overhead fluorescent lights.

2.7.2.1.3 Physiological Factors: the work station environment is specified at a temperature of 72° ± 2° F with relative humidity at 50% ± 5%. Vibration levels will be below 1 Hz.

2.7.2.1.4 Personnel Factors: operation of the work station requires a high school education. The operator must have a 10th grade reading/writing level and be able to type a minimum of 65 words per minute. No prior personal computer experience is required. With minimal training, the performance of daily tasks requires no interpretation or decision making.

2.7.2.2 Maintenance

2.7.2.2.1 Anthropometric Factors: work station maintenance can be performed by persons ranging anywhere between the 5th to 95th percentile of anthropometric data.

2.7.2.2.2 Human Sensory Factors: work station maintenance requires operator vision correctable to 20-20 or better. The noise range of the work station is not to exceed 50db. The illumination requirements for the work area is between 50 to 70 foot-candles. The illumination requirements for the maintenance area is between 100 to 200 foot-candles.

2.7.2.2.3 Physiological Factors: The maintenance environment has the same specifications as the work station. The difference in the two areas is that the maintenance area requires more illumination.

2.7.2.2.4 Personnel Factors: maintenance operations require one technician per 50 work stations. Each technician should be high school educated with technical training in hardware maintenance. Technicians must possess a 12th grade reading/writing level. Until fully trained, technicians require close supervision.

2.7.3 Logistics Support Allocation

This section covers the logistic support activities for the system through its life-cycle. The areas discussed are maintenance, supply support, test and support equipment, personnel and training, facilities, and retirement.

2.7.3.1 Maintenance

Organizational maintenance is unchanged from that provided in the maintenance manuals. Table 1 shows the organizational maintenance for a work station.

Table 1 Work station maintenance

Maintenance Task	Frequency
1. Clean Monitor	As required
2. Clean Air Filters	Weekly
3. PM CRTs	Weekly
4. Replace Filters	Weekly
5. Clean Disk Drives	Monthly

An evaluation was performed to determine repair versus discard trade-offs. As illustrated in Table 2, it was determined that depot maintenance should be performed at the intermediate level at the facility as opposed to shipping the hardware back to the factory.

Table 2 Work station repair costs

	MAINTENANCE STATUS			
ASSEMBLY NUMBER	REPAIR AT INTERMEDIATE COST ($)	REPAIR AT DEPOT COST ($)	DISCARD AT FAILURE COST ($)	REPAIR DECISION
WS-1	232	813	9756	INTERMED
WS-2	78	378	7013	INTERMED
WS-3	13030	17570	74900	INTERMED
WS-4	3414	5999	10001	INTERMED
WS-5	1233	1157	8066	DEPOT
WS-6	186	711	153	DISCARD
WS-7	230	543	212	DISCARD
WS-8	1353	1684	7911	INTERMED
WS-9	7255	7236	15564	DEPOT
WS-10	822	1110	6657	INTERMED
TOTALS	27833	37201	140233	INTERMED

The evaluation was based on the ten most common failures for a work station. As an example, Table 3 shows the evaluation criteria for one component. As a result, the CSB has been assigned the responsibilities of depot maintenance in addition to those already established.

Table 3 Repair evaluation for WS-3

EVALUATION CRITERIA	INTERMED MAINTENANCE	DEPOT MAINTENANCE	DISCARD
ACQUISITION COSTS	850	850	500
UNSCHED MAINT COSTS	400	640	N/A
SUPPLY SPT SPARED	3500	7000	15000
SUPPLY SPT PARTS	800	800	N/A
SUPPLY SPT INVENTORY	860	1560	12400
TEST EQUIP COSTS	5000	5000	N/A
TRANSPO/HANDLING COSTS	N/A	120	N/A
TRAINING COSTS	1500	1500	N/A
BURDEN RATE	120	100	N/A
TOTALS	$13030	$17570	$27900

2.7.3.2 Supply Support

Table 4 lists the spares, repair parts, and consumables for each level of maintenance. The procurement and acquisition procedures are defined in Division Policy 10.2, "Logistics Management and Support," Section 3.3.

Table 4 Parts list

COMPONENT	QUANTITY OF PARTS REQUIRED
INTERMEDIATE	
M-1	10
M-2	15
M-3	2
M-4	3
M-5	8
WS-1	30
WS-2	25
WS-3	4
WS-4	15
WS-5	2
WS-6	1
WS-7	5
WS-8	10
WS-9	1
WS-10	7
AS-1	1
AS-2	1
AS-3	2
ORGANIZATIONAL	
CK-1	5
PP-SP	10
TR-15	25
PP-1	10
PP-2	10
PP-3	10
PP-4	10
TP-1	10
TP-2	10
TP-3	10
TP-4	10
LP-IN	1
DM-R1	2

2.7.3.3 Test and Support Equipment

Table 5 lists the test and support equipment for each level of maintenance. The procurement and acquisition procedures are defined in Division Policy 10.2, "Logistics Management and Support," Section 3.7.

Table 5 Test equipment list

COMPONENT	QUANTITY OF PARTS REQUIRED
INTERMEDIATE	
TE-1	1
TE-2	2
TE-3	4
TE-4	1
TE-5	4
TE-6	1
ST-1	1
ST-2	1
ORGANIZATIONAL	
N/A	

2.7.3.4 Personnel and Training

Operator training on the work station will be conducted by the Computer Training Branch. The course is outlined in Training Bulletin 14 and includes basic entry-skill requirements. Intermediate and depot maintenance training are conducted at the factory. Course schedules are published quarterly. All of these training courses are for introductory purposes. Higher level training is accomplished on the job.

2.7.3.5 Facilities

The facilities plan for this organization is covered under Division Policy 43.19, "Space Planning Commission," Section 11.5. It covers square footage requirements, heating, ventilating, and air conditioning specifications, and estimated construction costs according to the Five-Year Plan.

2.7.3.6 Retirement

Recoverability of components and items is determined at the intermediate/depot levels. All major end items will be cannibalized for spares. All other components will be destroyed at a classified destruct site.

2.8 System Research Analysis

Selecting a single software package among the hundreds of options available can be a sizable job without the proper tools to facilitate the effort. In addition, the final options may appear to be equal in value and/or performance.

The primary focus of this section is to the present the use of multiattribute analysis in selecting the appropriate software option. Such an approach will preclude the expense of living with, working around, or having to resolve a wrong selection.

The use of multiattribute analysis can also provide justification for paying more money for an option based on its subjective value.

2.8.1 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was developed by Thomas Saaty and has been applied in numerous fields such as transportation planning, portfolio selection, corporate planning, marketing, and others.

The strength of AHP lies in its ability to structure a complex, multiperson, multiattribute, and multiperiod problem hierarchically. Pairwise comparisons of the elements can be established using a scale that indicates the degree to which one element dominates another. This scaling process can then be translated into priority weights for a comparison of alternatives. The suggested numbers to express degrees of preference between any two elements x and y are given in Table 6. (8)

Table 6 Preference numbers for pairwise comparisons

If x is . . . as (than) y,	then the preference number to assign is:
equally important/preferred	1
weakly more important/preferred	3
strongly more important/preferred	5
very strongly more important/preferred	7
absolutely more important/preferred	9

Source: Canada, John R., and William G. Sullivan. "Economic and Multiattribute Evaluation of Advanced Manufacturing Systems." Englewood Cliffs, NJ: Prentice-Hall, Inc., 1989.

2.8.2 Software Selection

The initial set of ten alternatives is subjected to the "must have" performance requirements developed by the evaluation committee. The resulting subset of three software packages are analyzed for tradeoffs among the desired attributes. Table 7 shows the initial list of nonmonetary attributes. Those deemed the most critical, again by the committee, are numbers 1, 2, 7, and 8.

These attributes are viewed as nonmonetary because there is no market mechanism conveniently available by which dollar values can be assigned to them. The following discussion assumes that the reader is familiar with AHP as there is no intent to explain the process beyond that which is presented.

Table 7 Nonmonetary attributes

1. **Flexibility**	rapid response to the introduction of design changes to existing problems
2. **Expandability**	allows removal of existing components and/or additions of new components with minimal disruption to normal operations
3. Implementability	feasible with respect to existing technology and accomplishable within a reasonable time frame
4. Reliability	ability to operate continuously with minimal interruption due to system failure
5. Integrity	minimize transmission errors
6. Security	protection of data from and/or alteration by unauthorized personnel
7. **Functionality**	minimize both response time to interactive users and turn-around time on batch jobs
8. **Manageability**	minimize required number of system operators by eliminating specialists for each system

The solution consists of the following four stages:

1. Determination of the relative importance of the attributes.
2. Determination of the relative weight (standing) of each alternative with respect to each attribute.
3. Determination of the overall priority weight (score) of each alternative.
4. Determination of indicator(s) of consistency in making pairwise comparisons.

Figure 22 represents the decision hierarchy for the selection of a software package based on the four attributes identified above.

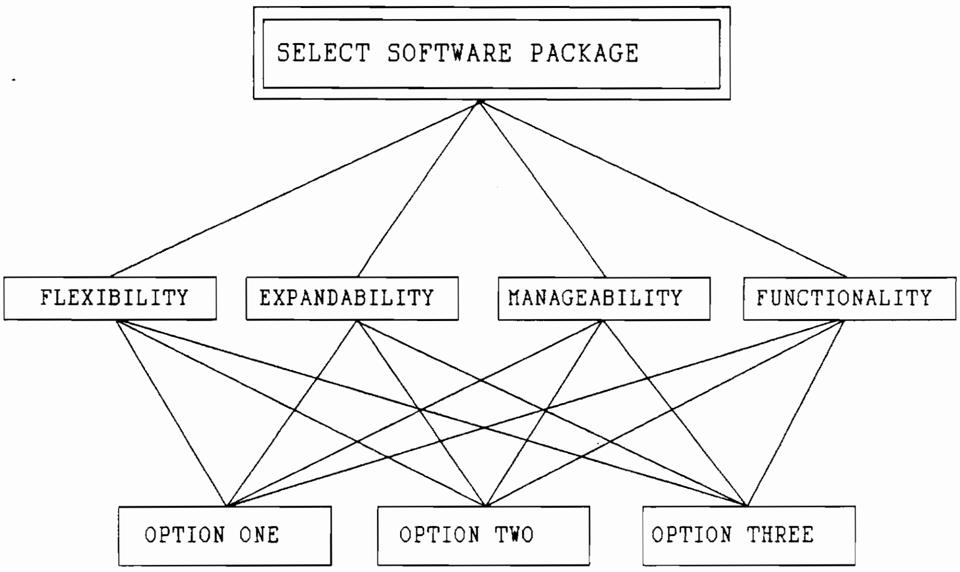


Figure 22 Decision Hierarchy

Table 8 shows the matrix of preference numbers as paired comparisons for the attributes as well as the normalized values and priority weights (the AVG column, equal to the row, Σ, divided by four). The subjective values resulted from demonstrations and individual evaluations of each software package.

The priority weights from Table 8 indicate that the most important attribute is manageability, followed by expandability, flexibility, and finally functionality.

Next, a consistency ratio (CR) is calculated to check the consistency of the pairwise comparisons made in Table 8. The matrix in that figure is multiplied by the priority

Table 8 Paired comparisons and priority weights

	A	B	C	D	A	B	C	D	AVG
A	1	7	1/3	3	.223	.318	.202	.326	.267
B	1/7	1	1/9	1/5	.032	.046	.068	.022	.042
C	3	9	1	5	.670	.409	.608	.544	.558
D	1/3	5	1/5	1	.075	.227	.122	.108	.133
Σ	4.48	22	1.64	9.2	1	1	1	1	1

weights (eigenvector). Each element of the product is divided by its corresponding element in the eigenvector. The resulting numbers are averaged to give the maximum eigenvalue, Ω max. Then the consistency index (CI) is determined using

$$CI = \frac{\Omega\ max - N}{N - 1}$$

where N is the number of attributes. The random indexes (RI) for various matrix sizes, N, have been approximated by Saaty. A portion of the RI is given in Table 9. The value CR is equal to the CI divided by the RI.

Table 9 Random indexes

N	1	2	3	4	5	6	7	8	...
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	...

The calculations discussed above are:

$$\begin{bmatrix} 1 & 7 & 1/3 & 3 \\ 1/7 & 1 & 1/9 & 1/5 \\ 3 & 9 & 1 & 5 \\ 1/3 & 5 & 1/5 & 1 \end{bmatrix} \begin{bmatrix} .267 \\ .042 \\ .558 \\ .133 \end{bmatrix} = \begin{bmatrix} 1.146 \\ 0.169 \\ 2.402 \\ 0.544 \end{bmatrix}$$

$$\Omega \text{ max} = \frac{\frac{1.146}{.267} + \frac{.169}{.042} + \frac{2.402}{.558} + \frac{.544}{.133}}{4}$$

$$= \frac{4.29 + 4.02 + 4.30 + 4.09}{4}$$

$$= 4.18.$$

$$\text{CI} = (4.18 - 4)/3 = 0.06.$$

$$\text{CR} = .06/.90 = \mathbf{0.07}.$$

The CR is less than 0.1; therefore, the consistency of the pairwise comparisons of the attributes is considered to be reasonable.

Next, a matrix of paired comparisons is made for each of the alternatives with respect to each attribute. Tables 10 through 13 below show each matrix along with the associated priority weights and CR. The calculations are identical to the procedure outlined above. The spreadsheet used to perform the calculations is included in Appendix A.

Table 10 Expandability priority weights

W/ RESPECT TO:		1	2	3	1	2	3	AVG
EXPANDABILITY **CR = .001**	1	1	5	9	.763	.769	.750	.761
	2	1/5	1	2	.153	.154	.167	.158
	3	1/9	1/2	1	.085	.077	.083	.082
	Σ	1.31	6.5	12	1	1	1	1

Table 11 Functionality priority weights

W/ RESPECT TO:		1	2	3	1	2	3	AVG
FUNCTIONALITY **CR = .012**	1	1	1/5	2	.154	.149	.200	.168
	2	5	1	7	.769	.745	.700	.738
	3	1/2	1/7	1	.077	.106	.100	.094
	Σ	6.5	1.34	10	1	1	1	1

Table 12 Manageability priority weights

W/ RESPECT TO:		1	2	3	1	2	3	AVG
MANAGEABILITY **CR = .016**	1	1	3	4	.632	.667	.571	.623
	2	1/3	1	2	.211	.222	.286	.239
	3	1/4	1/2	1	.158	.111	.143	.137
	Σ	1.58	4.5	7	1	1	1	1

Table 13 Flexibility priority weights

W/ RESPECT TO:		1	2	3	1	2	3	AVG
FLEXIBILITY **CR = .062**	1	1	1/5	4	.160	.153	.286	.199
	2	5	1	9	.800	.763	.643	.735
	3	1/4	1/9	1	.040	.085	.071	.065
	Σ	6.25	1.31	14	1	1	1	1

The CRs are less than 0.1; therefore, the consistencies of the pairwise comparisons are considered to be reasonable. Finally, a summary matrix is produced (Table 14) using the priority weights calculated above. The attributes A, B, C, and D correspond to expandability, functionality, manageability, and flexibility, respectively. The alternative weighted evaluation is equal to the sum of the products of the attribute weight times the evaluation rating.

Table 14 Summary matrix

	ATTRIBUTE				ALTERNATIVE WEIGHTED EVALUATION
	A	B	C	D	
Attribute Weights	.267	.042	.558	.133	
ALTERNATIVES					
Option One	.761	.168	.623	.199	**.584**
Option Two	.158	.738	.239	.735	.304
Option Three	.082	.094	.137	.065	.111

Option One, which allows access to the source code and can incorporate additional dBase code, has a weighted evaluation of 0.584 and is considered to be the most desirable alternative.

This is consistent with both the priority weights and CR values of the attributes and alternatives. Even though Option Two had higher priority values overall, Option One had higher values for the most important attributes.

2.8.3 Attribute Score Versus Cost

Even though the customer is not apprehensive about cost, an analysis is performed to compare the value of the selected option against the values of the other two. The weighted evaluation ratings from Table 14 are used as the value scores for the following analysis.

In addition to the initial costs of each software package, the evaluation committee applied a software maintenance cost of 150%. Assuming a 15% discount rate and a life of ten years, a present worth (PW) value was calculated for each alternative. The results are shown in Table 15.

Table 15 Summary of present worth

	OPTION ONE	OPTION TWO	OPTION THREE
Software Cost	4,200	3,800	2,000
Maintenance	3,162	2,861	1,506
TOTALS	$7,362	$6,661	$3,506

Monetary (PW) and nonmonetary considerations are now presented on a summary graph. PW is plotted on the left axis and value score is plotted on the right axis. This graph provides insight into which alternative ought to be recommended by displaying differences between the monetary and nonmonetary aspects of each. The scales of both axes are fixed so that a percent change between the maximum and minimum extremes of PW and value score are identical. (9)

Figures 23 through 25 are the graphs comparing Option One to Option Two, Option One to Option Three, and Option Two to Option Three, respectively. The shaded area shows the set of parameters that have the most significant difference.

The difference in the size of the shaded and non-shaded areas reflects the relative importance of the two indices, PW and value. For example, if the PW area is larger than the value area, this indicates that the additional cost of the more expensive package does not result in an equal gain in

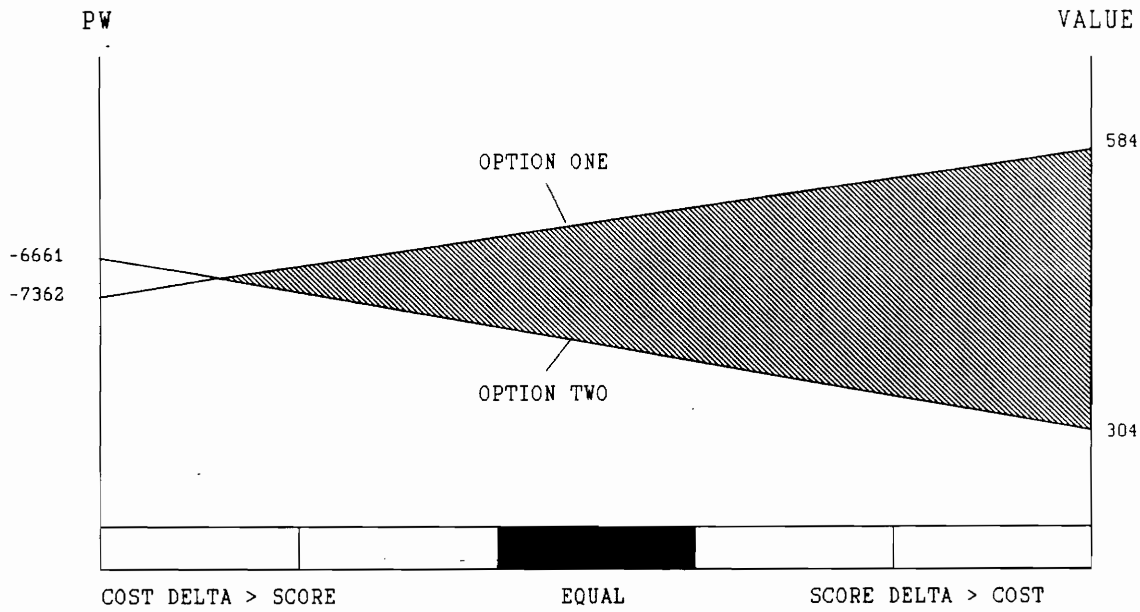


Figure 23 PW versus value score

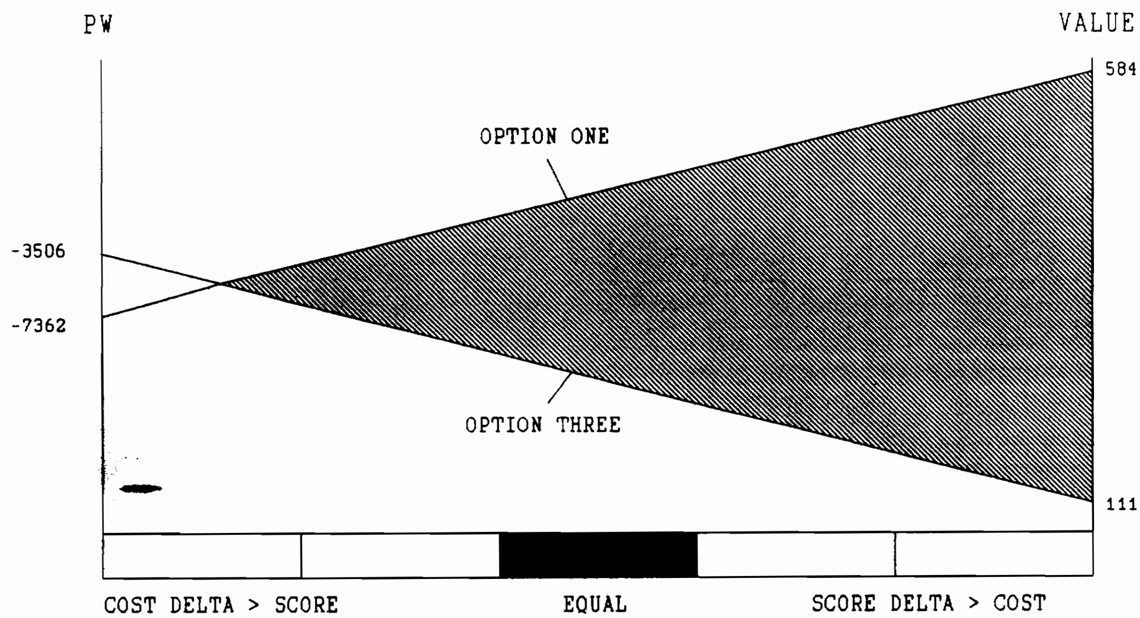


Figure 24 PW versus value score

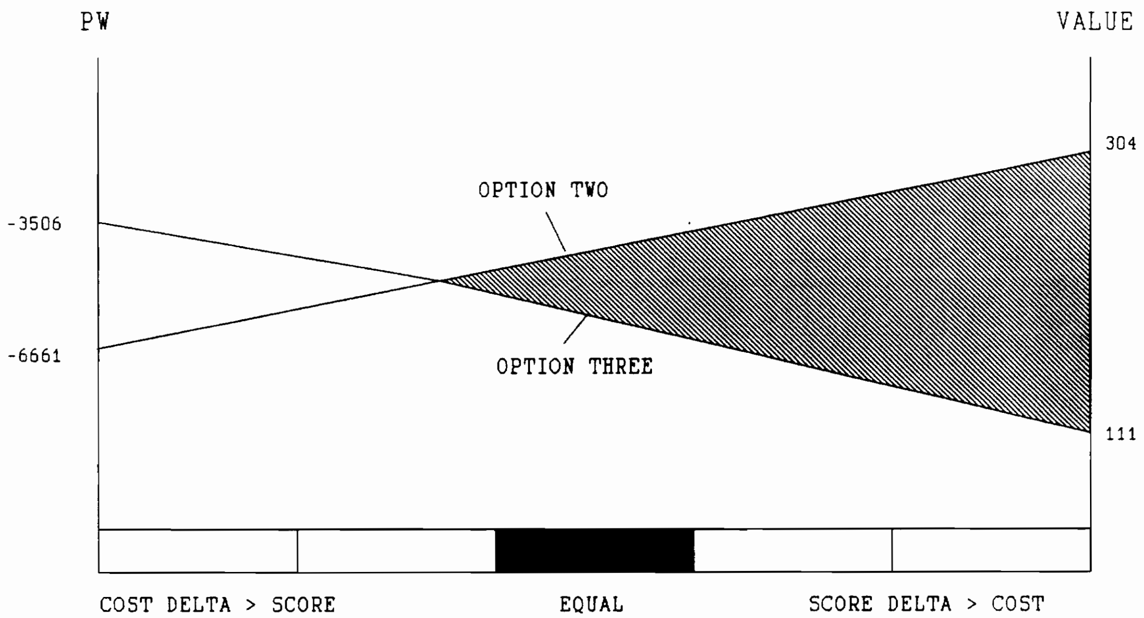


Figure 25 PW versus value score

value. Thus savings is more important than value and the least expensive option would be selected.

If the option lines cross within the area of the solid center rectangle, then either alternative is acceptable. This is almost the case as between Option Two and Option Three. However, the value of Option Two outweighs the lower cost of Option Three. It is clear that the optimal alternative is Option One. The extra nonmonetary value far exceeds the extra cost. Fortunately, the primary focus of the analysis from the outset was on nonmonetary attributes instead of price.

2.8.4 Hardware Selection

Even though there were no specific hardware requirements that dictated a choice between the ACME or the IBM, there were several nonmonetary attributes that the committee felt would enhance user acceptance. Though there was not a requirement or a need to do so, the procedures described above for software selection were repeated for hardware and the IBM came out on top. The primary issue was the poor history that the ACME had for mean time between failure and mean time to repair. They were equal in nearly all other areas, such as keyboard, speed, monitor resolution, and interface with peripherals. A PW versus value score analysis was also done and IBM was again the optimal choice.

2.8.5 The Design Phase

This section analyzes the system design function primarily as it pertains to the design of the selected software package, the extent of customization, and the additional coding required.

2.8.5.1 The Computer Plan

A computer plan of action is required to guide the creation of computer applications, allowing for growth in the project. Planning up front provides a uniform and maintainable structure for the future. It should be flexible enough to allow for innovation, but firm enough to reduce or eliminate redundant data, duplicated effort, and incompatibilities.

The process of designing computer applications systems is a process of evolution. After a pattern is set, a program can be created to accomplish the same task, freeing up more time to do other things. The following outline is used for the design of this computer plan:

I. Purpose and scope

II. Current configuration

- A. Hardware
- B. Software

III. Security

- A. Physical
- B. Software

C. Requirements for audit trail

IV. Required development documentation

A. Design documents

B. Data Dictionary requirements

C. Programming standards/ guidelines/suggestions

V. Considerations for growth

A. Storage requirements

B. Computing hardware

The purpose of the plan of action above is to lend continuity and conformity to a computer system. If the programs and processes conform to specific standards, it will be easier to change them later if required. The user should be able to rely on consistency from one application to another. The computer plan is where this consistency starts.

The standards set forth in the plan can be as detailed or as vague as the planner wants to make them. If the plan is too detailed, the applications created will be stiff and unyielding where flexibility is usually desired. Application systems will take longer to develop, and a multitude of exceptions will occur. A plan that is not detailed enough, however, will lead to total loss of control; information that could be vital to the organization might be missed because two different applications could not share data due to incompatibility.

The configuration of the hardware is known. The configuration of the software is evaluated over a two week period to determine the extent of customization required. This is accomplished primarily during the evaluation period.

The facility is secured with computer controlled badge access. The computer room is available for open use to anyone who is authorized entry into the area.

The software package will require additional coding to incorporate password security as required by the customer. It already has a password routine that limits access to the entire system; however, it does not restrict users from access to specific menu options.

There are no requirements for security audits with the exception of random checks to ensure that no classified data are being stored on the hard drive. This is the primary purpose for using the removable cartridge disk (RCD) system.

A computer engineer was tasked to direct the coding operation. There were no requirements for design documents or a data dictionary due to the short amount of time available. The only required development documentation was for a user's training manual.

Considerations for the training manual include what its contents will be; how to create backup copies of all programs, data, and formats; where backup copies are to reside;

and how to recreate the current system if necessary.

The final part of the plan is a prediction for the future, a picture of how the system might look in ten years. The growth rate of data files and records was evaluated and deductions were made about the future hardware storage that would be necessary to contain growing files.

The initial backup copy of the system will reside on an individual RCD. The backup copy of the data files will reside on a separate RCD. Initially, the history data will be stored on the original system disk for immediate access. When the system disk fills to capacity, in an estimated two years, the history files can be backed up to another RCD.

2.8.5.2 Program Design Analysis

Design requirements are developed from the computer plan and proceed through the conceptual design, preliminary design, and the detailed design. The very first design begins with simple flowcharts. Pseudocoding is added in later designs. This provides considerable aid later in the actual coding phase.

The coding phase is often considered to have its start during the design phase with the development of the pseudocode and prototypes. Pseudocode is a representation of a logic flow written in plain language instead of a pictorial flowchart. The prototypes are nothing more then the menus and screens needed in the system. This is accomplished before any programs are written in order to save the time that is inevitable with changes to the screen selections and layouts. A prototype also enables data entry to begin while the rest of the functions are still being designed and coded.

Full advantage of the feedback loop is taken at each step. The design of the screens and the selection options from the primary working screen undergo considerable transformation. The names of the data fields are changed. Some additional data points are added and others are eliminated. Even the logic for calculating dates is modified. An additional benefit to the feedback loop is that it allows users to see the setup of the application system so that they can learn the system.

Simple models are developed to demonstrate the resource leveling options and capabilities of the selected software package. The algorithms used by the program, however, are too rigid for the end users, who require more flexibility and manual override capabilities. This again changes the design of the program with the incorporation of a spreadsheet.

Most other points of contention are discussed and resolved by the committee. A few, which defy any logical engineering resolution, are arbitrated by management.

2.8.6 The Program Coding Phase

Computer programming is the use of language statements to manipulate items of information. The purpose of this manipulation is to produce a desired result in the form of reports, graphs, or tables of information. This unprocessed information is referred to as data. Data is the "raw" form of information; facts and figures that alone have little or no meaning. The purpose of computer programs is to arrange data into more meaningful and/or useful forms.

Two months elapsed from the identification of need to the point where the coding phase could begin. This leaves four months to write the code, have the system evaluated, installed, and tested, and to produce the user's manual.

The preliminary work conducted during the design phase plays a key role. The foundation has been laid with logic flowcharts, pseudocode, and menus and screens that have already been accepted in theory. The actual production of the code is bagatelle.

The only problems encountered are with changes to the source code. The seemingly infinite number of subroutines and multilinks create a lot of confusion. This factor adds an additional caveat when debugging occurs.

2.8.7 System Evaluation

The system is evaluated based on the initial requirements and any changes implemented during the planning, research, design, and production phases. The intensive use of the feedback loop throughout the project makes the evaluation period pass without incident. Toward the end of the programming phase, several test runs are conducted using current data. The reports and graphics that are generated are used for the ISB Meeting.

There are several new requirements that surfaced during the evaluation due to the publicity and popularity of the program demonstrations. These requirements are not within the scope of the original project and cannot be added as automated features. However, because the problems involve the direct application of operations research/management science, they are resolved with the purchase and addition of an integrated software package consisting of quantitative modeling techniques. An example of the most useful modeling application is included in Appendix D.

3 CONCLUSIONS

The increased availability and sophistication of information processing technology has created an ideal environment for the application of the systems engineering process in solving this problem. There is a major problem frequently associated with undertaking a project to customize computer solutions. The problem is that the organization does not understand exactly what the systems engineering process is or how to apply it.

Systems Engineering is the process of applying scientific and mathematical principles to the operational end of a system. It integrates and incorporates all of the steps that are necessary to fulfill a program's requirements. Systems engineering takes an operational need and manages it through its entire life-cycle. It brings together the players from a vast range of disciplines and focuses each group's attention on the objective.

Systems engineering is the epitome of the teamwork concept for problem solving. A group of experts works on a subsystem and designs according to factors of economics, feasibility, sociability, etc. Prior to the systems engineering approach, there was a great communications problem in gathering and combining those factors into the total system and resolving conflicts.

This problem could have been solved without the systems engineering process. The selection of the software package could have been accomplished using common sense. But that is because of the nature of this problem; what would the decision be if the desired software package cost twice as much? Common sense alone is no justification for determining the value of a product with a number of complicated and varying attributes.

Without systems engineering, the project's completion would have been more costly. This is especially true in terms of the rework that would have been necessary. The facilities organization does not have an established means for coordinating projects such as this. The irony is that planning, communicating, and feedback are integral parts of FSB's daily function. In the past, programmers have been given the resources, placed in a computer room, and were expected to "just do it." Again, this relates to this particular group. It cannot be said that other organizations would operate in the same manner in the absence of systems engineering.

The major steps in the systems engineering process are the identification of need, the planning function, research, design, production/construction, evaluation, consumer use and logistic support, and phase-out. The key steps for this project were the identification of the customer's need and the planning function. Identifying the correct requirements is important because a perfect solution to the wrong problem is as bad as (or sometimes worse than) no solution at all. And thorough planning upfront ensures less confusion later in the project. It is important to utilize the feedback loop in both phases so that back tracking is minimized.

From a human factors perspective, decision making is considered to be the heart of information processing. It is recognized as a complex process by which we evaluate alternatives and select a course of action. It involves seeking information relevant to the decision at hand, estimating probabilities of various outcomes, and attaching values to the anticipated outcomes.

Unfortunately, humans, are not optimal decision makers and often do not act according to objective probabilities of gain and loss. A number of biases are inherent in the way we seek information, estimate probabilities, and attach values to outcomes that produce this behavior.

In working on this project, it has been recognized that we give undue weight to early evidence or information and are generally conservative. We do not extract as much information from sources as we should. As more information is gathered or presented, we become more confident in our decisions, but not necessarily more accurate. Additionally, we often treat all information as if it were equally reliable, even though it is not.

As engineers, we must base our decisions on what we believe to be the facts. If we do not have facts, we have speculation. If we have speculation, it must be based on some logical premise. When there are many alternatives to choose from, it is not paramount that the optimal decision is reached. It is more important that the decision be based on a logical, common sense assessment. Wrong decisions are made because of the absence of this approach; good, but not optimal decisions are reached only due to a lack of experience or missing information.

A disturbing problem with this project is the customer's attitude towards cost. We need to carefully educate the customer who believes that you cannot associate a cost with nonmonetary attributes. It is my contention that you **can** associate a cost with a perceived value.

Corporations spend a considerable amount of money on training without regard to cost because of its recognized value. I do not think that management is so blind, however, that they would not question a week long training course that costs $100,000 if similar courses cost an average of $1,000. Does it cost too much or is it just not a good value?

As an analogy, if a student taking a test knows that he must add two numbers but multiplies them instead, did he make an error or did he make a mistake? He actually did neither;

he made an oversight. The incorrect answer was omitted as a result of his lack of attention. An error stems from a belief in something that is wrong, apart from what is morally or ethically right; on the other hand, a mistake is the result of misunderstanding. Both words are used interchangeably but by definition an error is more severe than a mistake, especially in placing blame. In the end, the student does not get credit for a correct answer, and we know why.

Going back to the training example, let's say that the $100,000 course is for new technology that a corporation is breaking into. It would indeed be difficult to conduct an accurate cost-benefit analysis. The corporation cannot determine its return on investment for this particular training course, but it can make an appraisal that will lead to a decision. If the corporation had little or nothing to do with the new technology, the cost of the course might be unreasonable. On the other hand, if it was costing the company $20,000 a month by not having trained personnel, the cost of the course might be deemed a bargain.

Most cases are not this simple and value analysis can be nearly as difficult to orchestrate as cost-benefit analysis. The difference is that cost-benefit analysis is expected to be precise whereas value analysis is accepted as a nonquantifiable appraisal. In the end you must have a combination of the two.

4 RECOMMENDATIONS

Projects such as this one are easily worked out without a structured approach. Because of the competitive costs of commercial software packages, common sense can be used to evaluate the best option to suit one's needs. This, however, is not a recommendation to abandon the systems engineering process. On the contrary, one of the keys to the success of systems engineering is the ability to adjust to a situation's existing environments. You have to be able to focus on the factors that are most important and disregard those that are irrelevant.

A caution must be issued when adopting the present worth versus value score method presented in this report. Cost and value should not always be considered with equal weighting. Depending on what the circumstances dictate, a weighting factor may be necessary. For example, a tight budget might be more critical than a few extra "bells and whistles." You can make that determination the same way that you analyze nonmonetary attributes.

Computer-aided decision making is in vogue. It is recognized that computers are better than the human brain for aggregating probabilities as new information is obtained, keeping track of several hypotheses, alternatives, or outcomes of sequential tests, and selecting the best sources of information to test specific hypotheses.

Despite these perceptions, we have a long way to go in obtaining the acceptance and full use of DSS and other computer applied management science techniques. Regardless of the logic of such approaches, managers are human decision makers and "computers do not make the right decisions but contribute to them; the human makes the final decision". (9)

You should always maintain a sensitivity to human factors aspects with any project. As today's managers are replaced with today's innovators, the systems engineering - computer decision making link will become more natural. Your success will be assured with continued efforts in the education and promotion of the effectiveness, versatility, and efficiency of the systems engineering process and its vast range of applications across all professions.

5 REFERENCES

1) Prague, Cary N., and James E. Hammitt. dBase IV Programming. Blue Ridge Summit, PA: Windcrest Books, 1989.

2) Dannenbring, David G., and Martin K. Starr. Management Science An Introduction. New York, NY: McGraw-Hill, Inc., 1981.

3) Aggarwal, Raj, and Inder Khera. Management Science. San Francisco, CA: Holden-Day, Inc., 1979.

4) Lifson, Melvin W. Decision and Risk Analysis for Practicing Engineers. Boston, MA: Cahners Books, 1972.

5) Blanchard, Benjamin S. Logistics Engineering and Management. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1986.

6) Schinbeckler, Bradford A. "Adaptability in the Systems Design Process". Project Report. VPI&SU, 1989.

7) Blanchard, Benjamin S., and Wolter J. Fabrycky. Systems Engineering and Analysis. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1981.

8) Canada, John R., and William G. Sullivan. Economic and Multiattribute Evaluation of Advanced Manufacturing Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1989.

9) Sullivan, William G., and Hampton R. Liggett. "A Decision Support System for Evaluating Investments in Manufacturing Local Area Networks". Manufacturing Review. Oct. 1988: 151-157.

10) Hillier, Frederick S., and Gerald J. Lieberman. Introduction to Operations Research. Oakland, CA: Holden-Day, Inc., 1986.

11) Emmons, Hamilton, A. Dale Flowers, Kamlesh Mathur, and Chandrashekhar M. Khot. STORM, Quantitative Modeling for Decision Support. Oakland, CA: Holden-Day, Inc., 1986.

12) Drew, Donald R., and Charng-Horng Hsieh. A Systems View of Development. Taipei, Republic of China: Cheng Yang Publishing Company, 1984.

13) Sprague, Ralph H., and Eric D. Carlson. Building Effective Decision Support Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1982.

14) Sprague, Ralph H., and Hugh J. Watson. Decision Support Systems, Putting Theory into Practice. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1986.

15) Brusaw, Charles T., Gerald J. Alred, and Walter E. Oliu. Handbook of Technical Writing. New York, NY: St. Martin's Press, Inc., 1987.

6 APPENDICES

It is unfortunate that appendices are necessary for this report, but the alternative would have required ten additional volumes. They include supplemental tools, figures in lieu of computer code, and highlights in the place of detail.

Appendix A is the spreadsheet used for the multiattribute evaluation problem from Section 2.8.2. Appendix B describes the FACTS spreadsheet that is used in place of the resource leveler included in the software package. Finally, Appendix C covers the solution to a subproblem which surfaced from this project.

APPENDIX A

The purpose of the spreadsheet in this section is to simplify the procedure used in the AHP method by eliminating the need to make redundant calculations. The first three columns are ratings of the three software options with respect to the attribute (in bold print). The spreadsheet automatically totals each column and normalizes the ratings by dividing each one by its respective total. Those values are reflected in the next three columns. Note that each column sums to one.

Each row in the second three columns is then averaged. The average column vector is multiplied by the matrix consisting of the first three columns. Each number in the product, column [X], is divided by its corresponding element in the average column. The sum of these values is divided by the number of options. This value is referred to as Ω max which is used to calculate CI and then CR.

The CI must be less than 0.1 for the ratings to be considered reasonable. It is a self check that is convenient for uncovering errors in the rating scheme.

Once the formulas for the first spreadsheet are entered, the subsequent tables are created by registering a new set of rating numbers. The resulting spreadsheets are exhibited below.

SUMMARY OF PAIRED COMPARISONS AND PRIORITY WEIGHTS
FOR ALTERNATIVES WITH RESPECT TO EACH ATTRIBUTE

EXPANDABILITY

	1	2	3	1	2	3	AVG	[X]	[Y]
1	1.00	5.00	9.00	0.76	0.77	0.75	0.76	2.284	3.003
2	0.20	1.00	2.00	0.15	0.15	0.17	0.16	0.473	3.001
3	0.11	0.50	1.00	0.09	0.08	0.08	0.08	0.245	3.000
								Ω max =	3.001
	1.31	6.50	12.00	1.00	1.00	1.00	1.00		

CI = (Ω max-N)/(N-1) = 0.001
CR = CI/RI* = 0.001

FUNCTIONALITY

	1	2	3	1	2	3	AVG	[X]	[Y]
1	1.00	0.20	2.00	0.15	0.15	0.20	0.17	0.504	3.008
2	5.00	1.00	7.00	0.77	0.75	0.70	0.74	2.237	3.031
3	0.50	0.14	1.00	0.08	0.11	0.10	0.09	0.284	3.004
								Ω max =	3.014
	6.50	1.34	10.00	1.00	1.00	1.00	1.00		

CI = (Ω max-N)/(N-1) = 0.007
CR = CI/RI* = 0.012

MANAGEABILITY

	1	2	3	1	2	3	AVG	[X]	[Y]
1	1.00	3.00	4.00	0.63	0.67	0.57	0.62	1.891	3.034
2	0.33	1.00	2.00	0.21	0.22	0.29	0.24	0.722	3.014
3	0.25	0.50	1.00	0.16	0.11	0.14	0.14	0.413	3.007
								Ω max =	3.018
	1.58	4.50	7.00	1.00	1.00	1.00	1.00		

CI = (Ω max-N)/(N-1) = 0.009
CR = CI/RI* = 0.016

FLEXIBILITY

	1	2	3	1	2	3	AVG	[X]	[Y]
1	1.00	0.20	4.00	0.16	0.15	0.29	0.20	0.608	3.049
2	5.00	1.00	9.00	0.80	0.76	0.64	0.74	2.321	3.157
3	0.25	0.11	1.00	0.04	0.09	0.07	0.07	0.197	3.012
								Ω max =	3.072
	6.25	1.31	14.00	1.00	1.00	1.00	1.00		

CI = (Ω max-N)/(N-1) = 0.036
CR = CI/RI* = 0.062

*RI = 0.58 (from Table 9)

APPENDIX B

The modifications spreadsheet is a working document used to assist in the balancing of the ISB schedule. This option was requested in place of the requirement for the automatic resource leveling capability, which was available with the base software program.

Figure B1 illustrates a sample spreadsheet. The menu, in bold print, is a customized macro menu which depicts the options that are available.

Enter   Delete   Month_out   Fix   Print   Save   Quit   Help

	90					90			
PROJECT TITLE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
ANNEX 200 WING	100	78	90	40					
INSTALL PRINTER (B18)	5								
PROJECT I DISK DRIVE	11								
LOCKER RM MOD	30	35	20						
SYSTEM TEST	5	7							
PROJ II RELOCATION	21	14	10						
CY 90 CRT INSTALL	6	6	6	6	6	6	6	6	6
LAB IV AREA MOD	35								
PROJ X COMPARTMENT	64								
REWIRE PDU'S	32	15							
LOBBY MODS	107	45	20						
NEW SUBSTATION	25	20	20						
MOD 2KB5		185	95	25					
COMPART 2G10		75	75	50					
3BO1/2G10 MOD		100	110	90	50				
...									
TOTAL MONTHLY MANDAYS	600	600	600	600	600	600	600	600	600

Figure C1 Sample spreadsheet

The spreadsheet does nothing more than keep a running total of the number of mandays estimated for all projects during each month. As projects are added, deleted, or changed, the totals update automatically and allow the user to make adjustments as necessary.

The totals always appear at the bottom of the screen in a spreadsheet window. The FPS is required to maintain a balanced effort of 600 mandays per month. As simple as this tool is, the past method involved manual calculations done over and over again. What took hours and sometimes days, now takes only minutes.

APPENDIX C

This appendix is the direct result of illustrating what the systems engineering process can provide towards solving a wide variety of problems. The issue presented in this section deals with the common problem of space allocation. In the past, there was no scientific explanation for why space allocations were done the way they were. There was some logical basis of need and priority, but nothing more. This solution presents irrefutable technical answers based on cost and need.

Problem Statement

There are five customers requesting space within an area of 11,000 contiguous square feet (ft^2). The space has been made available by the relocation of a tenant into a newly completed block. Three of the five customers are expanding to support a new program. The other two customers are new tenants to the facility.

The vacated space is comprises 6,600 ft^2 of raised computer flooring, and 4,400 ft^2 of office space. The five customers are requesting 5,040 ft^2 of office space and 6,300 ft^2 of raised flooring space, or a net of 340 ft^2 more than what is available. This request is the result of the initial

SPC meeting where people and requirements were reduced to a more realistic level.

This facility expansion problem requires the fitting of the new programs into the space that is available and to ensure that the modifications are completee in time for their delivery obligations.

Linear programming is used to minimize the cost associated with allocating space to the five various groups. This section includes a description of each aspect of these management science tool and the data obtained for use in the model.

Linear Programming

The linear programming model uses the Simplex Method as its solution algorithm. It was developed by George Dantzig in 1947 and has been used successfully in the solution of problems concerning the assignment of personnel, blending of materials, distribution and transportation, and investment portfolios. (10)

Linear Programming Data

The relocation of a tenant has freed up 11,000 ft^2 of contiguous space in a block. The space is currently broken down into 4,400 ft^2 of office space and 6,600 ft^2 of Computer Processing Area (CPA) space.

Two new projects, PI and PII, and three support groups all have requirements for this space. The support groups include the Computer Services Branch (CSB), the Engineering and Maintenance Branch (E&MB), and Communications (Commo). The amount of space that each group is requesting is driven by the number of each type of employee the group requires.

Each type of employee, such as manager (MGR), supervisor (SUPV), secretary (SECY), individual contributor (IC), or engineer (ENGR) is allocated a certain amount of space based on the Facility Standard. It is rare for any employee to get this "ideal" amount of space; and as such, each employee category has an absolute minimum space allocation. The number of employees for each group, by type, is presented in Table C1.

Table C1 Employee breakdown

	PI	PII	CSB	E&MB	COMMO
MGR	1	2	-	-	-
SUPV	2	2	4	2	-
IC	4	9	7	-	2
SECY	3	3	2	1	-
ENGR	5	2	7	7	-

The Facility Standard and space allocation limits are presented in Table C2. The cost associated with modifying each type of worker's space is also presented in Table C2. These modification costs are based on 14 years of experience modifying office space.

Table C2 Space allocation standards and modification costs

INDIVIDUAL	SPACE MAX (ft^2)	SPACE MIN (ft^2)	MOD COST ($\$/ft^2$)
Unit level manager	120	100	75
Supervisor	100	80	90
Individual contributor	65	50	75
Secretary	75	60	75
Technical Engineer	75	60	110

Table C3 illustrates the comparison between the baseline space available and the amount of space requested based on facility standards. The table shows that the office space requirement exceeds the available space by 640 ft^2, whereas there is an excess of 300 ft^2 of CPA space. It is possible to convert CPA space to office space at a cost of $\$350/ft^2$, but even with the additional 300 ft^2, there is still a shortage of 340 ft^2.

It is clear that at least some of the requesting organizations will not receive the standard amount of space for each of their employees. The linear programming model is used to determine what the optimal space allocations are for each type of employee given that modification costs are to be minimized.

Table C3 Baseline versus space requested

	OFFICE	CPA
SPACE AVAILABLE	4400	6600
SPACE REQUESTED	5040	6300
BALANCE:	-640 ft^2	300 ft^2

Definition of Decision Variables

Solving a linear programming problem involves several steps: defining the decision variables, developing the objective function and constraints, and finally analyzing the results. The goal of the linear programming portion of the facility expansion problem is to minimize the cost of modifying the available office space for each type of employee. Therefore, a decision variable is required to represent the amount of space allocated to each type of employee. The decision variables and the abbreviations used in the equations are defined as:

MGR - amount of ft^2 space allocated to managers

SUPVR - amount of ft^2 space allocated to supervisors

IC - amount of ft^2 allocated to ind. contributors

SECY - amount of ft^2 space allocated to secretaries

ENGR - amount of ft^2 space allocated to engineers.

Objective Functions and Constraints

The objective function for the facility expansion problem is developed from the information found in Tables C1 and C2. Two cases are examined; the first assumes that all five groups need to fit into 4400 ft^2, the second assumes that the 300 ft^2 of excess CPA space is converted to office space. In the second case, the total available space is 4700 ft^2.

Figures C1 and C2 show the objective functions and constraints associated with the two respective cases. The coefficients of the objective functions are found by multiplying the total number of each type of employee by the corresponding cost associated with modifying space for that type of employee. Note that for case two, where converting the CPA space is considered, the conversion cost needs to be added to the optimal objective function value.

Minimize

+ 225 MGR SF + 900 SUPVR SF + 1650 IC SF + 675 SECY SF
+ 2310 ENGR SF

Subject to

+ 3 MGR SF + 10 SUPVR SF + 22 IC SF + 9 SECY SF
+ 21 ENGR SF >= 4400

100 <= MGR SF <= 120
80 <= SUPVR SF <= 100
50 <= IC SF <= 65
60 <= SECY SF <= 75
60 <= ENGR SF <= 75
All employees SF >= 0

Figure C1 Case 1 objective functions and constraints

Minimize

+ 225 MGR SF + 900 SUPVR SF + 1650 IC SF + 675 SECY SF
+ 2310 ENGR SF

Subject to

+ 3 MGR SF + 10 SUPVR SF + 22 IC SF + 9 SECY SF
+ 21 ENGR SF >= 4700

100 <= MGR SF <= 120
80 <= SUPVR SF <= 100
50 <= IC SF <= 65
60 <= SECY SF <= 75
60 <= ENGR SF <= 75
All employees SF >= 0

Figure C2 Case 2 objective functions and constraints

The primary constraints seek to maximize the amount of space each type of employee receives while keeping the total amount of space allocated within 4400 ft^2 and 4700 ft^2 for cases 1 and 2, respectively. The additional constraints define the upper and lower bounds for each type of employee. The upper bounds correlate to the facility standards presented in Table C1, and the lower bounds are the absolute minimum allocations given in the same table.

Results of the Linear Programming Model

The optimal objective function values and the optimal values for the decision variables are presented in Figures C3 and C4. The optimal objective function value for case 2 does not include the CPA conversion cost of $105,000; when added, the total office modification cost comes to $516,450. Distributing the 300 ft^2 excess CPA space is approximately $130,000 more than limiting the office space to 4400 ft^2.

FACILITY EXPANSION PROBLEM - CASE 1
OPTIMAL SOLUTION - SUMMARY REPORT (NONZERO VARIABLES)

	Variable	Value	Cost
1	MGR	120.0000	225.0000
2	SUPV	80.0000	900.0000
3	IC	66.0000	1650.0000
4	SECY	63.0000	675.0000
5	ENGR	60.0000	2310.0000

Objective Function Value = 386100

Figure C3 Case 1 solution

FACILITY EXPANSION PROBLEM - CASE 2
OPTIMAL SOLUTION - SUMMARY REPORT (NONZERO VARIABLES)

	Variable	Value	Cost
1	MGR	119.0000	225.0000
2	SUPV	98.0000	900.0000
3	IC	65.0000	1650.0000
4	SECY	75.0000	675.0000
5	ENGR	60.0000	2310.0000

Objective Function Value = 411450

Figure C4 Case 2 solution

Another Look at the Objective Function and Constraints

The linear programing example illustrated so far does not have any type of priority scheme associated with it. In trying to fit 5040 ft^2 of requirements into 4400 ft^2 of space, cuts were made evenly across all five groups and across all types of employees. Instead of allowing the program to decide where the cuts are to be made, management science judgement is used to establish some priorities and de-emphasize certain allocations.

Statistics show that the secretaries spend the greatest percentage of their time at their desks. In contrast, the individual contributors in the communications branch are rarely at their desks. The nature of their work keeps them circulating throughout the building trouble-shooting problems. Finally, the engineers in the CSB have the heaviest workload and fully utilize their office space.

In order to have the linear program recognize the priorities discussed above, a new set of decision variables is defined. Instead of having one variable that represents the space allocated for all the managers, there is a decision variable for each group that is requesting a manager; likewise there is a variable for each type of employee that each group requests. The re-definition of the objective functions and constraints based on this priority scheme are illustrated in Figure C5. The goal of the objective function has not changed, nor has the primary constraint. The difference is the incorporation of all the new decision variables. The prioritization scheme is put into effect in the definition of the upper and lower bounds. Note that the individual contributors for the communications branch now have a lower bound of 25 ft^2, lower than the minimum allocation requirement. The secretaries for all the groups and the engineers in the CSB have their upper and lower bounds fixed to ensure the maximum amount of space.

Only a few of the decision variables are used to set priorities. However, in defining a variable for each type of employee for each group, any number of priorities can be set.

FACILITY EXPANSION PROBLEM

Minimize

```
 + 75 MGR I + 150 MGR II + 200 SUPVR I + 200 SUPVR II
       + 400 SUPVR ODC + 200 SUPVR E&MB + 300 IC I
       + 675 IC II + 525 IC ODC + 150 IC COMMO + 225 SECY I
       + 225 SECY II + 150 SECY ODC + 75 SECY E&MB
       + 550 ENGR I + 220 ENGR II + 770 ENGR ODC
       + 770 ENGR E&MB
```

Subject to

```
TOTAL SF
 + 1 MGR I + 2 MGR II + 2 SUPVR I + 2 SUPVR II + 4 SUPVR ODC
       + 2 SUPVR E&MB + 4 IC I + 9 IC II + 7 IC ODC
       + 2 IC COMMO + 3 SECY I + 3 SECY II + 2 SECY ODC
       + 1 SECY E&MB + 5 ENGR I + 2 ENGR II + 7 ENGR ODC
       + 7 ENGR E&MB >= 4400

                    100 <= MGR I <= 120
                    100 <= MGR II <= 120
                     80 <= SUPVR I <= 100
                     80 <= SUPVR II <= 100
                     80 <= SUPVR ODC <= 100
                     80 <= SUPVR E&MB <= 100
                     50 <= IC I <= 65
                     50 <= IC II <= 65
                     50 <= IC ODC <= 65
                     25 <= IC COMMO <= 50
                     60 <= SECY I <= 75
                     60 <= SECY II <= 75
                     60 <= SECY ODC <= 75
                     60 <= SECY E&MB <= 75
                     60 <= ENGR I <= 75
                     60 <= ENGR II <= 75
                     75 <= ENGR ODC <= 75
                     60 <= ENGR E&MB <= 75
                     All employees SF >= 0
```

Figure C5 Prioritized objective function

Results of the Prioritization Scheme

The optimal objective function value and the optimal decision variable values are presented in Figure C6. The secretaries and the engineers in the CSB have their 75 ft^2 of space as specified in the constraints. The individual contributors in Commo have their space reduced to 25 ft^2. As expected, the objective function value is greater for case 2 (values not shown) where the excess CPA space is used for office space.

FACILITY EXPANSION PROBLEM - PRIORITIZED
OPTIMAL SOLUTION - SUMMARY REPORT (NONZERO VARIABLES)

	Variable	Value	Cost
1	MGR I	120.0000	75.0000
2	MGR II	120.0000	150.0000
3	SUPV I	80.0000	200.0000
4	SUPV II	80.0000	200.0000
5	SUPV CSB	80.0000	400.0000
6	SUPV E&MB	80.0000	200.0000
7	IC I	65.0000	300.0000
8	IC II	60.0000	675.0000
9	IC CSB	50.0000	525.0000
10	IC COMMO	25.0000	150.0000
11	SECY I	75.0000	225.0000
12	SECY II	75.0000	225.0000
13	SECY CSB	75.0000	150.0000
14	SECY E&MB	75.0000	75.0000
15	ENGR I	60.0000	550.0000
16	ENGR II	60.0000	220.0000
17	ENGR CSB	75.0000	770.0000
18	ENGR E&MB	60.0000	770.0000

Objective Function Value = 397775

Figure C6 Prioritization solution

Sensitivity analysis is used to experiment with the upper and lower bounds of the decision variables. When small adjustments are made, the optimal decision variable values are adjusted slightly, but the optimal objective function value is kept constant. This is because in most cases the space is moved between groups that have equal modification costs.

The solution for case 1 is the optimal solution based on total modification costs. The totals are $1,648,550 and $1,778,090 for cases 1 and 2, respectively.

Recommendations

The integer programming method is used initially, only to keep the assigned square footages in whole numbers. In practice, there is enough tolerance associated with the actual design layouts to negate any honest attempts at being accurate. For this reason, and the fact that the processing time experienced in a few cases was exorbitant, integer programming is discarded as a solution method.

A great deal of information is gathered to solve facility expansion problems. However, before a recommendation can be made, a set of criteria and priorities must be established. Which is more important, time, money, or the social and political ramifications?

For facility expansion problems, meeting the time schedule is of primary importance. Several other programs are dependent on the completion of the expansion and therefore the decision is out of the hands of local management. The lowest priority is cost; the expansion absolutely must be completed and the money will come from somewhere. In setting the highest and lowest priorities, the social and political ramifications must then fall in between. Social issues are not as important as the time schedule, but are more important than keeping the cost low.

Recall that two options are considered. The first case does not convert the excess CPA space, and the second does. Case 1 only provided 4400 ft^2 to be distributed amongst the 5 groups; case 2 provided 4700 ft^2. In consideration of the social and political issues, case 2 is preferred because more space is provided for the employees. In terms of cost, case 1 is preferred because the cost is approximately $130,000 less than the total modification cost for case 2.

The last criterion to consider is the time schedule. In using the scenario presented in case 1, all of the deadlines can be met. However, with option 2, only 1 of the 5 deadlines is met.

Given the priorities of time, social issues, and cost (in that order) and the results of the management science models, case 1 is preferred as the solution to this facility expansion problem. The cost is lower, but more importantly, all the critical timelines can be met. Some of the employees end up with less space than they would have if case 2 is chosen, but in planning for the future expansion of the CSB, it is advantageous to leave the excess space in its current CPA configuration.